Urban Flood Management

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NOTE

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COURSE ON

Urban Flood Management

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Addition of case studies

Juan Carlos Bertoni

INTRODUCTION

This text was prepared as a basis for a course of the same title aimed at decision-makers, professionals of various fields of knowledge, working in the field of the urban environment as administrators, legislators, engineers, architects, geologists, biologists and others. The course aims to present a comprehensive view of the management of urban rainwater, which will also include urban drainage and river flooding in cities. The course does not address project-specific aspects, but attempts to tackle the strategic aspects of management and the interfaces with the various aspects of urban water and other elements of city planning and management.

This course was initially given in Brazil and later in a number of cities in South America in cooperation with various national and international bodies, with the aim of bringing an end to unsustainable urban development and the resulting impact on rainwater.

Chapter one offers a general overview of urban development and identifies the two main causes of flooding: urban development (or urban drainage) and river flooding. Chapter two looks at the latter type of flooding, how to evaluate it, control measures for mitigating its impacts and managing it within cities. Chapter three presents the main aspects of management in urban drainage such as control strategies and principles, and sustainable control measures for various circumstances. Chapter four looks at the various aspects of comprehensive management in an urban environment, along with its interrelations and interfaces. Chapter five presents the elements of the Urban Rainwater Plan and its relationship with the other elements of urban infrastructure and the Watershed Plan. Chapter six presents case studies of conflicts and management.

Although this text is very broad and tackles a number of economic, social, environmental and climatic situations, it clearly does not address all the issues of the topic, but it does show how to include innovative solutions based on fundamental principles of sustainable development.

Porto Alegre, March 2006
Carlos M. Tucci

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Chapter

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1. Urban water

Comprehensive approach to the aspects of infrastructure related to urban flooding

Urban development accelerated in the second half of the 20th century with high concentrations of population in small spaces, and impacts on the terrestrial and aquatic ecosystems and on the population itself through flooding, disease and reduced quality of life. This process occurs owing to poor control of the urban area leading to direct effects on the water infrastructure: supply, sanitation, urban drainage and river flooding, and solid waste.

This chapter describes the main processes involved in urban water sustainability as a whole and the interrelations of the management of this combined infrastructure. We also present a general overview of urban development and land use, and describe the main elements of urban water infrastructure: water supply, sanitation, solid waste and storm water, and health aspects.

1.1. Urban development

1.1.1. The urbanization process

Urban growth in developing countries has taken place in an unsustainable way, with a consequent degradation of quality of life and the environment. However, this process is more significant in Latin America where 77% of the population is urban (47.2% worldwide). There are 44 cities in Latin America with a population over 1 million (out of a total of 388 cities in the world, UN, 2003). Some 16 megacities (over 10 million inhabitants) grew up in the late 20th century, representing 4% of the world population, and at least four of those cities are in Latin America ([Table 1.1]), representing over 10% of the region's population.

Urban growth in developing countries has been significant since the 70s. In developed countries, the population has stopped growing and is tending to decrease as the birth-rate is less than 2.1 children per marriage, so keeping the population stable. The present population is recovering or being maintained only through controlled migration. In developing countries growth is even higher and the United Nations projection is that the population will not stabilize until 2150. Urbanization is a worldwide process, with differences between continents. In Latin America urbanization has been high as the rural population has moved to the cities. This process is tending to stabilize population growth in the medium term. It is assumed that around 2010 there will be 60 cities with more than 5 million inhabitants, and most of them will be located in developing countries. Table 1.1 shows the most highly populated cities in the world and in Latin America.

The growth rate of the population of Latin America and the Caribbean fell from 2.1% in the early 80s to 1.5% in the first five years of the new millennium, and the trend is heading for 1.2% for the year 2015. This reflects the process of urbanization which is tending to reduce the rate of population growth.

Table 1.1. Largest cities in the world and in Latin America (UN, 2003)

Largest in the world		**Largest cities in Latin America**	
City	**Population millions**	**City**	**Population millions**
Tokyo	26.44	Mexico City	17.8
Mexico City	18.07	São Paulo	16.3
São Paulo	17.96	Buenos Aires	12.02
Bombay	16.09	Rio de Janeiro	10.65
Los Angeles	13.21	Lima	7.44
Calcutta	13.06	Bogotá	6.77
Shanghai	12.89	Santiago de Chile	5.47
Dakar	12.52	Belo Horizonte	4.22
Delhi	12.44	Porto Alegre	3.76

Figure 1.1 shows the proportion of growth of urbanization observed in Latin American countries, and a projection. It can be seen that South America and Mexico are more than 70% urbanized, while Central America is close to 50%.

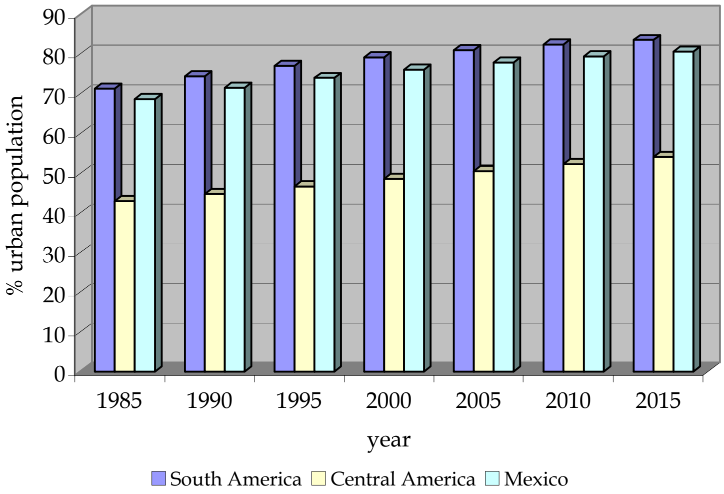

Figure 1.1. Urbanization in Latin American countries

It is therefore possible that the problems faced by South American countries and Mexico may be reproduced in Central America as the trend towards urbanization continues. By mid-2015 the whole region will have a total proportion of 80.7% of urban population, mainly due to the most populated countries which have the highest rates of urbanization.

Table 1.3 shows some of the Latin American countries by order of population and urbanization in 2000. Figure 1.2 shows the relationship between urbanization and the population of these countries. Two trends are observed for countries with lower population, one for countries with higher per capita income, which have high levels of urban population, and another for lower-income countries, which have a lower urban population.

Table 1.2. Population and urbanization in some Latin American countries (Cepal, 2002)

Country	**Population 1000 inhabitants**	**Urban population %**
Brazil	172 891	79.9
Mexico	98 881	75.4
Colombia	43 070	74.5
Argentina	37 032	89.6
Peru	25 939	72.3
Venezuela	24 170	87.4
Chile	15 402	85.7
Ecuador	12 879	62.7
Guatemala	11 385	39.4
Bolivia	8 516	64.6
Honduras	6 485	48.2
El Salvador	6 397	55.2

Paraguay	5 496	56.1
Nicaragua	5 071	53.9
Costa Rica	4 112	50.4
Uruguay	3 337	92.6
Panama	2 856	55.7
Total / mean	483 919	76.14

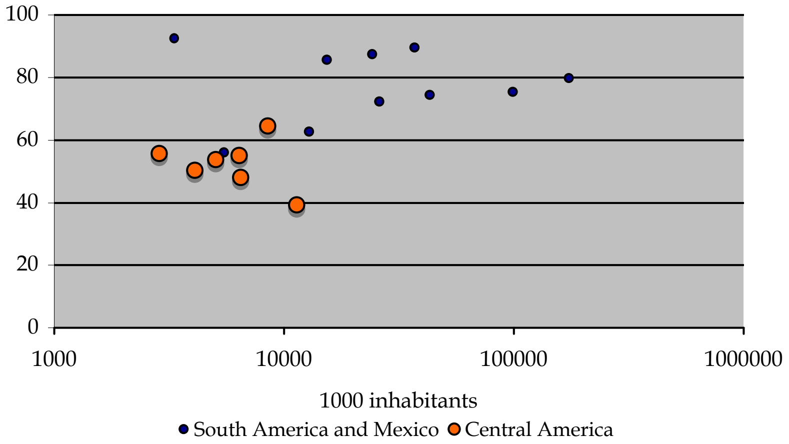

Figure 1.2. Relationship between population and urban population.

1.1.2. Impact on urban infrastructure

The main problems relating to infrastructure and urbanization in developing countries, especially for Latin America, are:

- *Population highly concentrated in small areas*, with an inadequate transport system, water supply and sanitation, polluted air and water, and flooding. These poor environmental conditions are the main limitations on development as they diminish the hygiene conditions and the quality of life of the population and have serious environmental impacts;
- *Uncontrolled growth of cities* owing to the rural exodus as people migrate to the large cities in search of work. These districts generally have no security, traditional infrastructure for water, sewage, drainage, transport or refuse collection, and are dominated by groups of delinquents generally involved in drug trafficking.
- *Urbanization is spontaneous* and urban planning is limited to the parts of the city occupied by the

middle- and high-income population. In the absence of spatial planning, housing is built in areas at risk of flooding and landslip, leading to frequent deaths in the rainy season. In January 2004 alone, 84 people died in Brazil as a result of flood-related events. A substantial proportion of the population lives in some type of emergency housing. As a result, there is the *formal city* and the *informal city*. Urban management generally tackles only the former, the formal city.

Urbanization problems occur as a result of one or more factors over time and these have increased in recent decades. Some of these factors are:

- Populations migrating to the cities are generally of low income and have no investment capacity, and tend to invade public areas or buy marginal land with no infrastructure or formal urbanization. These areas include areas at risk from flooding and landslip.
- A high employment, income and housing deficit.
- Inadequate legislation on the control of urban space.
- Inability of the municipality to plan and anticipate urbanization and invest in the planning of safe and suitable spaces for urban development.
- Economic crises in the countries.
- The municipality only manages to control the areas of medium and high economic value with land-use regulations, where the formal city is.

1.1.3. Urban infrastructure planning

Urban planning is carried out for the formal city, and there is hardly any analysis of land-use trends for the informal city. The main problems related to water infrastructure in the urban environment are as follows:

- Untreated sewage: most cities in the region have no sewage treatment and discharge the effluent into the storm drains, which run in urban rivers (this is the case in most Brazilian cities);
- Systems for discharging sewage (often untreated) without implementing an urban drainage system, causing the cities to suffer frequent flooding and an increase in impermeability;

- Settlement of flood plains, subject to frequent flooding;
- Impermeabilizing and canalizing of urban rivers with an increase in the peak flow (up to seven times) and frequency; increase in the solid residue load and reduction in storm water quality in the rivers close to urban areas;
- Deterioration in water quality owing to untreated effluents, leading to potential risks for supplying the population in various circumstances; one of the most critical aspects has been the settlement of watersheds for reservoirs supplying the city, which become eutrophicated, so creating risks to public health.

There is a limited understanding of what is meant by comprehensive management of urban land and infrastructure. Most of the problems raised were created by one or more of the aspects described below:

- *Insufficient knowledge* on the part of the public and professionals in various areas about the problems and their causes. Lack of knowledge by decision-makers leads to high costs, as some firms take advantage of the situation to increase their profits. For example, the use of canalization for drainage is very widespread, although it is expensive and tends to aggravate the problems it is supposed to solve. When flooding occurs, the public themselves request a canal to be built to control it. Once the canal has been built, flooding is transferred downstream, affecting other population groups. Engineering firms make a lot of money out of it since this type of work costs ten times as much as a more sustainable measure.
- *Inadequate understanding by professional engineers of the planning and control of systems:* many of the engineers working in the urban environment are not up to date with environmental aspects and generally look for structural solutions, which degrade the environment, creating too many impervious areas and thereby increase the temperature, flooding, pollution, etc.
- *Sectoral approach to urban planning:* urban areas are planned and developed without taking account of the various components of water infrastructure; many professional working in this field have a limited sectoral approach.

- *Lack of management skills:* the municipalities do not have a proper structure for planning and managing the various aspects of water in the urban environment.

1.2. Urban water systems

The main systems related to water in the urban environment are as follows:

- water sources,
- water supplies,
- treatment of sewage effluent,
- urban drainage control,
- river flooding control.

Urban *water sources* provide water for human, animal and industrial consumption. They may be surface or underground sources. Surface sources are rivers close to communities. The availability of water in this system varies over the years; sometimes the quantity of water available is insufficient to meet demand, often requiring a reservoir to be built to guarantee the availability of water for the community over time. Groundwater sources are aquifers supplying water from the subsoil and demand can be met by pumping this water. In this way, groundwater is generally used in small and medium-sized cities, as this depends on the flow that can be pumped out of the aquifer without upsetting the balance of incoming and outflowing water.

The *supply of water* involves the use of the water available in the source, which is transported to the water treatment plant (WTP) and then distributed to the population via the water mains. This system involves major investments, generally by the public sector, to ensure an adequate quantity and quality of water.

Sewage effluent sanitation is a system for collecting effluent (domestic, commercial and industrial) and transporting it to a treatment plant and discharging the treated water back into the water courses.

Urban drainage is the system for collecting water (and solid waste) from precipitation on urban surfaces, treating and discharging it into the rivers.

Control of river flooding aims to prevent the population being affected by natural flooding. In the rainy season the rivers naturally leave their minor beds to occupy their flood plains. As this occurs irregularly over time, the population tends to settle the flood plain, and is thus subject to flooding.

1.3. Water availability

All the components of the water systems are closely interrelated owing to the way in which they are managed within the urban environment. In recent years man has been experiencing a situation in which the elements that are essential to life, which are given their proper importance only when they are in short supply (such as water and energy), may be scarce for longer time than we are used to. Could we be returning to the times of our grandparents when the infrastructure was still unreliable? These are doubts in the minds of many people, with the avalanche of information, often contradictory, appearing in the media.

On this planet, the total amount of water extracted from the rivers, aquifers and other sources has increased almost nine fold, while usage per person has doubled and the population has tripled. In 1950 world reserves represented 16 800 m^3/person; this reserve has currently dropped to 7 300 m^3/person, and it is expected to drop further: 4 800 m^3/person over the next 25 years, as a result of the increasing population, industrialization, agriculture and pollution. When we compare uses, the quantity of water available and human needs, one could incorrectly conclude that there is sufficient water. However, the distribution of water varies widely around the planet over time and space; there are various vulnerable regions, in which some 460 million people (some 8% of the world's population) suffer from frequent water shortages and some 25% are headed in the same direction. Table 1.3 summarizes the supply of water used by organizations linked to the United Nations.

The natural water cycle consists of various physical, chemical and biological processes. When man acts on that system and congregates in a space, major changes occur that dramatically alter that cycle, leading to significant (often irreversible) impacts on man himself and nature.

Table 1.3. Acceptable proportion of "improved"[1] – water supply and sanitation in urban areas (WHO and UNICEFJMP, 2002)

Region	**Water supply**[2]	**Sanitation**[3]
Africa	86	80
Asia	93	74
Latin America and Caribbean	94	86
Oceania	98	86
Europe	100	99
North America	100	100
World	**95**	**83**

1- *This is a generic qualitative definition for water provided and disposed of without contaminating the population. It is not the same thing as "safe" water, which should be based on the quantitative measurement of indicators.*
2- *Here, "water supply" means the supply of water to the population.*
3- *Here, "sanitation" means the disposal of sewage in piped systems or the ground, not necessarily involving collection or treatment.*

One of the first impacts is the risk of water shortages. Nature has shown that supplies of water, that runs in rivers and depends on rainfall, are random and that there is a wide variation between the rainy and dry seasons. Throughout history, man has tried to control this water for his own benefit using hydraulic structures. These structures attempted to reduce shortages by regulating the flow, thereby increasing availability over time.

In the past, when cities were smaller, the population drew off water from the river upstream and discharged untreated water downstream, leaving nature to deal with the environmental impact and restore the quality of the water. There was less impact owing to the low volume of sewage discharged. With growing urbanization and the use of chemicals in agriculture and the environment in general, large quantities of water used in cities, industry and agriculture are being discharged with a high pollution load into the rivers. With the increase in the population there will always be a city upstream and another downstream, and as the surface water source, the river or the water discharged into the river is polluted, the various strata of the subsoil where the water is drawn from are also polluted.

The consequence of expansion with no environmental perspective is a deterioration of the water sources and a reduction in the supply of safe water to the population, or a scarcity of quality water (see Figure 1.3 for the pollution cycle in cities). This process requires a number of preventive urban and environmental planning measures aimed at minimizing the impacts and ensuring sustainable development.

The risks of flooding and deterioration of water quality in the rivers of cities in developing and developed countries are a prevalent process of the late 20th and early 21st centuries. It is caused by:

- Contamination of surface and groundwater sources with urban effluent such as sewage, storm water and solid waste discharge;
- Poorly sited sewage, storm water and solid waste discharges in cities;
- Flooding in urban areas due to urbanization;

- Erosion and sedimentation creating degraded areas;
- Settlement of river banks, with the risk of flooding, and of steeply sloping areas, such as urban hillsides, subject to landslip after the rainy season.

Most of these problems are caused by an incorrect approach to the control of storm water by the community and professionals, who are still giving priority to centralized projects, with no overview of the watershed or the social and institutional aspects of the cities. The paradox is that the poorest developing countries are giving priority to economically unsustainable action, such as structural measures, while developed countries are attempting to prevent the problems with more economical, non-structural measures that are sustainable.

1.4. Assessment of urban water components

1.4.1. Contamination of water sources

Urban development has led to a cycle of pollution, caused by the effluents of the urban population, such as domestic, industrial and storm water discharges (Figure 1.3). This occurs owing to:

- Discharge of untreated liquid sewage into the rivers, polluting them since they have a limited capacity to dilute it; lack of investment in sanitation systems and treatment plants; those that do exist are inefficient;
- Discharge of storm water containing large quantities of organic pollutants and metals into rivers in the rainy season; this is one of the most significant sources of diffuse pollution;
- Pollution of groundwater by industrial and domestic discharges, through septic tanks, and leakage from liquid sewage and storm-water systems;
- Deposits of solid urban waste, which are a continuous source of pollution of the surface and groundwater;
- Urban land use that takes no account of its impact on the water system.

As the years go by, places with water supplies tend to suffer reduced water quality or require more chemical treatment of the water supplied to the population. Therefore, even if there is a good water supply today, it may be compromised unless steps are taken to control the pollution cycle.

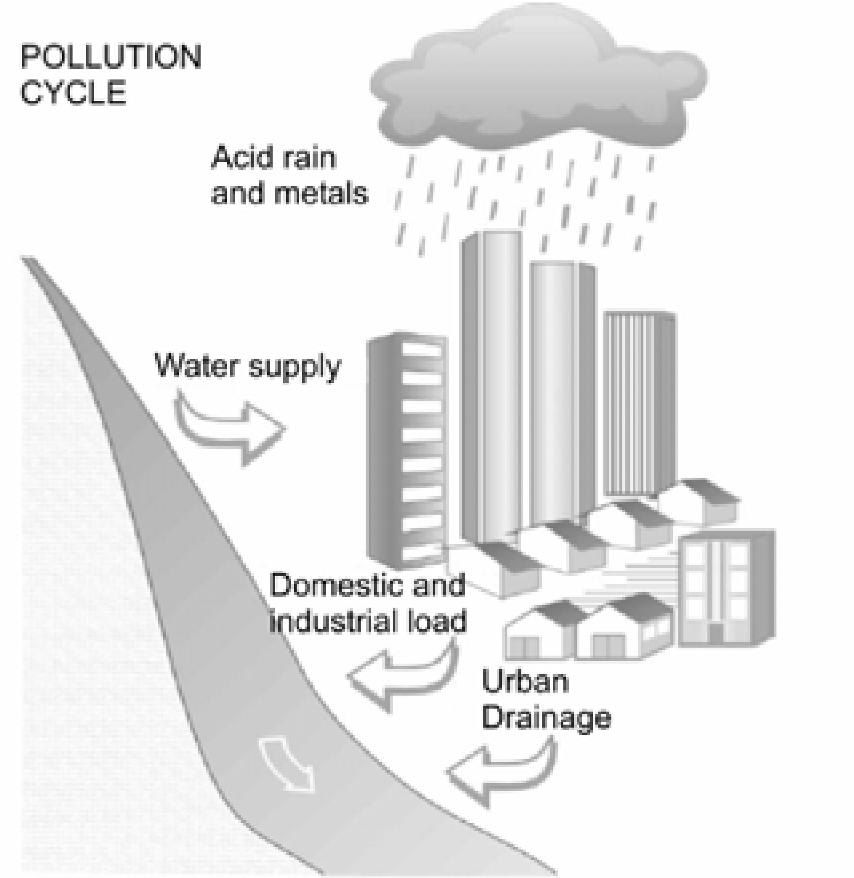

Figure 1.3. Pollution cycle in cities.

Many cities use urban reservoirs to satisfy a community’s regular demand for water. Since the reservoirs are located close to the cities, there is high pressure for urban settlement in the catchment area upstream of the reservoir. Unfortunately the local authorities have little control over this and much illegal or clandestine urbanization takes place over water sources. In Brazil, legislation has been passed to protect these areas, but its effect was entirely the opposite of what was expected (see Box 1.4).

As a consequence of this settlement and the lack of sewage treatment, the polluting load is discharged directly into the reservoir, increasing the likelihood of eutrophication (richness in nutrients). A eutrophic reservoir tends to produce algae that consume the nutrients. These algae may produce toxins which, when absorbed by man, act cumulatively on the liver, producing potentially fatal illnesses, mainly in the case of dialysis treatment (as happened in Caruaru, Brazil, where several people died in a dialysis clinic using contaminated water). The toxins also accumulate in the bottom of lakes and some fish feed on them. Conventional water treatments do not remove these toxins.

Box 1.4. Legislation for protecting water sources in Brazil

The legislation for protecting water sources that has been approved in most Brazilian States protects the catchment area used to supply the cities. In these areas, urban and other uses that could jeopardise the quality of the water supply are prohibited.

With the growth of the cities, these areas were put under pressure for settlement by the neighbouring property values and the lack of the owners' interest in protecting the area, since its value dropped as a result of the legislation. These areas are not suitable for the low-income population and the immediate consequence is an increase in pollution. Many owners encouraged the invasion so as to be able to sell the property to the authorities.

The main lesson to be drawn from this example is that when the water catchment area was declared to be of public utility, it should have been bought by the authorities or some economic value should have been created for the property by generating indirect markets for the area, or even other benefits for the owners, to compensate them for not being able to use the land.

The main sources of pollution of urban aquifers are:

- Sanitary landfills that contaminate groundwater via the natural processes of precipitation and infiltration. Sanitary landfills should not be sited in catchment areas, and areas of low permeability should be chosen. The effects of contamination of groundwater should be examined when the landfill site is chosen.
- Most Brazilian cities discharge all sewage into septic tanks. This system tends to contaminate the top of the aquifer. This pollution can compromise the urban water supply when there is communication between various strata of the aquifers by percolation and incorrectly bored artesian wells.
- The storm drain system can pollute the ground by volume lost in transit and also through obstructed sections of the system that force the contaminated water out of the piping system.

1.4.2. Water supply and sanitation

Access to water and sanitation reduces infant mortality by 55% on average (WRI, 1992). Well implemented infrastructure and sanitation are essential for proper urban development.

In 1990, developing countries had water supplies covering 80% of the population but only 10% of the population had sanitation. Even with 80% of the population covered, there were a billion people without access to clean water. During that period, 453 million people – or nearly 33% of the population – did not have access to sanitation (meaning simply collection and not necessarily collection and treatment). In four years, 70 million were provided with sanitation, but the population grew fast, increasing the proportion of people without access to sanitation to 37% (Wright, 1997).

In many South American cities the water services suffer from chronic problems, with water leaks in the distribution system and no rationalization of domestic or industrial water consumption. Cities lose 30 to 65% of the water entering the distribution system. Table 1.5 shows the difference in losses in the systems of cities in developed countries and cities in South America, despite higher *per capita* consumption. When water is needed, the tendency is to look for new sources without reducing the losses and without developing awareness of water rationalization.

Box 1.6 shows an example of rationalization of water use in New York. The city of Las Vegas grants subsidies to citizens who change the type of vegetation in their homes so that they consume less water. The city of Denver did not obtain approval for building new dams to cater for rising water demand, and so had to rationalize the use of water and buy up the farmers' water rights.

Several South American cities have developed with moderate coverage of sewage collection systems, and practically no sewage treatment (Table 1.7). Initially, when the city has low density, sewage is discharged into septic tanks. As the city grows the authorities do not invest in the system and the untreated liquid sewage goes into the storm drain system. This is discharged into the urban rivers and the *downstream* river system, with the impact on water quality already mentioned. See the figures in Table 1.8 for coverage in Brazil.

Table 1.5. Water mains consumption and losses (World Bank, 1996)

Place	**Year**	**Consumption litres / person /day**	**Losses in network %**
Brazil (mean)	1989	151	39
Brasilia	1989	211	19
São Paulo	1988/1992	237	40
Santa Catarina	1990	143	25
Minas Gerais	1990	154	25
Santiago	1994	204	28
Bogotá	1992/1991	167	40
Costa Rica	1994	197	25
Canada (mean)	1984	431	15
USA (mean)	1990	666	12
Tokyo	1990	355	15

Even in countries where sewage is collected and treated, little is known about its efficiency and the level of downstream pollution. This process can get worse with privatization, if the awarding authority does not have adequate inspection capabilities.

Box 1.6. Rationalization of water use (Scientific American, 2001)

In the early 90s the city of New York experienced a major water supply crisis and was about to plunge into chaos as the population grew. The city needed more than 90 million gallons (340 million m^3) a day, about 7% of the city's total consumption. The alternative was to spend more than a billion dollars to pump water from the Hudson river, but the city decided to reduce demand.

In 1994, a rationalization programme was launched, with an investment of US$ 295 million, to replace a third of all the city's toilet installations. Each toilet had a cistern consuming around 5 gallons per flush, and these were replaced with cisterns of 1.6 gallons. On completion of the programme in 1997, 1.33 million cisterns had been replaced in 110 000 buildings, reducing each building's water consumption by 29%, thereby cutting consumption by 70 to 90 million gallons a day.

Table 1.7. Access to sanitation* as % (World Bank, 1999)

Country	**1982 (%)**	**1995 (%)**
Argentina	76	80
Bolivia	51	77
Brazil	33	74
Chile	79	95
Colombia	96	70
Ecuador	79	70
Paraguay	66	20
Peru	67	78
Uruguay	59	56
Venezuela	57	74

* access to sanitation denotes the proportion of the population that has sewage collection either by a public system or local disposal.

Table 1.8. Water supply and sewage discharge in Brazil (IBGE, 1997)

Service type	**Population served (%)**		
	Brazil	**Urban**	**Rural**
Water supply:			
Water mains	75.93	90.56	19.91
Other	24.07	9.44	80.09
Sewage system:			
Collection system	37.83	46.79	3.50
Septic tank	23.03	25.45	13.75
Other	27.70	23.59	43.48
None	11.43	4.17	39.26

In Brazil in recent years sanitation companies have invested in sewage collection systems and treatment plants, but the proportion of the volume produced by the cities that is actually treated before being discharged into the river is still very low.

Here are some of the issues:

- When sewage systems are implemented or designed, often no provision is made for connecting discharges from homes or buildings to them. In this way the systems do not collect the planned volume of sewage and the plants do not receive the flow of sewage that they were designed for. In this case the project was not designed properly or was not implemented as it should have been.
- Since the sewage continues to flow into the storm drainage system the environmental impact on the river system continues to be high. The conclusion is that public investment is inadequate, taking account only of the companies carrying out the work, and not of the society contributing the resources, and no account is taken either of the need for environmental conservation.
- As many companies are paid for the collection and treatment service regardless of whether the treatment is carried out, what motivation would these firms have for completing the coverage of collection and treatment of sewage? Another common scenario is the increase in collection without treatment, thereby aggravating the problem as river pollution is concentrated.
- When the "polluter pays" system is implemented, who will pay the penalties for the pollution generated?
- There is currently a discussion on the concession of water and sewage services in Brazil that has brought the funding and privatization of the sector to a standstill. The Federal Constitution states that concessions for water and sewage services are the responsibility of the municipalities, while the water and sanitation companies are generally a provincial responsibility. Since they do not have the concession, their financial value is reduced on the privatization market.

The Federal Government recently sent a bill to the National Congress on the issue, reviving the controversy a involves major conflicts of interest.

1.4.3. Solid waste

Waste production is the sum of the total collected from domestic, industrial and commercial premises, plus the total collected in the streets and what arrives in the drainage.

$$TR = Tc + T1 + Tdr \quad (1.1)$$

where TR is the total produced by society and the environment, Tc is the total collected, TI is the total from urban refuse collection and Tdr is the total reaching the drainage system. The first two volumes can be recycled, thereby reducing the volume to be dumped in the environment. The less efficient are the urban collection and refuse services, the higher the volume of Tdr, so increasing the cost of collection, obstruction of the sewers and the environmental subsidy received by the polluting society.

In urban development we observe the following distinct stages in the production of solid material in urban drainage (Tdr):

> *Initial stage:* when there is a change in the coverage of the watershed, through the removal of its natural protection, the soil is unprotected and erosion increases in the rainy season, thereby also increasing sediment production. Examples of this are: during housing developments the soil remains unprotected; building on large areas or lots leads to large quantities of soil movement, which is carried in surface runoff. In this phase, sediment predominates and little refuse is produced.
>
> *Intermediate stage:* during this stage, the population is established but there is no major soil movement due to new building. The population produces refuse in addition to the production of sediments.
>
> *Final stage:* in this stage practically all the urban areas are consolidated and urban waste only is produced, with a smaller proportion of sediment from a few areas where building is taking place or which have no consolidated cover.

The total volume of waste reaching the drainage system depends on the efficiency of the urban services and factors such as: frequency and coverage of refuse collection, frequency of street cleaning, recycling, type of waste disposal by the population and frequency of precipitation.

Refuse collected in Brazil is of the order of 0.5 to 0.8 kg / person / day, but no information is available on the quantity of refuse that goes into the drains. There is little information at international level. In San José, California, refuse going into the drains has been estimated at 1.8 kg / person / year. After the streets are cleaned, 0.8 kg / person / year goes into the drains (Larger *et al*., 1977). In Brazil this volume must be higher, as solid waste is often discharged into the drains.

In the past decade there has been a visible increase in urban refuse owing to plastic packaging that is not readily recycled. The rivers and the whole drainage system are full of bottles and plastic packaging of all kinds.

The main environmental consequences of sediment production are as follows:

- clogging of sections of drain pipe, thereby reducing the discharge capacity of urban conduits, rivers and lakes. For instance, the lagoon of Pampulha (in Belo Horizonte) is an example of an urban lake that has been clogged. Since it is very wide and shallow, in the dry season the Diluvio stream in Porto Alegre has deposited sediment from the watershed in the canal, leading to growth of vegetation and reducing flow capacity during floods.
- The sediment carries pollutants that contaminate the storm water.

1.4.4. Storm water runoff

Storm water runoff can lead to flooding and impacts in urban areas by means of two processes, separately or in combination.

Flooding of riverside areas: natural flooding that occurs in the flood plains of rivers owing to temporal and spatial variations in precipitation and runoff in the catchment area;

Flooding due to urbanization: flooding from the urban drainage system due to the effect of soil impermeabilization, canalization or obstruction of water flow.

Flooding of riverside areas

Rivers generally have two beds: the minor bed, where the water runs most of the time. The minor bed is delimited by the risk of 1.5 to 2 years. Tucci y Genz (1994) obtained a mean value of 1.87 years for the rivers in Alto Paraguay. Flooding occurs when the water runs above the level of the minor bed and enters the major bed. The levels of the major bed determine the magnitude and risk of the flooding. Flooding has an impact when this risk area is populated (Figure 1.4). This type of flooding generally occurs in medium-sized and large watersheds (> 100 km^2).

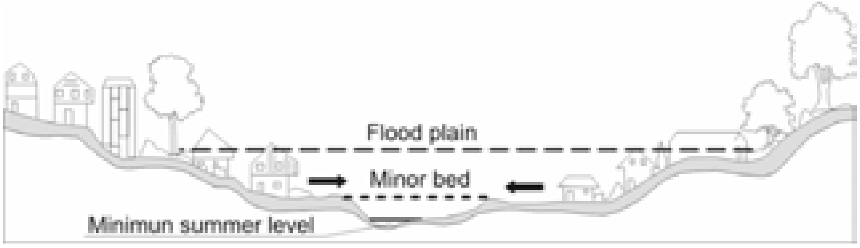

Figure 1.4. Characteristics of river beds

Flooding of a river's major bed is a natural process, as a *consequence of the water cycle*. When the population settles the major bed, which is a risk area, impacts are frequent. These conditions are caused by the following actions:

- Cities' urban development master plans generally impose no restrictions regarding the settlement of areas at risk of flooding; the number of years without flooding is enough for entrepreneurs to divide up these areas for urban settlement;
- Invasion of government-owned areas near rivers, by low-income population;
- Settlement of medium-risk areas, less often flooded, but when they are they suffer significant damage.

The main impacts on the population are:

- Material damage and loss of life;
- Interruption of economic activity in the flooded areas;
- Infection by water-borne diseases such as leptospirosis, cholera, etc.;
- Water pollution by flooding of dumps of toxic materials, treatment plants, etc.

Current management offers no incentive to prevent such problems, since when a flood occurs the municipality declares a public emergency and receives resources that are not monitored since there is no need to make public invitations to tender to spend them. When most sustainable solutions involve non-structural measures and restrictions on the population, a mayor is unlikely to choose such a solution, as the public generally expects some structural works to be carried out. To implement non-structural measures, the government will have to interfere with the interests of the owners of risk areas, which is politically complex at local level.

To change this scenario, there is a need for a programme at provincial (departmental) level, involving public education, plus action with the banks funding works in risk areas.

Flooding due to urbanization

Flooding is becoming more frequent and severe owing to the impermeabilization of the soil and the construction of storm drain systems. Urban development can also create obstructions to runoff, such as sanitary landfills, bridges, inadequate drainage, obstructions of runoff and conduits, and clogging. This flooding is generally regarded as local since it involves small watersheds (< 100 km^2, and very often < 10 km^2).

As the city develops, the following impacts generally occur:

- Increase in peak flows (up to 7 times, Figure 1.5) and in frequency owing to the higher runoff capacity through conduits and canals, and impermeabilization of surfaces;
- Increased sediment production from unprotected surfaces and production of solid waste (refuse);
- Deterioration in quality of surface and ground water, owing to street cleaning, transport of solid material and clandestine sewage and storm water connections;

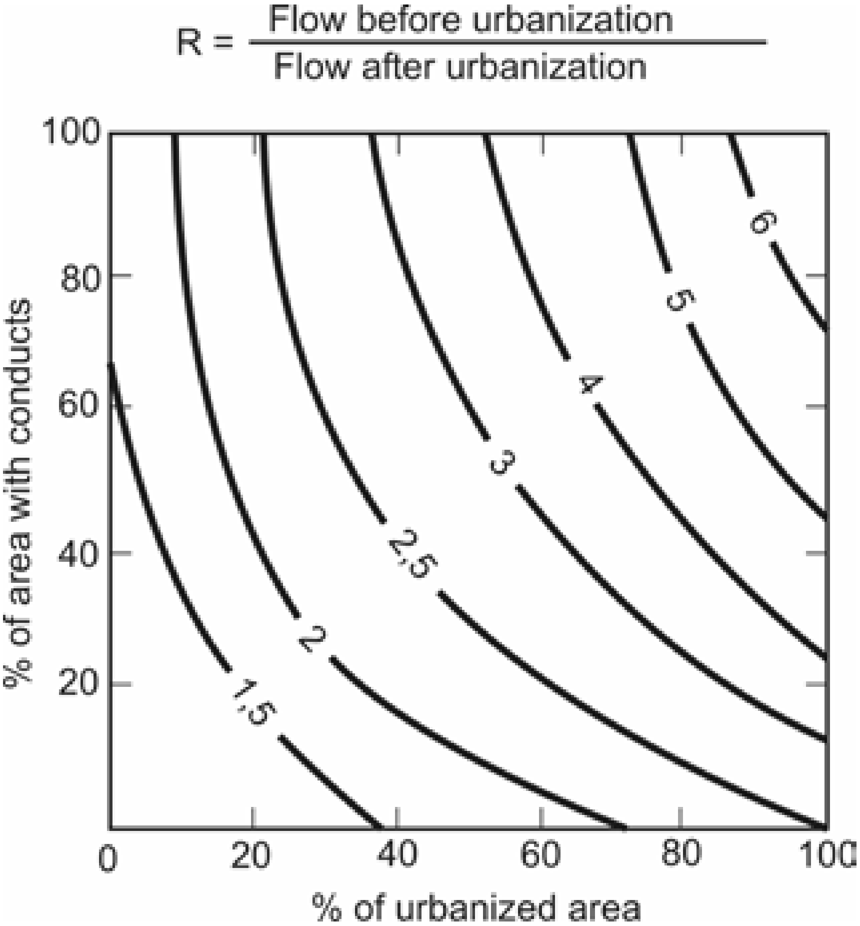

Figure 1.5. Curves for the value of R: increase in mean flood flow as a function of the impervious area and canalization of the drainage system (Leopold 1968).

- Disorganized implementation of urban infrastructure, such as: (a) bridges and street embankments obstructing runoff; (b) reduced channel section due to backfilling in bridges and building in general; (c) deposition in and obstruction of rivers, canals and conduits by refuse and sediments; (d) inappropriate drainage projects and works, with reduced downstream diameters, drainage without runoff, etc.

Quality of storm water

The quantity of material suspended in storm water drainage represents a very high load owing to the flows involved. This volume is more significant at the onset of flooding. The first 25 mm of surface runoff generally carry most of the polluting load originating in storm water (Schueller, 1987).

One way of assessing the quality of urban water is to use parameters characterizing organic pollution and the quantity of metals. Table 1.9 gives some concentration values described in the literature. Schueller (1987) states that the mean concentration of the events does not vary as a function of the volume of the event, but is characteristic of each area drained.

Sewers may be combined (sewage and storm water in the same conduit) or separate (separate storm water and sewage systems). The law requires separate systems, but in practice this does not happen owing to clandestine connections and the lack of a sewage system. Owing to a lack of financial resources to build a sewage system, some municipalities have allowed sewage to be discharged into the storm drains, which can be an inappropriate solution since the sewage is untreated. When a sewage system is implemented, the major difficulty is to remove the existing connections to the storm drains, which in practice results in two mixed systems with different load levels.

Table 1.9. Mean values of storm water quality parameters (mg/l) in some cities

Parameter	**Durham [1]**	**Cincinatti [2]**	**Tulsa [3]**	**Porto Alegre [4]**	**APWA [5]** **Min.** **Max.**
DBO		19	11.8	31.8	1 700
Total solids	1 440		545	1 523	450 14 600
pH		7.5	7.4	7.2	
Coliforms (NMP/100ml)	23 000		18 000	$1.5x10^7$	55 $11.2x10^7$
Iron	12			30.3	
Lead	0.46			0.19	
Ammonium		0.4		1.0	

I – Colson (1974); 2 – Weibel et al (1964); 3 -AVCO (1970); 4 - Ide (1984); 5-APWA (1969)

The advantages and disadvantages of the two systems have led to wide-ranging discussions all over the world. Considering the *interrelation with drainage, a single system increases the cost of quantitative control of storm water runoff* in that it requires the detention basins to be buried. This type of construction has a unit cost seven times higher than open detention systems (IPH, 2000). The other disadvantages are: in the dry season in urban areas there may be a significant odour; during flooding, when overflows occur, there is a high potential for proliferation of disease. This scenario is very serious when overflows are frequent.

On the other hand, cities that give priority to the sewage system and ignore storm water suffer frequent flooding as urbanization advances, as happened in Barranquilla, Colombia and some areas of Santiago.

There are no single miracle solutions, but there are appropriate and rational solutions for each situation. The ideal is to reconcile the collection and treatment of sewage effluent with the retention and treatment of storm water runoff, within an integrated approach that caters for both health and environmental aspects.

The quality of the water in the storm drains depends on a number of factors: the type and frequency of urban cleaning; the precipitation intensity and its distribution in time and space, the time of year and the use made of the urban area.

1.4.5. Summary of the present situation

Currently one of the main problems, if not the main problem of water resources in Brazil, is the impact of urban development, both within the municipalities and outside them, as pollution and flooding are exported *downstream*.

The metropolitan areas have ceased to grow at the core but they are expanding in the suburbs, precisely where the water sources are concentrated, so aggravating the problem. Cities tend to keep looking for increasingly distant and expensive sources. Public inefficiency is observed in:

- The major loss of treated water in urban distribution systems. It is not rational to use new sources when leakage continues at such high levels. The losses can be financial and physical, the former being related to metering and payment and the latter due to leakage from the system.
- When there is leakage, the treatment systems do not collect sufficient sewage, so the treatment plants continue to operate below their rated capacity. The investment in extending coverage does not help to achieve the Millennium Goals approved in international fora.
- The storm drainage system suffers from two problems: (a) in addition to carrying sewage not collected by the sanitation system, it also carries pollution in storm water runoff (organic load and metals); (b) excessive construction of canals and conduits merely transfer flooding from one place to another within the city, at costs that the municipalities cannot afford.

1.5. Water-borne disease

There are many diseases that are transmitted in water. Diseases transmitted through water can be classified according to the scheme of White *et al.* (1972) and presented by Prost (1993):

> *Water-borne diseases:* these depend on water for transmission, such as cholera, salmonella, diarrhoea, leptospirosis (developing during flooding by mixing with mouse urine), etc. The water acts as a passive vehicle for the infection agent.
> *Water-washed diseases:* these depend on the education of the population and the availability of safe water.
> These diseases are linked to ear, skin and eye infections.
> *Water-related diseases:* the agent uses the water to develop, as with malaria and schistosomiasis.

Many of these diseases are related to poor coverage of treated water and sanitation, such as diarrhoea and cholera; others are related to flooding, such as leptospirosis, malaria and dengue. Table 1.10 shows the rate of infant mortality and water-borne diseases in Brazil. Table 1.11 shows the proportion of coverage of water services and sanitation in Brazil by income group. The table clearly shows the low level of services for the low-income population. Table 1.12 shows values for Brazil.

Table 1.10. Mortality due to water-borne diseases in Brazil (Mota and Rezende, 1999).

Age	**Intestinal infection**		**Others ***	
	1981	**1989**	**1981**	**1989**
< 1 year	28 606	13 508	87	19
aged 1 to 14	3 908	3 963	44	21
> 14 years	2 439	3 330	793	608

*cholera, typhoid fever, poliomyelitis, diarrhoea, schistosomiasis, etc.

Table 1.11. Proportion of coverage of services, by income group in Brazil as % (Mota and Rezende, 1999).

Households (MW)*	**Treated water**		**Sewage collection**		**Sewage treatment**	
	1981	**1989**	**1981**	**1989**	**1981**	**1989**
0 - 2	59.3	76.0	15	24.2	0.6	4.7
2 - 5	76.3	87.8	29.7	39.7	1.3	8.2
> 5	90.7	95.2	54.8	61.2	2.5	13.1
All	78.4	89.4	36.7	47.8	1.6	10.1

- MW = minimum wage

Table 1.12. Total number of occurrences in Brazil in 1996 (MS, 1999).

Type	Number
Cholera	1 017
Malaria	444 049
Dengue	180 392
Mortality rate through infectious and parasitic diseases per 100 000 inhabitants (1995)	24.81

Diseases transmitted through water consumption are a cause for concern, due mainly to the following:

Domestic loads: the excess of nutrients has led to eutrophication of the lakes, increasing the level of algae, which produce toxins. These toxins may remain soluble in the water or may deposit on the bottom of rivers and lakes. The toxins attack the human liver and cause degenerative diseases such as cancer and cirrhosis.

Industrial loads: industrial effluent consists of a wide variety of compounds and, as industry evolves, new ones are produced every day. The inspection teams are not readily in a position to keep track of the process;

Diffuse loads: diffuse loads from farming areas contain pesticide compounds, and there are new ones every year. We mentioned the diffuse load from an urban area above; it can have a cumulative effect on the human organism.

1.6. Comparison between developed and developing countries

Table 1.13 compares the state of urban water infrastructure in developed and developing countries.

Table 1.13. Comparison of water-related aspects in the urban environment

Urban infrastructure	Developed countries	Developing countries
Water supply	Solved, full coverage	Widespread coverage; tendency for reduced availability owing to pollution of sources; major leakage from the water mains
Sanitation	Widespread coverage of effluent collection and treatment	Lack of sewage system and treatment plants; those that exist fail to collect the planned amount of sewage
Urban drainage	Quantitative aspects are controlled; management of water quality	Unresolved quantitative impacts; unidentified impacts due to water quality

River flooding	Non-structural control measures such as flood insurance and zoning	Heavy losses owing to lack of control policy

It can be seen that in developed countries many of the problems of water supply, sewage treatment and control of the quantity of runoff in urban drainage have been solved. In the latter case, priority has been given to control by means of non-structural measures that oblige the population to control the impacts of urbanization at source. The main problem in developed countries is control of diffuse pollution carried by storm water. Whereas in developing countries the problem is still at the stage of sewage treatment.

In some countries, such as Brazil, the problem of the water supply, which could be solved, owing to the wide coverage of the supply, reappears owing to major contamination of sources. This problem is caused by poor coverage of sewage collected and treated. There are actually many treatment systems and plants, but the proportion of untreated sewage is still very high. Owing to the contamination cycle, caused by an increasing volume of untreated sewage for a constant dilution capacity, the objectives also concern public health, since the population becomes contaminated by all the sewage produced by the city, that we term the *urban pollution cycle* (Figure 1.3).

An example of this scenario is the city of São Paulo, Brazil, which is in the catchment area of the river Tietê and has a total water demand of some 64 m^3/s. Half of the water ($33m^3/s$) is imported from the Piracicaba river basin (headwaters in the Cantareira mountains). This is done because some of the sources near the city are contaminated by untreated sewage. The quality of the Billings and Guarapiranga springs is compromised.

The quantitative control of urban drainage water is still limited in developing countries. The stage of controlling the quality of drainage water is still further off in those countries. In South America, as in most developing countries, the aim is to bring the quantitative impact of storm water drainage under control. For example, the detention systems built in the Brazilian cities focus only on controlling the impact of flooding, without tackling water quality control.

Problems

1. What are the main sources of urban water? When are they used and under what conditions?
2. What are the main causes of contamination of water sources?
3. What are the main problems with collecting and treating sewage effluent?
4. Describe the pollution cycle.
5. What is the difference between river flooding and flooding caused by urbanization?
6. What causes the problems of these types of flooding?
7. What is the difference between the pollution loads of urban drainage and sewage effluent?
8. What are the types of solid urban waste? When are they produced?
9. Why is the flow higher in an urban watershed than in rural conditions?
10. Is this flow uniform or does it vary with the magnitude of flooding? Why?
11. Analyse the causal chain in the deterioration of water quality in rivers *downstream* of cities.
12. What are the critical periods in which the worst cases occur?
13. How does storm water get polluted?
14. Why do total solids increase with urbanization? How do they vary as urbanization progresses?
15. Why is it important to monitor water quality, sediments and water quality when planning the urban watershed? If it is not possible to monitor all watersheds, why then do we invest in doing so? What difficulties are involved in this type of action?
16. Since the impacts of flooding and water quality are caused by urbanization, what are we doing about it today? and what strategies could be adopted to avoid them?
17. Consider an urban sub-watershed with an area of 50 km^2 and a dense population of the order of 120 inhabitants/ha. Estimate the total annual refuse carried in the drainage. Assume that 1.5 and 10% of the total refuse collected reaches the drainage system. Assume a cost of 5 dollar cents/kg for collecting and disposing of this volume. Calculate the annual amount

per person. This is the subsidy that the population is receiving from the environment.

References

APWA,1969. *Water pollution aspects of urban runoff*. Water Quality Administration. (Water Pollution Control Research Series. Report No WP-20-15).

ASCE, 1992. Design and Construction of Urban Stormwater Management Systems. American Society of Civil Engineers. 753p.

AVCO, 1970. *Stormwater pollution from urban activity*. Water Quality Administration. (Water Pollution Control Research Series. Report No 11034 FKL).

COLLISCHONN, W. TUCCI, C. E.M. 1998. *Drenagem urbana e Controle de Erosão.* 6th National Symposium of Erosion Control. 29/3 to 1/04 1998, Chairman Prudente, São Paulo.

COLSON, N.V., 1974. Characterization and treatment of urban land runoff. EPA. 670/2-74-096.

GUARULHOS, 2000. *Código de Obras do Município de Guarulhos*, Law 5617 of 9 November 2000, Municipality of Guarulhos.

IBGE, 1998 "*Anuário Estatístico do Brasil – 1997*", Brazilian Institute of Geography and Statistics, Rio de Janeiro, 1998 (CD-ROM).

IDE, C., 1984. *Qualidade da drenagem pluvial urbana*. Porto Alegre: UFRGS – Postgraduate course in water resources and sanitation 137f. Dissertation (masters).

IPH 2000. *Plano Diretor de Drenagem Urbana de Porto Alegre: 1o fase*. Prefeitura Municipal de Porto Alegre, Instituto de Pesquisas Hidráulicas da Universidade Federal do Rio Grande do Sul, 5 vols.

LARGER, J.^{a}; SMITH, W.G.; LYNARD, W.G.; FINN, R.M.; FINNEMORE, E.J. 1977 *Urban Stormwater management and technology: update and user's guide*. US EPA Report – 600/8-77-014 NTIS N. PB 275654.

LEOPOLD, L.B., 1968. *Hydrology for Urban Planning* - A Guide Book on the Hydrologic Effects of Urban Land Use. USGS circ. 554, 18p.

LLORET RAMOS, C.; HELOU, G. C. N.; BRIGHETTI, G. 1993 *Dinâmica do transporte sólido nos rios Tietê e Pinheiros na região metropolitana de São Paulo. Anais.* 10th Brazilian symposium on water resources. Gramado.

MOTTA, R.; REZENDE, L. 1999. The impact of sanitation on waterborne diseases on Brazil in: Peter H. May (org.) Natural Resource Valuation and Policy in Brazil: Methods and Cases pp 174-187 New York Columbia University Press.

MS, 1999 "Ministério da Saúde" (Ministry of Health), Home page.

NAKAE, T.; BRIGHETTI, G. 1993 Dragagem a longa distância aplicada ao desassoreamento da calha do rio Tietê. Anais. 10th Brazilian symposium on water resources. Gramado.

OLIVEIRA, M. G. B.; BAPTISTA, M. B. 1997 Análise da evolução temporal da produção de sedimentos na bacia hidrográfica da Pampulha e avaliação do assoreamento do reservatório. Anais. 12th Brazilian symposium on water resources - ABRH. Vitória.

PMBH, 1996 Plano Diretor Urbano. Prefeitura Municipal de Belo Horizonte.

PMPA, 2000. Segundo Plano de Desenvolvimento Urbano e Ambiental de Porto Alegre. Prefeitura Municipal de Porto Alegre.

PROST, A. (1992) 'The Management of Water Resources, Development and Human health in the Humid Tropics' In: Hydrology and Water Management in Humid Tropics. Cambridge University Press, p. 437-453.

RAMOS, M.M.G. 1998 *Drenagem Urbana: Aspectos urbanísticos, legais e metodológicos em Belo Horizonte*. Masters dissertation, Federal University College of Engineering, Minas Gerais.

ROESNER, L.A; TRAINA, P. 1994. Overview of federal law and USEPA regulations for urban runoff. *Water Science & Technology* V29 Nos 1-2, p. 445-454.

SCHUELLER, T. 1987. Controlling Urban Runoff: *A Practical Manual for Planning and Designing Urban BMPs.*

SCIENTIFIC AMERICAN, 2003. How we can do it. Scientific American, February, p. 52-55.

SILVEIRA, A L. L., 1999. Impactos Hidrológicos da urbanização em Porto Alegre. 4th Seminar on Urban Hydrology and Drainage. Belo Horizonte ABRH.

TUCCI, C.E.M. 1993. Hidrologia: Ciência e Aplicação. EDUSP, Editora da UFRGS, ABRH, 952p.

TUCCI, C.E.M. 2000 a. Plano Diretor de Drenagem Urbana da Região Metropolitana de Curitiba Memorando n. 8. CHMHill / SUDHERSA.

TUCCI, C.E.M., GENZ, F., 1994. Medidas de controle de inundações in: Estudos Hidrossedimentológicos do Alto Paraguai, IPH/MMA.

TUCCI, C. E. M.; PORTO, R. L. 2000. Storm hydrology and urban drainage. In: Tucci, C. Humid Tropics Urban Drainage, chapter 4. UNESCO.

WEIBEL, S.R., ANDERSON, R.J; WOODWARD, R.L., 1964. Urban Land Runoff as a factor in stream pollution. Journal Water Pollution Control Federation. Washington, V. 36, No 7, 914-924.

WILKEN, P., 1978 *Engenharia de drenagem superficial*. São Paulo: CETESB.

WHO, 1999 "*World Health Report - 1999* - Statistical Annex", World Health Organization, Home page.

WORLD BANK, 1999. World development indicators. Urbanization. World Bank.

WRI, 1992. *World Resources 1992-1993*. New York: Oxford University Press. 385p.

WRIGHT, A M. 1997 'Toward a Strategic Sanitation Approach: Improving the Sustainability of Urban Sanitation in Developing Countries'. UNDP – World Bank 38p.

Chapter

2

2. River flood management

Control of risk areas in river flood plains is fundamental to the management of riverside areas.

2.1. Characteristics of river flooding

Flooding occurs when water from rivers, streams and storm-water tunnels leaves its normal channel, exceeds the capacity of one of these systems, and overflows into the space that the population uses for housing, transport (streets, highways and public thoroughfares), recreation, commerce, industry, etc.

When precipitation is heavy and cannot infiltrate into the soil, most of the volume flows into the drainage system, exceeding its natural discharge capacity. The excess volume that cannot be drained off runs into the flood plain, following the topography to flood the areas near to the rivers. These events occur at random depending on local and regional climatic processes. In this manual we refer to this type of flooding as *river flooding*.

Flooding is caused by the meteorological and hydrological conditions. Our knowledge of long-term weather patterns is very limited owing to the many factors involved in meteorological phenomena and the interdependence of the physical processes affecting the earth's atmosphere. The hydrological conditions leading to flooding may be natural or artificial. The natural conditions are those occurring as a result of the watershed in its natural state. These conditions include: relief, precipitation type, vegetation cover, and drainage capacity.

At their headwaters, rivers normally drain steep areas producing high speed runoff. During flooding the level may change by several metres in a few hours. When the relief is hilly the most suitable areas for human settlement are the flat and low-lying parts, precisely those that are at high risk of flooding. A river's flood plain grows significantly in its middle and lower tracts, where the gradient reduces and there are more flat areas. The most intense precipitation reaches localized areas and is generally of convective or orographic types. These forms of precipitation generally fall on small areas. The rain that fell in Porto Alegre on 13 February 1981 – nearly 100 mm in one hour – is an example. Frontal precipitation falls over wide areas causing more flooding in large rivers.

Vegetation cover has the effect of intercepting part of the precipitation that can generate runoff and protecting the soil against erosion. Loss of that cover through farming use has led to more frequent flooding owing to precipitation not being intercepted and clogging of the rivers.

The artificial conditions in the watershed are caused by human action. Some examples are: hydraulic structures, urbanization, deforestation, reforestation and farming. In a rural watershed there is more interception by vegetation, more pervious areas (infiltration into the soil), less surface runoff and slower drainage. An urban watershed has impervious surfaces such as roofs, streets and paved areas, and accelerates runoff by means of canalization and surface drainage. The effects of urbanization on runoff are: increased peak flow and surface runoff, reduced peak time and lower base time. Urbanization and deforestation increase the frequency of flooding from small and medium flood events. In large flood events their effect is less, since the soil has reached its saturation and storage capacity and the final effect is little different.

2.2. Settlement of urban areas and impact of flooding

Flooding has been around on earth longer than man. Humans have always tried to settle near rivers, using them for transport, water supplies and waste disposal. The areas near to rivers are generally flat and suitable for human settlement, hence the human presence.

The historical development of the use of free areas explains the today's urban constraints. Owing to the major challenge of transport in the past, the river was used as a main route. Cities developed on the banks of rivers or on sea or lake shores. Through the experience of the former inhabitants, the population always tried to inhabit the highest areas where the river was least accessible. With the rapid and disorderly growth of the cities, mainly in the second half of the last century, the high-risk areas, such as flood plains, were settled, leading to much loss of life and material damage.

The losses were caused by a lack of spatial planning and ignorance of the risk of the areas liable to flooding. People already had experience of flood management thousands of years ago. According to the historical note in Box 2.1, 3 000 years ago there was already land use planning for flood plains, yet it is still not common practice today.

Box 2.1. History of the settlement of areas liable to flooding.

The city of El-Amarna in Egypt, which Akhenaton (1340 BC) chose as the new capital, was planned taking account of areas liable to flooding: Running from east to west two river beds, *in which nothing was built for fear of the sudden floods*, divided the city into three parts: the centre and the northern and southern residential districts, Brier (1998).

In various parts of the world history shows that humans have tried to live with flooding, from the most frequent to the rarest. The Catholic church has learnt from experience throughout history, since whenever there is flooding in a city, the church building, despite being one of the oldest structures, is located on a safe site.

Management of flooding involves minimizing the impacts, but they are difficult to eliminate altogether, on account of financial constraints and our limited knowledge of nature. Box 2.2 is taken from the preface of Hoyt and Langbein (1959), describing the limits of human control over flooding.

Floods account for 50% of water-related natural disasters, 20% of which occur in America. Figure 2.1 shows the graph of annual losses from river flooding in the United States. Note that the values vary from 0.02 to 0.48% of GDP, averaging 0.081% (nearly US$ 8.1 billion).

Box 2.2. History and assumptions showing the limitations of flooding management (preface from the book “Floods” by Hoyt and Langbein, 1959)

“In the land of Canaan in 2957 BC, Noah and his family were saved from a great flood, probably centred near Ur on the Euphrates. A flood resulting from 40 days and 40 nights of continuous rainfall occurred in the region. Land was flooded for 150 days. All the living creatures drowned with the exception of Noah, his family and animals, saved two-by-two in an ark that finally came to rest on Mount Ararat” (passage from the bible on the Flood, quoted in the above-mentioned preface). This text describes an event with a very low risk of occurrence.

“Egypt 23rd dynasty, 747 BC. The floods were followed by droughts. The

Pharaoh announced that the whole valley of the river Nile was flooded, the temples were full of water and man seemed like a water plant. The polders were apparently not high or strong enough to confine the flood waters within the normal section. This disaster is a good illustration of nature's caprices. Another Pharaoh claimed that for seven years the Nile did not rise". This text, which can also be found in Biblical accounts, also emphasizes our inability to forecast the weather and its impacts when they occur.

"At some place in the United States in the future (the author mentioned the year 2000, a long way off at the time), nature will inexorably take its toll. 1000-year floods cause indescribable damage and loss of life. Engineers and meteorologists believe that this storm is caused by a combination of meteorological and hydrological conditions occurring once in a thousand years. Reservoirs, dykes and other controlling structures that were regarded as effective for a century and are effective for their design capacity are incapable of controlling the large volumes of water involved. This disaster teaches us that protection against flooding is relative and nature eventually exacts a very high price from those who settle on flood plains".

River flooding occurs mainly through settlement of the land in the major bed of rivers. During periods of minor flooding there is a tendency to settle the risk areas and when major flooding occurs the losses are significant. We present below some examples of impacts due to this kind of scenario:

a. In the river Itajaí in Santa Catarina, Brazil, there have been a number of maximum flood levels since 1852. This historical record shows that the three largest floods in Blumenau (Santa Catarina, Brazil) took place between 1852 and 1911, the worst being in 1880 with 17.10 m (Figure 2.2). Between 1911 and 1982 no flood occurred with a level higher than 12.90 m, so the population forgot the critical events and settled the flood plain. In 1983, when the city was already developed with a population of nearly 500 thousand inhabitants, a flood occurred (the fifth most serious in the last 150 years) attaining a maximum level of 15.34 m. The resulting losses throughout the Itajaí valley were equivalent to nearly 8% of the GDP of Santa Catarina. The lesson we learn from this example is that memories of floods fade over time and the population stops regarding them as a risk. As there is no planning of the risk area, people settle there and the losses are significant. However, the Hering company[2] in Blumenau (founded in 1880, the year of the most serious flood) remembered the value of 17.10m and built its premises above that level. In the

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[2] Translator's note: a major textle firm of the State of Santa Catarina, Brazil.

absence of planning, historical accounts are the only information available to guide people.

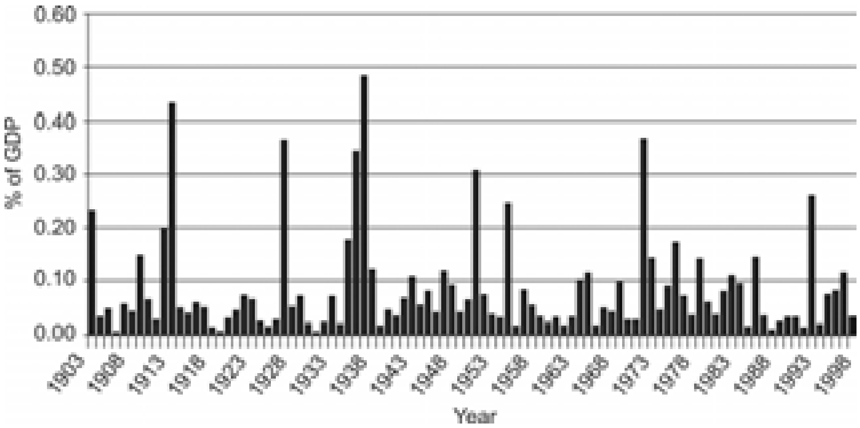


Figure 2.1. Historical series of annual losses due to flooding in the United States as % of GDP (Priscoli, 2001).

b. Figure 2.3 shows the flood levels of the river Iguaçu in União da Vitoria, Brazil. Between 1959 and 1982 there was only one flood with a risk greater than five years. This was precisely the period of highest economic growth and expansion in Brazilian cities. The floods after 1982 caused significant losses in the community (Table 2.3).

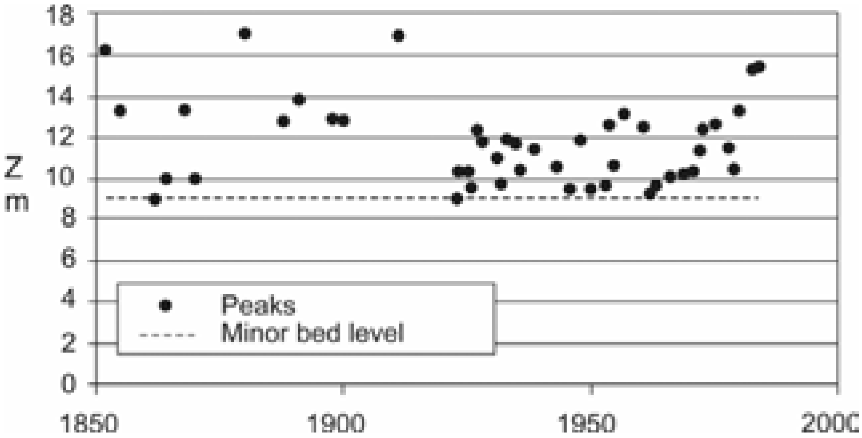


Figure 2.2. Flood levels in Blumenau, Santa Catarina, Brazil.

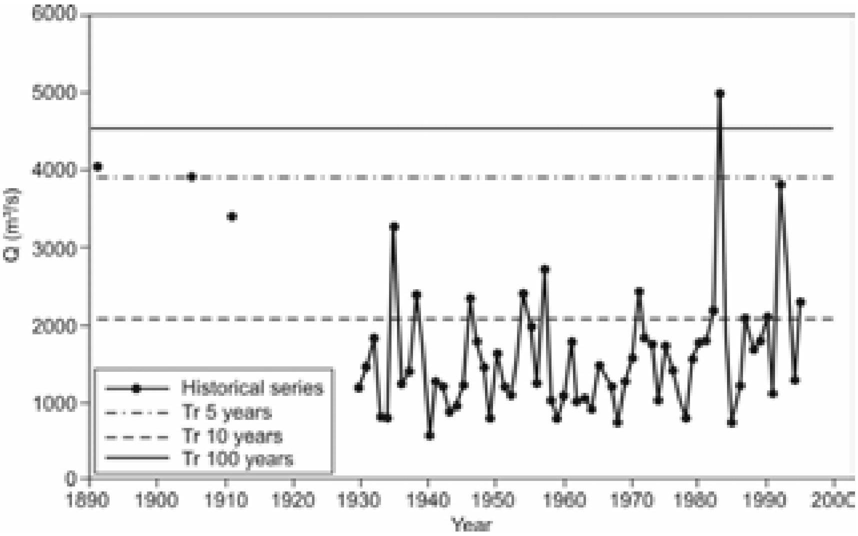


Figure 2.3. Maximum flood levels in the river Iguaçu, União da Vitoria, Brazil (watershed of some 25 000 km^2). (Tucci and Villanueva, 1997).

c. On the upper reaches of the river Paraguay (Brazil) is one of the largest wetland areas in the world, known as Pantanal. In this region people have always coexisted peacefully with the environment. Figure 2.4 shows the maximum flood levels in Ladário since the beginning of the last century. Table 2.4, shows the values of the maximum average flooding level and of the flooded areas of Pantanal in three different periods. Note the marked difference between the 1960s and the other decades. During that period the plains were flooded for long periods and not only gradually. The population was removed from the area in the following decades on account of the increasingly frequent flood levels. The immediate consequence was a financial loss in the value of the properties and the lack of economic support. The population went to live in poverty on the outskirts of the region's cities. A property that flooded 20% of the time in the 60s is now 97% flooded.

Table 2.3. Losses through flooding in União da Vitoria and Porto União (ICA, 1995).

Year	**Losses US$ million**
1982	10 365
1983	78 121
1992	54 582
1993	25 933

d. For Porto Alegre, Rio Grande do Sul, Brazil, there are flood level data since 1899, when various events were observed over a period extending up to 1967 (Figure 2.5). In 1970 a lateral dyke was built to protect the city and no flood has occurred since 1967 with a return time of more than 10 years (2.94 m). In recent years there has been a movement in the city to have the flood dyke removed, as there have been no flood events for the past 38 years. This incorrect perception of the flood risk led the Councillors to approve the demolition of the dyke, which the municipality fortunately did not carry out.

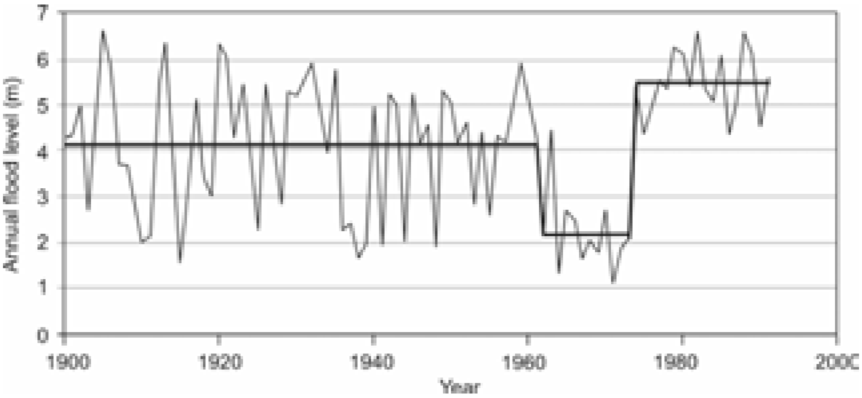


Figure 2.4. Maximum annual levels of the river Paraguay at Ladário and mean for the periods: (a) 1900-1961; (b) 1961-1973; (c) 1973-1991

The institutional environment of flood control in developing countries is not generally conducive to a sustainable solution. There are only a few isolated measures by a few professionals. In general, flooding receives attention only after it occurs. The problem tends to be forgotten after each flood, and remembered the next time. This is due to several factors, including:

Table 2.4. Estimated values of levels and flooded areas in Pantanal (approximate values)

Period	**Mean peak level (m)**	**Mean flooded area in Pantanal* 1 000 km^2**
1900-1959	4.16	35
1960-1972	2.21	15
1973-1992	5.49	50

• approximate values obtained from Hamilton (1995).

- City planners uninformed about flood control;
- Disorganization at federal and provincial (or departmental)

levels on flood management;

- Insufficient technical information on the topic for engineering graduates;
- Political losses for public administrators when implementing non-structural control (zoning), as the public is always expecting a hydraulic structure;
- Public uninformed about flood control;
- In some places there is no interest prevention flooding, as when it occurs, resources are handed out free of charge.

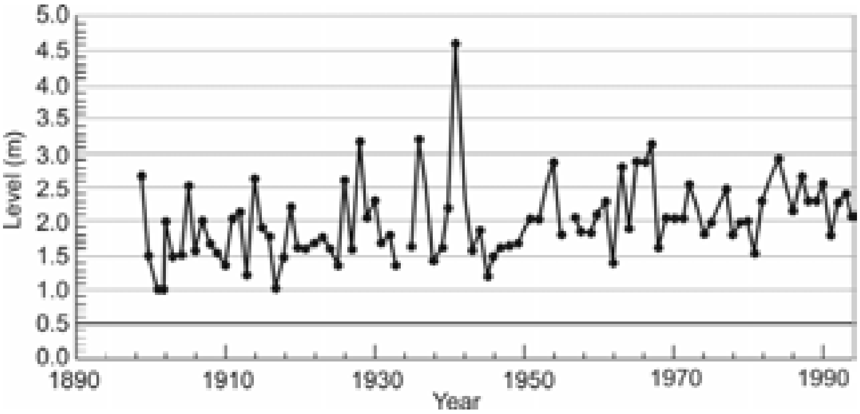


Figure 2.5. Flood levels in Porto Alegre 1899-1994.

2.3. Evaluation of flood events

Changes in a river’s level or flow depend on the climatological and physical characteristics of the watershed. The main climatological conditions are the distribution of precipitation over time and space. These can be predicted no more than a few days or hours in advance, so flood levels cannot be forecast very far ahead. The maximum possible time for forecasting a flood, from when the rain falls, is limited by the average time the water takes to move from the watershed to the area of interest.

Water levels in a river can be forecast over a short or long period. Flood forecasting over the short term or for the present time, also called real-time forecasting, can establish the level and the time at which it will occur for a section of river that depends on a forecast of precipitation and movements of flood water in the watershed. This type of forecast is used to warn the riverside population and operators of hydraulic structures.

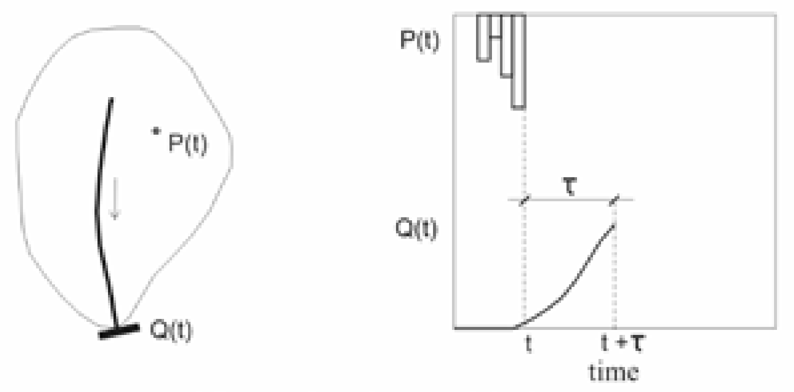
Long-term flood forecasting quantifies the chances of flooding occurring in statistical terms, but cannot predict when a flood will occur. Long-term forecasting is based on statistics of past water levels and can establish flood levels for certain selected risks.

2.3.1. Real-time flood forecasting

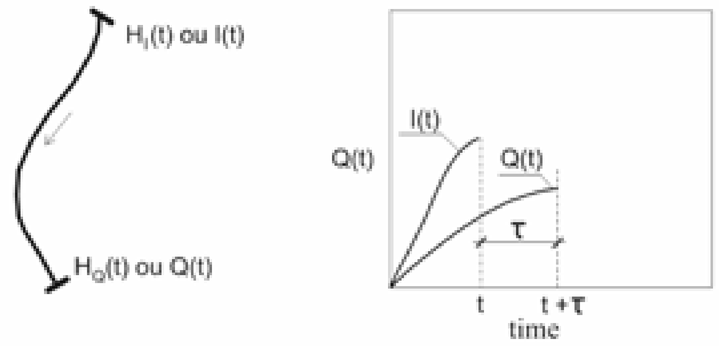
The following are required for short-term flood forecasting: data collection and transmission systems and an estimating methodology. The systems are used to transmit precipitation, level and flow data as the event occurs. Estimates are made using mathematical models representing the behaviour of the various phases of the water cycle. When the flood reaches an inhabited area, a civil defence plan is also needed, and an emergency and operation system is required for reservoirs.

Flood levels can be forecast on the basis of Figure 2.6: (a) precipitation forecast; (b) precipitation data; (c) upstream flow; (d) combination of the last two. In the first case it is necessary to estimate the precipitation that will fall on the watershed by using equipment such as radar or remote sensing. Next, with data on the precipitation over the watershed, it is possible to estimate the flow and level using a mathematical model simulating the conversion of precipitation into flow.

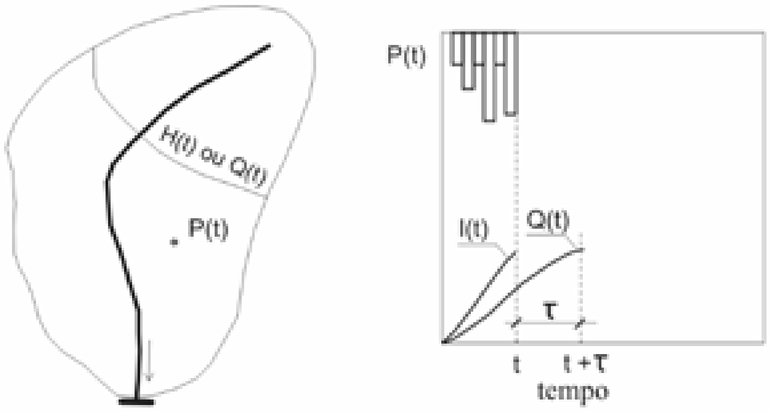
When the precipitation in the watershed is known, the forecast uses a computerized data collection and transmission network (in the previous case such a network is indispensable) and the mathematical model for converting the precipitation into flow. This gives a shorter range forecast that is limited to the average time the flood water takes to arrive (Figure 2.6 a). The short-term forecast based on a measurement station upstream of the section of interest depends on the characteristics of the river or the monitored area of the watershed. In this case, the forecast has a shorter range than the previous ones (Figure 2.6 b). When an intermediate watershed between the stations makes a significant contribution, the two previous processes are combined to produce the real-time forecast (Figure 2.6 c). A description of real-time forecasting models is beyond the scope of this book and may be found in the specialist literature.



a) forecast based on precipitation



b) forecast based on level or flow



c) forecast based on precipitation or flow

Figure 2.6. Real-time forecasting

2.3.2. Probability or risk of flooding

In this text the risk of a flow or precipitation means the probability (p) of the occurrence of an equal or higher value in any year. The return time (T) is the inverse of probability (p) and represents the *mean* time at which this event is likely to recur.

$$T = \frac{1}{P} \qquad (2.1)$$

For example, consider a *die* with six faces (numbered 1 to 6). At any time the probability of throwing a number 4 is p = 1/6 (one chance in six). The return time is the *mean* number of throws for the desired number to come up again. In that case, using equation 2.1 gives T = 1/ (1/6) = 6. Therefore, *on average*, the number 4 comes up every six throws. We know that this number does not come up exactly every six throws, but the average will certainly hold true after thousands of throws. Therefore, the number 4 can come up twice in a row or it may not come up for a long time, but on average it will come up every six throws. By analogy, each throw of the *die* is a year in which flooding can occur. A return time of ten years means that, on average, the flood may be repeated every 10 years or that every year this flood has a 10% chance of occurring.

Flooding estimates for a particular place can be made on the basis of: (a) an observed series of flows; (b) regionalization of flows; (c) precipitation and use of a rainfall-flow model. These methodologies estimate the risk of flooding at the place on the basis of the historical data and assume that the historical series of flows are:

- *Homogeneous or steady*, i.e. their statistics do not vary over time. This means that the mean or standard deviation of the flows should not vary over time. For instance, when a dam is built upstream of a section of river, with a large volume to attenuate flooding, the risk of flooding should change because the series is no longer homogeneous;
- The recorded series of flood levels are *representative* of the occurrence at the place: a few years of data may not be representative of a place's true risk. In the example of Blumenau, if series were used from 1935 only, in 1982 the risk of a flood like the one that occurred in 1983 would have had a risk of more than 100 years; however, taking into account the levels occurring in the 19th century, and even the floods of 1983 and 1984, it would be seen that the risk was actually of the order of 30 years;
- The values are independent of one another. Generally,

a maximum flood level for one year has no dependence on the following year if chosen within the so-called "water year", which is the period from the start of the rainy season to the end of the dry season.

The first two points involve more uncertainties and it is essential to use flooding marks to obtain a reliable fit of the probability curve of flows at the places of interest. The methodologies for determining the probability curve are described in the hydrology books (Tucci, 1993).

2.4. River flood control measures

Flood control measures may be structural or non-structural. Structural measures are those that alter the river system by means of structures in the watershed (extensive measures) or in the river (intensive measures) to prevent flood water overflowing into the flood plain.

Non-structural measures are those in which the losses from flooding are reduced for the convenience of the population, using preventive measures such as flood warnings, zoning of risk areas, flood insurance, and individual protection measures ("flood proofing").

It would be naïve to think that we can control flooding completely; the measures – even structural ones – always aim to minimize its consequences. For example, in the 1930s, the project for flood control and farming land use in the river Pò, in Italy, was an example of a highly successful water resource project. In 1951, a combination of heavy rainfall and high tide levels destroyed the polders, caused 100 deaths and the loss of 30 000 head of livestock, plus agricultural losses (Hoyt and Langbein, 1955). This example confirms our limited ability to manage river flooding described in box 2.2.

Flooding is controlled by a combination of structural and non-structural measures enabling the riverside population to minimize its losses and continue to live in harmony with the river. These include engineering and social, economic and administrative measures. Planning of protection against flooding and its effects involves research into the ideal combination of these measures.

One example of flood management policy comes from the United States. In 1936 a federal law on flood control was passed, stipulating that flood reduction programmes were a government responsibility and that the introduction of physical or structural measures was one means of reducing such damage. In this way it was not necessary to check cost-benefit ratios to justify the protection of areas liable to flooding. As a result, the development and settlement of flood plains accelerated, thereby increasing damage from flooding. The loss of public funds was insufficient to buck this trend. In 1966, the Government acknowledged that the previous measures were not appropriate and placed emphasis on non-structural measures that enabled the population to live with flooding. In 1962 the committee on flood control set up by the American Society of Civil Engineers, reported as follows (Task, 1962): “The limitations of the present (in 1962) National Flood-Control Policy, which is based primarily on the construction of flood-control structures, are acknowledged in this report, which emphasizes the need to regulate flood plains as an essential part of a rational plan for reducing flood losses”.

In 1973 a law was passed on protection against flood disasters, promoting non-structural measures, calling attention to and requiring flood insurance, regulating land use and protecting new buildings against floods with a 100-year return time. In 1974 specific articles on flooding were approved within the water resource development legislation, providing for non-structural measures and cost distribution, as in Article 73 of the 1974 law: “in research, planning or design by any Federal Agency, or any project involving protection against flooding, priority shall be given to non-structural alternatives for reducing flood losses, including but not limited to flood-proof construction, regulation of flood plains, use of flood plains for recreational purposes, fishing, animal life and other public purposes, and transfer with the aim of providing the most acceptable economic, social and environmental solution for reducing flood damage”.

Figure 2.7 shows the trend in annual benefits, cumulative benefits and investments in flood management up to 1999 (with values adjusted to the 1999 dollar). This figure shows that the cumulative benefits are far greater than the investments in flood management.

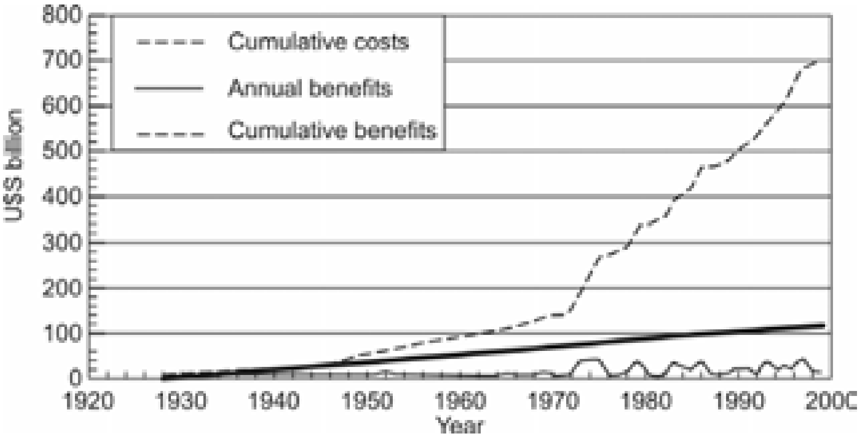


Figure 2.7. Trend of annual and cumulative benefits and of flood management expenditure in the United States (Priscoli, 2001).

2.5. Structural measures

Structural measures are engineering works implemented to reduce the risk of flooding. These measures may be extensive or intensive. Extensive measures are those that act in the watershed, aiming to change the relationships between precipitation and flow, such as altering the vegetation cover of the soil, which reduces and delays the flood peaks and controls erosion in the watershed. Intensive measures are those that react in the river and may be of three types (Simons *et. al.,* 1977): (a) *accelerating flow:* construction of dykes and polders, increasing discharge capacity and cutting meanders; (b) *delaying flow:* attenuation reservoirs and basins; c) *diverting flow*: structures such as diversion canals. Table 2.5 summarizes the main characteristics of structural measures.

2.5.1. Extensive measures:

Extensive measures are:

Vegetation cover: vegetation cover can store a part of the volume of precipitation water through interception and by increasing consumptive water use and reducing the speed of surface runoff in the watershed. When vegetation cover is removed there tends to be an increase in runoff and flood water volume and a reduction in droughts, thereby increasing flow variability. Increasing cover is an extensive flood-reduction measure, but can be applied to small watersheds (< 10 km^2) where it is more effective. This type of measure mainly effects the most frequent events with a high risk of occurrence. For rare low-risk events vegetation cover tends not to have much effect.

Table 2.5. Structural measures (Simons *et al.* 1977).

Measure	Main advantage	Main disadvantage	Application
Extensive measures			
Alteration of vegetation cover	Reduction in flood peaks	Impracticable for large areas	Small watersheds
Control of soil loss	Reduces sedimentation	Similar to previous item	Small watersheds
Intensive measures			
Dykes and polders	High level of protection of an area	Significant damage in the event of failure	Large rivers and on plains
Improvements to channel:			
Reduction of roughness by removal of obstructions	Increases flow for little investment	Localized effect	Small rivers
Cutting off meander	Increases the area protected and accelerates flow	Adverse impact in rivers with alluvial bottom	Narrow flood plain
Reservoir:			
All reservoirs	Downstream control	Difficult to site owing to expropriation	Intermediate watersheds
Reservoirs with sluices	More efficient for same volume	Vulnerable to human error	Multi-purpose projects
Flood-control reservoirs	Operation with a minimum of stones	Cost not shared	Limited to flood control
Alteration of channel:			
On course of flood	Attenuation of volume	Depends on topography	Large watersheds
Diversions	Reduces flow in main channel	Similar to previous item	Medium and large watersheds

Control of soil erosion: increased erosion has environmental implications owing to the transport of sediment and aggregates, and can contaminate rivers downstream, reducing their section and upsetting the rivers’ load and transport balance. One of the factors is a reduction of the section of the rivers and more frequent flooding in places where there is more sedimentation. Soil erosion can be controlled by reforestation, small reservoirs, stabilization of river banks and good farming practice. This measure helps to reduce the impact of flooding.

2.5.2. Intensive measures

Intensive measures are:

Reservoir: A flood-control reservoir works by retaining the volume of the hydrograph during high water levels, thereby reducing the peak and the impact *downstream* of the dam. Figure 2.8 shows a river's natural hydrograph. Assuming a volume V of the hydrograph that a reservoir can retain, a reduction can be observed in the peak flow and the resulting hydrograph.

Flood-control reservoirs can be used solely for that purpose or can have multiple uses. The first aims only to minimize flooding, while the second has multiple aims, which may come into conflict.

A reservoir without operating control is one that has no spillway sluices or bottom sluices and the flood water is regulated by the conditions at the ungated spillway. When there are sluices the available volume can more often be used to control flood water. During the rainy season the first hydrographs tend to be less steep until the losses are made up and the soil is saturated. These hydrographs can occupy the available volume in the reservoir, leaving little room for reducing the peak of the higher waters to come (Figure 2.9 a).

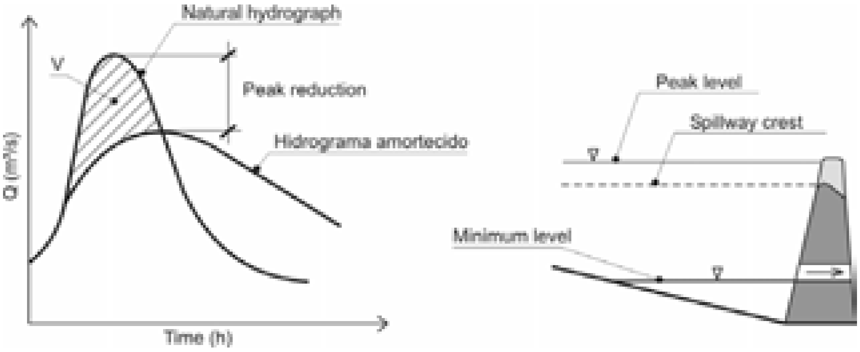
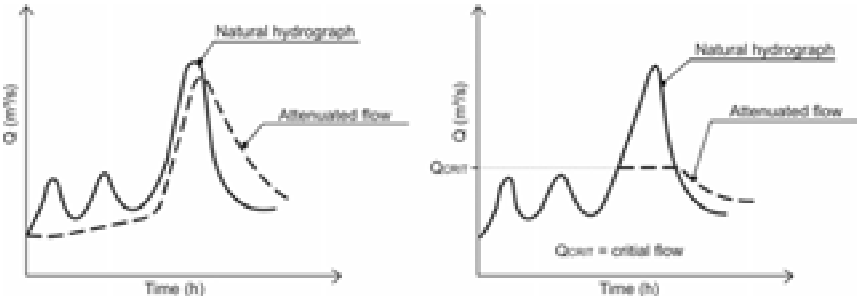


Figure 2.8. Effect of reservoir

The operational rule can be as follows: (a) the reservoir must operate in such a way that that the natural flow runs off until the downstream critical level is attained (Qcrit); (b) from that point on the reservoir volume is used to maintain or reduce the flow (Figure 2.9 b). These operating conditions depend on the design of the reservoir and its discharge mechanisms. In order to find the optimum design and operating conditions, runoff into the reservoir has to be simulated to identify the most efficient type of operation.

Planning of dams must take account of the impacts they may have *downstream* and *upstream* of the structure.

Downstream: There are generally areas liable to flooding *downstream* of a dam. With the construction of a dam the reservoir tends to attenuate the flood water in those riverside areas, unless there are operational problems at the dam. However, if the downstream area is unoccupied, its proximity to the structure will lead to it being settled, thereby becoming vulnerable to flooding. If the dam does not manage to attenuate flooding, public opinion will expect the downstream impacts to be reduced. In this way, the peak flow downstream is restricted to Q_{crit}, above which the river floods its banks. In periods of high water events will occur where the dam is unable to attenuate the flow, and flooding will occur. The public perception of the situation is generally that the dam is to blame and it is therefore necessary for the structure to have an efficient operational system and a reliable system for observing the hydrological data needed to demonstrate the operational conditions, in order to defend its action.



(a) without control **(b) with control**

Figure 2.9. Reservoir operation

Upstream: The construction of a reservoir can have the following effects *upstream*:

a. Depending on the incoming flow, the operating rule and the runoff capacity, the backwater level may cause flooding or create a reservoir upstream;
b. The conditions of the previous item may change over time as the reservoir silts up, which happens initially in its *upstream* reaches. Flooding may exceed the previously planned levels, covering areas beyond the boundaries of the expropriated land.

An example of a system of flood-control dams can be found in the valley of the river Itajaí-Açu, Santa Catarina, Brazil (Figure 2.10): the West dam located on the river Itajaí-Oeste *upstream* of the city of Taió (completed in 1973), the South dam on the Itajaí do Sul (completed in 1975) upstream of the city of

Ituporanga, and the Ibirama dam on the river Hercílio (completed in the late 1980s). The latter had not been built at the time of the 1983 and 1984 floods. These dams are designed with bottom sluices with a capacity to hold a large volume in the reservoirs, discharging over a very long period. The first two dams made an insignificant contribution to the 1983 flood owing to the high volume of precipitation that fell in seven days. For the 1984 flood, which lasted only two days, they made a greater contribution. After examining the peak flow series before and after the dams were built, an unexpected result was observed in that the mean and standard deviation of the floods for a section downstream of one of the dams actually increased. However, this increase was also due to the increase in precipitation in the watershed just between the two periods. Table 2.6 shows some statistics of this comparison. The West dam, which did not produce any increases, proved more effective in containing the floods, while the volume or design of the South dam appears not to enable it significantly to reduce flooding.

Table 2.6. Statistics before and after the construction of the dam on the river Itajaí

Statistic	**West dam m^3/s**	**South dam m3/s**	**Annual precipitation mm**	**Precipitation[1] mm**
Mean				
Before dam	292,2	488,5	1309	224,1
After dam	274,5	513,3	1658	291,7
Standard deviation				
Before	73,2	267,1		
After	56,2	356,6		
Period				
Before	1934-1972	1935-1974	1942-1972	1942-1972
After	1973-1983	1975-1984	1973-1984	1973-1984

1 – precipitation for the month in which the highest annual water level occurred.

Multi-purpose reservoir: When a reservoir is designed for water storage, irrigation or electrical power, the aim is generally to keep the reservoir volume as high as possible. In this case, it has a minimal flood attenuation capability. There is a natural conflict between these uses.

The method generally used to achieve these conflicting objectives is based on keeping a standby volume in the reservoir that minimizes the impacts of flooding upstream and downstream of the dam (Figure 2.11). This volume is kept free to receive flood volumes and reduce the downstream flow, attempting to cater for water restrictions upstream and downstream.

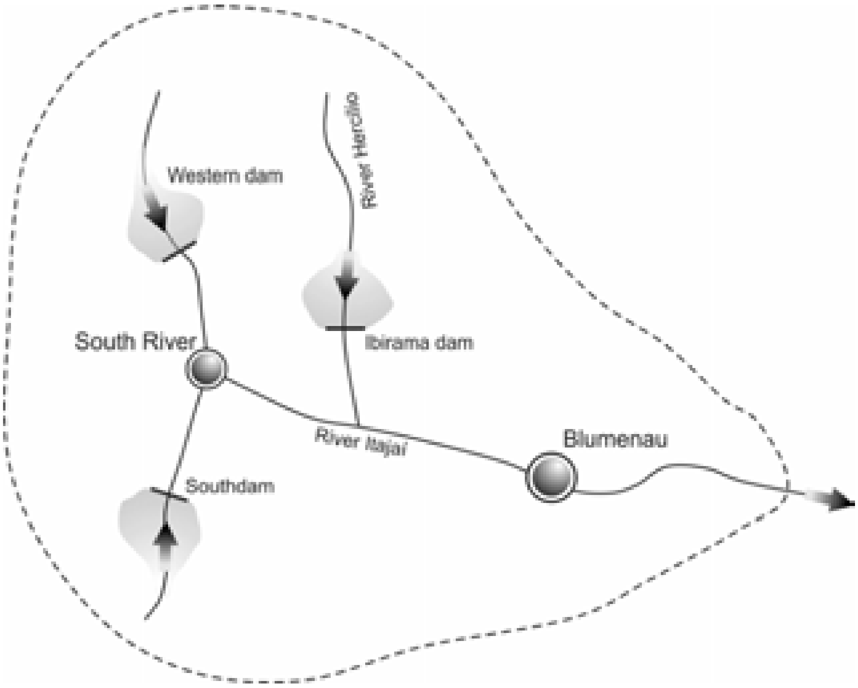


Figure 2.10. Watershed of the river Itajaí and flood-control dams

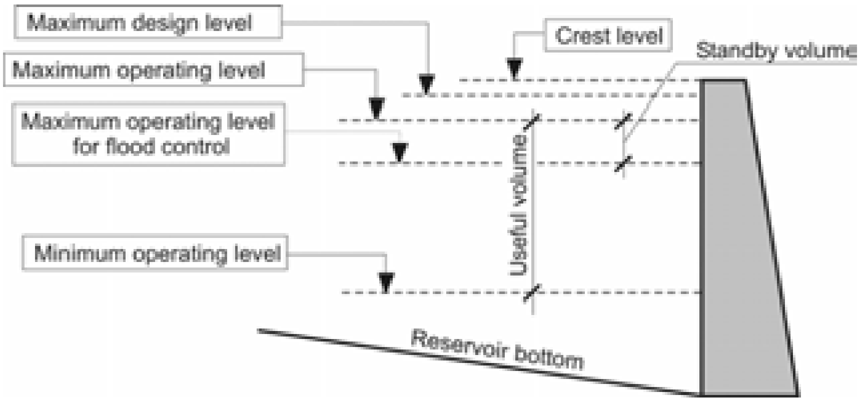


Figure 2.11. Operational levels of a dam

There are a number of methods for estimating this volume on the basis of statistics and historical flow series of the dam. The following methods have been used in the Brazilian power generation industry: Volume x Duration Curve Method (adapted from the method presented by Beard, 1963) or the critical trajectories method (Kelman et al., 1983). The first uses the observed historical series while the second uses series of flows generated by a stochastic model. Both methods statistically determine the standby volume that should be maintained in the reservoir on each day of the rainy season for a given analysis risk.

These procedures take no account of the existing information on the watershed during the period of flooding. For watersheds with an ill-defined seasonal pattern the model can overestimate the standby volume, leading to substantial losses. These may be losses from flooding on the one hand and lost power generation on the other.

Dykes and polders: These are lateral walls of earth or concrete, sloping or upright, built at a certain distance from the banks, to protect riverside areas against overflows. The effects of reducing the channel width and of confining the flow are a rise in water level in the section for the same flow, an increase in velocity, erosion of the banks and of the section in general, and a reduction of the flood wave travelling time, aggravating the situation of other places downstream. The major risk involved in building a dyke lies in correctly determining the probable peak flood level, as there will always be a risk of collapse, and in this case the damage will be more serious than if there were no dyke.

The dyke provides localized protection for a riverside area. Very high dykes should be avoided, as there is always a risk of failure in the event of a water level higher than the design level, possibly leading to a more serious impact than if there were no dyke.

In terms of hydraulics, the dyke reduces the section of the channel and can increase both velocity and flooding levels (Figure 2.12). To avoid this happening, the flow conditions must not be altered after the dyke is built. These conditions can be simulated in a steady state for the design flows. This method must not be used for channels subject to tidal effects, as it will over-specify the high level. A hydrodynamic model must therefore be used.

Dykes are normally built of earth with a rockfill and concrete, depending on the local conditions.

When building dykes for protecting farming areas, a higher risk of collapse may be adopted than in urban areas provided that the potential damage is only financial. When a collapse can lead to human losses, the acceptable risk is lower and the structure should be complemented by a forecasting and real-time warning system. For both rural and urban watersheds, pumping must be provided from the lateral areas contributing to the dyke. Otherwise rainfall in those side basins will be dammed by the higher level of the main river, accumulating within them in the absence of drains with sluices (Figure 2.13).

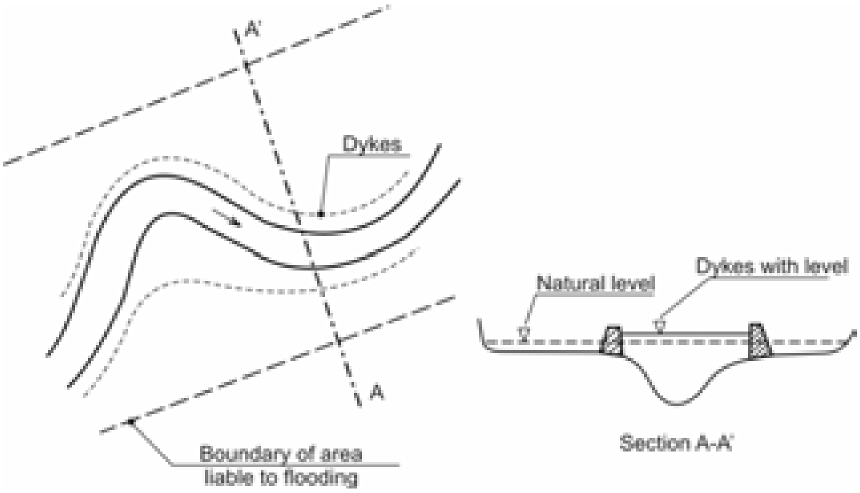


Figure 2.12. Impact of dyke construction

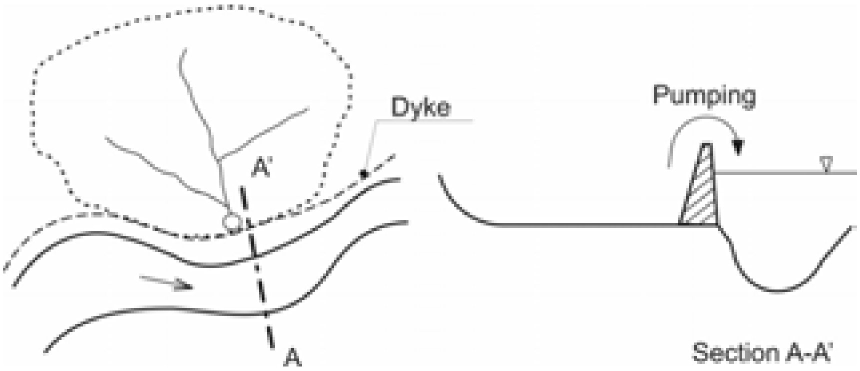
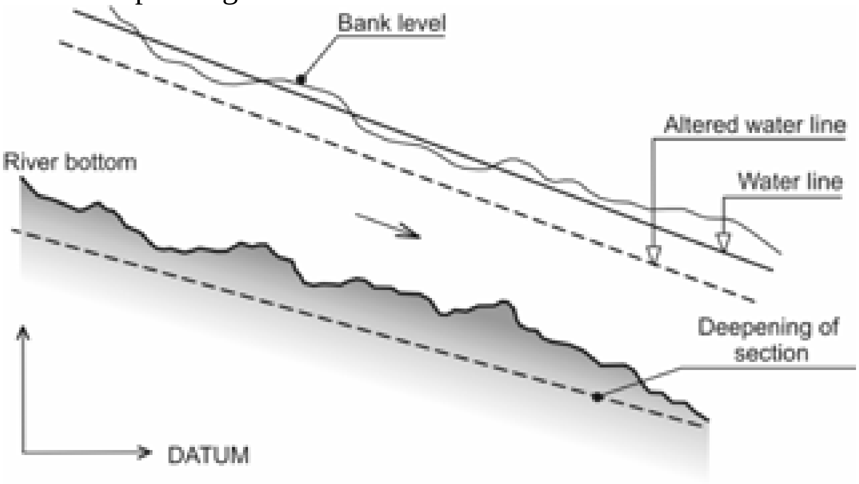


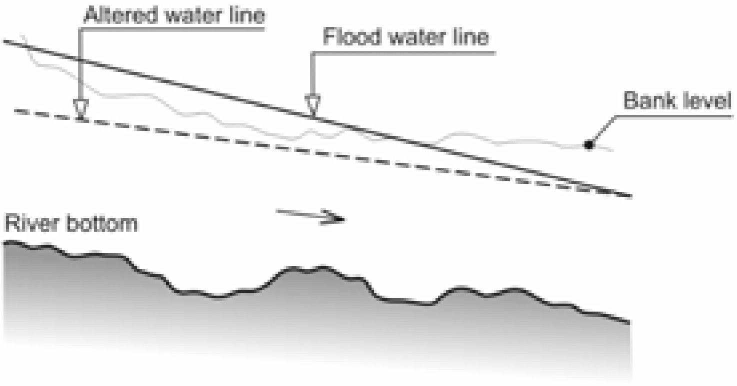
Figure 2.13. Dyke – drainage of the side basin

Alterations to the river: Alterations to the river morphology are designed to increase the flow at the same water level, so reducing flooding frequency. This can be achieved by increasing the cross section or increasing the velocity. To increase the velocity it is necessary to reduce the roughness, removing obstructions to flow, dredging the river, increasing the gradient by cutting off meanders or deepening the river. These are generally high-cost measures.

For a section of river carrying a flow Q, the resulting level depends on the cross-sectional area, roughness, hydraulic radius and gradient. These variables can be manipulated to reduce the level for a given flow. For the alteration to be effective these conditions have to be modified for the tract that acts hydraulically on the area of interest. By deepening the channel, the water line is lowered and flooding avoided, but the works may involve a very extensive section of river to be effective, which increases the cost (Figure 2.14 a). Widening the measurement section reduces the gradient of the water line and lowers the upstream water levels (Figure 2.14 b). These works must be examined in terms of the changes they may cause in the river's energy and the stability of the bed. Reaches of the river upstream and downstream of the works may be liable to sedimentation or erosion depending on the alterations made.



a - Deepenign the section



b - Widening the section or reducing the roughness

Figure 2.14. Alterations to a river

2.6. Non-structural measures

Structural measures are not designed to give total protection. This would require protection against the highest possible flood level. Such protection is physically and financially unviable in most situations. The structural measure can create a false sense of security, allowing further settlement of areas liable to flooding, which could lead to significant damage in future. Non-structural measures, with or without structural ones, can significantly minimize losses at lower cost. The cost of protecting an area liable to flooding with structural measures is generally higher than for non-structural measures. In Denver (United States) in 1972, the cost of protection with structural measures of one quarter of the area was equivalent to the cost of implementing non-structural measures to protect the other three quarters of the area liable to flooding.

The main non-structural measures are of the preventive kind, such as: flood forecasting and warning, zoning of areas at risk of flooding, individual flood insurance and protection. Flood forecasting was discussed in the previous section.

2.6.1. Forecasting and early-warning system

The forecasting and early-warning system is designed to anticipate the occurrence of flooding, warning the population and taking the measures necessary to reduce losses due to flooding.

- A real-time forecasting and warning system involves the following (Figure 2.15):
- System for collecting and transmitting weather and hydrological information; monitoring system over computerized network, satellite or radar and transmission of that information to the forecasting centre;
- Forecasting centre: reception and processing of information; model for forecasting (see previous item), evaluation and warning;
- Civil defence: prevention programmes: education, warning map, critical places, etc.; warning to public systems: schools, hospitals, infrastructure, etc.; warning of population at risk, removal and protection of population affected during the emergency or by flooding.

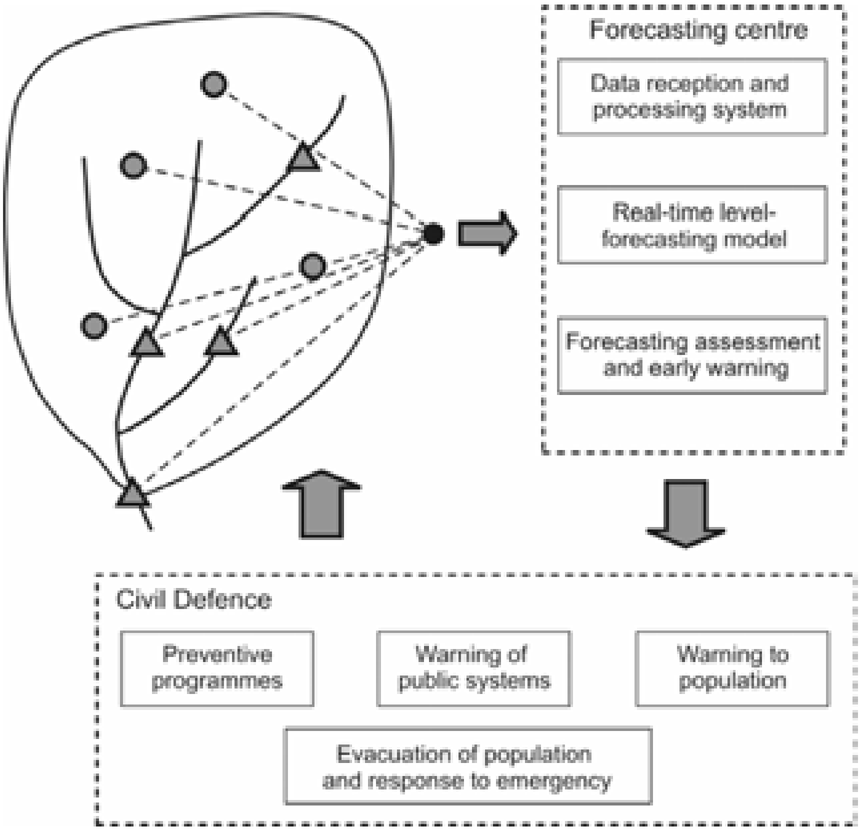


Figure 2.15. Forecasting and warning system

This system operates in three distinct phases, namely: prevention, warning and mitigation. Prevention consists of activities to minimize flooding when it occurs. This involves training the Civil Defence team, educating the public through information campaigns, the warning map identifying areas flooded during the occurrence, planning of the areas to receive the affected population, etc.

Warning is the phase of handling the actual occurrence of the rainfall events as follows:

1. *Monitoring levels:* level from which technical staff monitor the development of the flood water. At this point, a warning is issued to Civil Defence of the possibility of a flood event. Real-time level forecasting is just beginning;
2. *Warning levels:* these are the levels from which the relevant agencies forecast that a potentially damaging water level will be attained within the time horizon of the forecast. Next, Civil Defence and the municipal authorities regularly receive the forecasts for the city;
3. *Emergency levels:* level at which material damage and

human losses occur. The information is passed on to the population. This information that the population receives are the current and forecasted levels and the probable error range produced by the models;

The *mitigation* phase concerns the measures to be taken to reduce the population's losses when flooding occurs. Includes action such as sealing off streets and areas at risk, evacuating the population and animals, and protecting places of public interest.

The *warning map* is prepared with water level values for each corner of the risk area. On the basis of the absolute water level of the corners, this value has to be converted into the water level referred to the staff gauge. This means that, when a gauge is indicating a given water level value, the population will know how much higher it has to go to flood each corner. This helps to deal with flooding as it occurs.

In order to determine this map, it is necessary to obtain all the water levels of each corner and proceed as follows:

1. For each corner level, trace a perpendicular from its location in relation to the river axis;
2. Assume the level of that corner to be the same in that section of the river;
3. Obtain the gradient of the water line. Select the approximate return time for the belt (planning map) in which the corner is located;
4. The gauge level of the corner will be:

$$\mathrm{CR} = \mathrm{CT} \pm \mathrm{DxDist} \qquad (2.2)$$

where CR is the gauge level, CT is the topographic level of the corner, D is the gradient along the river and Dist is the distance along the river between the gauge section. The sign will be negative if the corner is *upstream* of the gauge section and positive if it is *downstream*. The value to be placed on the map is CR. However, if the population is more accustomed to the gauge value rather than the absolute level, use the gauge level, namely:

$$\mathrm{NR} = \mathrm{CR} - \mathrm{ZR} \qquad (2.3)$$

where NR is the gauge level ; CR is the gauge reading and ZR is the gauge zero reading.

2.6.2. Zoning of areas liable to flooding

The zoning of areas liable to flooding involves the following stages: a) determining the risk of flooding; b) mapping flooding areas; c) zoning. Estimating the risk was mentioned in section 2.2We describe below the aspects of mapping and zoning.

City flooding map

Flooding maps can be of two kinds: *planning maps and warning maps.* A *planning map* defines the areas affected by flooding for selected return times. The *warning map* was described in the previous section.

The following data are needed to produce these maps: a) absolute zero benchmark for the gauge; b) topography of the city using the same absolute reference as the staff gauge. Street level in the middle of each corner of the risk areas; c) study of the probability of flooding levels for a section near the city; d) flood levels, or marks throughout the city enabling the waterline to be established; e) bathymetric sections along the river at the urban perimeter. If the observation section is located outside the urban perimeter, the bathymetry must go as far as that section. The spacing of the sections depends on changes in the bed and the gradient of the water line, but spacings between 500 and 1 000 m are sufficient; f) inventory of obstructions to runoff over the urban section, such as bridges, streets, etc.

When the gradient of the waterline through the city is very shallow and there are no significant streams in the urban perimeter, points d, e and f are unnecessary. If there are obstructions, they may be important if they significantly reduce the cross section.

In practice, it is very complicated to obtain all the information listed above, so it is easier to divide the study into two phases. In the first, preliminary phase, the areas liable to flooding will be delimited with low precision on the basis of existing topographical maps and high-water marks. In the second phase, using the approximate delimitation of the flooding areas, a more detailed topography of the area will be determined, with the river bathymetry.

Preliminary mapping: In cities with more than 10 000 inhabitants there are water-supply projects. For these projects there is a need to obtain the topography with a minimum spacing of 5 m (1:10 000). These maps are not sufficiently accurate for this kind of study, but they can be used in the preliminary phase. The errors can be minimized by site visits, aerial photographs and checks of characteristic points of the survey. These maps do not always refer to the desired absolute level; in this case the desired comparison plane (datum) has to be obtained and the reference with the available map established. Next, the relationship can be established between the zero of the gauge and the chosen datum, used to prepare the topographical map.

Since the high-water levels are known in the gauge section, to transpose it to the sections along the urban reaches, the gradient of the waterline must be known. This gradient can be obtained using the flood marks or by measuring it during the dry season. This procedure may produce errors, as if there are obstructions to runoff during flooding, the gradient may be significantly altered.

In order to determine the gradient of the waterline, the topographer must be advised to proceed as follows: a) level all existing flood levels in the city; b) measure the water level at intervals of 500 m to 1 000 m along the urban reaches, noting the gauge level at the time of the reading.

The following can be used to check the topographer's work: a) check whether the gradient falls in the direction of flow; b) to check the levelling of the marks in the vicinity of the staff gauge section add to the gauge zero the values observed in the gauge and check whether they correspond to the levelled marks. The flood mark does not necessarily to the maximum level occurring, since the river stains the wall when the level is maintained for some time. If the river stays at the peak level for a very short time, the mark should appear for lower levels.

The criteria for determining the waterline and flood levels through the city are as follows:

a. Knowing the frequency curve for flooding levels in the section of the gauge, obtain the absolute levels corresponding to the desired return times;
b. Define the sections along the river; these sections are chosen on the basis of the existing marks and/or the levels measured every 500 m and 1 000 m;
c. Calculate the gradient of the waterline for the various sections defined for the referenced sections. The gradient is calculated with the distance measured along the river. Take care when there are bridges or streets obstructing the flow;
d. For the levels calculated in the sections of the station, obtain the corresponding levels for the other sections, using the gradient of the waterline obtained.

Final mapping: In this case it is necessary to make a detailed survey of the topography of the risk areas with a return time of up to 100 years. The choice of return time is arbitrary and depends on the definition of the zoning to be carried out. If a flood has occurred with a return time exceeding 100 years, choose the highest value that has occurred.

The detailed survey includes the determination of the level curves at a spacing of 0.5 or 1.0 m, depending on the ground conditions. In some cities the spacing may be very detailed. This survey should record the level of the middle of the street at each corner in the risk areas.

Besides the topography it is necessary to record obstructions to runoff, such as bridge piers and edges, streets with embankments, buildings, describing the type of cover and obstruction in plan and section.

Using bathymetry throughout the city it is possible to determine the flood levels as follows:

a. The waterline must be calculated using a steady-state runoff model. The method is used initially to adjust the roughnesses, based on the flood marks and the discharge curve of the fluviometric station. To do this, the waterline is determined for the flow recorded at the fluviometric station and the corresponding level in the direction *downstream* to *upstream*. The correct roughness will produce a waterline that best approximates to the high-water marks;
b. Once the roughnesses are known the waterline can be established for the flows corresponding to the various return times and, as a consequence, the affected areas can be mapped.

Zoning

Zoning is actually the definition of a set of a rules for the settlement of the areas at most risk of flooding, with the aim of minimizing future material damage and loss of human life as a result of major floods. This means that urban zoning will allow rational development of riverside areas.

The regulation of the use of flooding zones is based on maps marking out areas of different risks and on the criteria for occupying them, as well as for the construction aspects. In order for these regulations to be used, for the benefit of the communities, they should be integrated into municipal legislation on housing developments (or subdivisions), buildings and dwellings, so that they can be enforced. In this way, this chapter is intended to serve as a basis for regulating the flood plain, through the urban master plans, enabling municipalities to exercise effective control. The Department of Water and Electrical Power of the State of São Paolo (DAEE) submitted a proposal for the text of the section on water resources of that State's municipal organic laws, recommending zoning in the following terms: "Article 2. In the field of water resources, the municipality shall be responsible for: IV – zoning areas liable to flooding, erosion or landslip, laying down restrictions and prohibitions on the use, subdivision and development of unsuitable or critical areas, with the aim of safeguarding safety and public health".

The Water Resources Council (1971) defined zoning as "the division governmental units into districts and the regulation within those districts of: a) uses of structures and land; b) height and volume of structures; c) size of plots of land and density of use". The distinguishing feature of zoning in relation to other controls, is that the regulations vary from district to district. Zoning may therefore be used to establish special patterns of land use in areas liable to flooding. The division of land into districts through the community is usually based on global use plans, which guide the growth of the community.

Technical conditions of zoning: The risk of flooding varies with the altitude of the flood plain. The lowest-lying areas are obviously liable to more frequent flooding. This being the case, the delimiting of zoning areas depends on the altitudes of the urban areas.

A river normally has one or more beds. The minor bed is the channel in which the water runs in the dry season, or with average levels. The major bed can have various ramifications depending on the cross section considered and the topography of the flood plain. The river generally occupies this bed during flooding. When the return time for overflow out of the minor bed is greater than two years, the population tends to settle the flood plain in the most diverse and significant socioeconomic ways. Flooding of such settlements leads to substantial damage to the occupants of these areas and also to populations *upstream* which are affected by the raised levels resulting from the obstruction of the natural runoff caused by the first settlers (Figure 2.16).

The section in which the river runs can be divided into three main parts (Figure 2.17), described below:

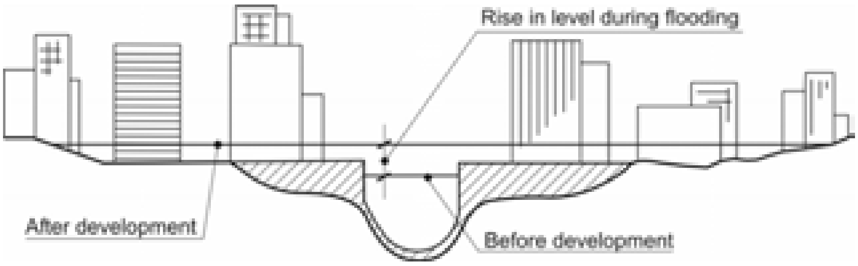


Figure 2.16. Invasion of flood plains

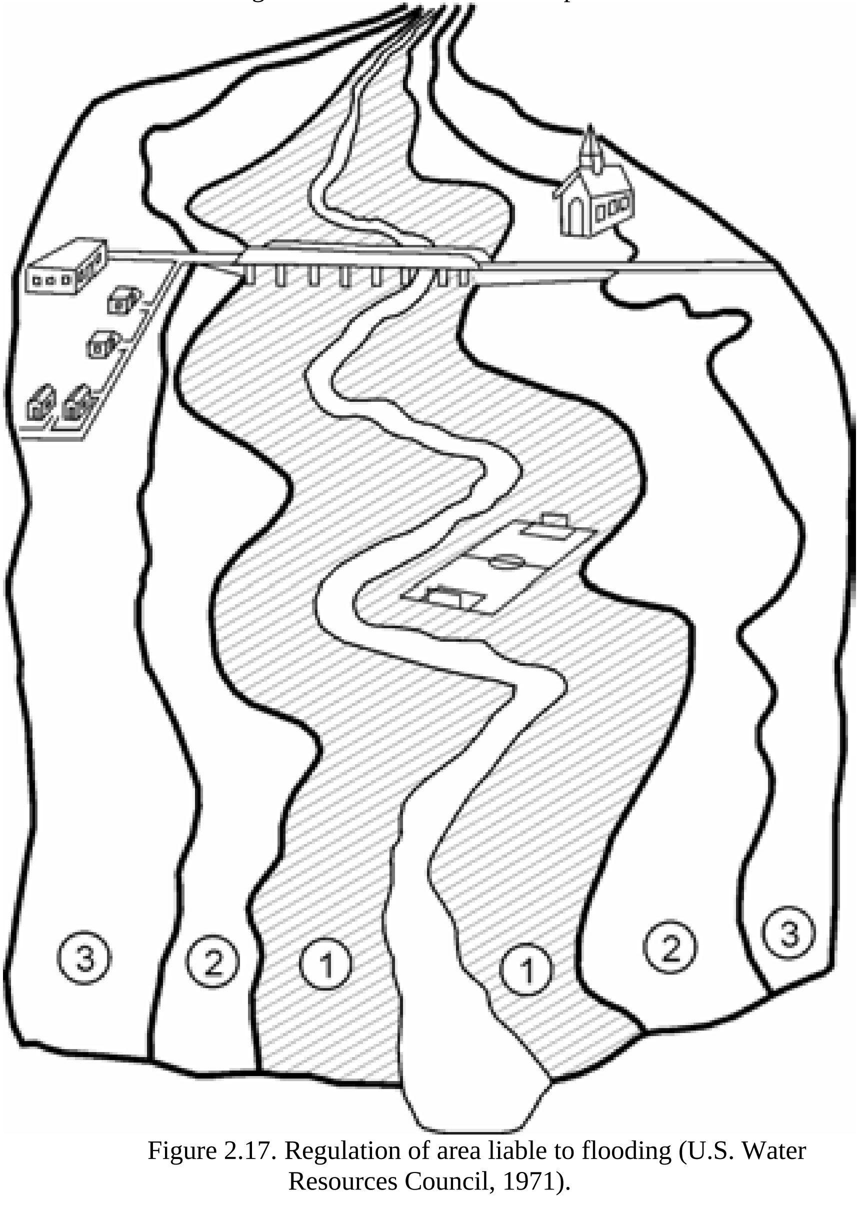


Figure 2.17. Regulation of area liable to flooding (U.S. Water Resources Council, 1971).

Flood belt (1). This part of the section functions hydraulically and allows the flood water to run off. Any building this area will reduce the runoff area, raising the water levels above this section (**Figure 2.18**). In any urban planning, this area must therefore remain unobstructed.

The following technical criteria are generally used:

a. Determine the high water level for a 100 year return time of the level that delimits the flood plain.
b. The flood belt is the one that avoids raising levels for the main bed and for the flood plain. Since this value cannot really be zero, a minimum acceptable increase is adopted for the main bed. In the United States a minimum increase of one foot or 30.45 cm has been adopted. See Figure 2.18 for the definition of this belt of the flood plain.

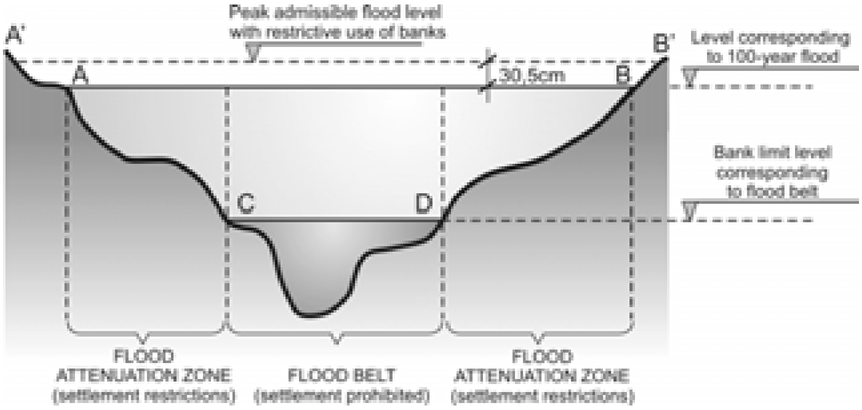


Figure 2.18. Definition of flood belt

This belt of the river must remain unobstructed to avoid major damage and flooding. No new building should be allowed in this belt and the authorities can gradually move existing buildings.

For the construction of roads and bridges, checks must be carried out to see whether they obstruct runoff. For existing structures, the effect of the obstruction must be calculated to see what measures can be taken to correct it. No backfills may be built that could obstruct runoff. This area could be used for farming or other purposes involving little change to the natural conditions. On the other hand, transmission lines or water conduits may be built, or any type of structure that does not obstruct runoff, such as car parks, sports fields, etc.

In some cities it may be necessary to build near to the rivers. In these circumstances, the effect of the obstruction must be assessed and the works must be structurally protected against flooding.

Restricted belt (2). This is the remaining part of the area liable to flooding that must be regulated. This area will flood, but owing to the shallow depths and slow velocities involved, it does not contribute much to the drainage of the flood water.

This area can be subdivided into subareas, but may have essentially the following uses:

a. Parks and recreational or sports areas which are simple and cheap to maintain after flooding. Normally simple cleaning will bring them back into working order in a short space of time;
b. Farming;
c. Dwellings with more than one storey, where the upper storey at least will remain above the high-water level, and structurally protected against flooding;
d. Industrial and commercial, such as areas for loading, parking and storing equipment or machinery that is easily removed or which is not liable to flood damage. In this case, storage must not be permitted of perishable goods, especially if toxic;
e. Basic services; transmission lines, roads and bridges, provided that they are properly designed.

Low-risk belt (3). There is a low probability that this area will be flooded; in exceptional years it will be affected by shallow water at low velocities. It is a good idea to define this area to informing the population about the magnitude of the risk involved. This area does not require regulations regarding flooding.

In this area, delimited by low-frequency flooding, individual protection measures for dwellings can be dispensed with, but the population must be given guidance about the possibility of flooding and measures to protect against the resulting losses, recommending the use of structures with at least two stories, where the second can be used in critical periods.

Regulation of areas liable to flooding: In cities in developing countries, it is usually the lower income and marginalized population that settles in the higher risk riverside areas. Regulation of the settlement of urban areas is an iterative process, involving a technical proposal that is discussed by the community before being incorporated into the city’s master plan. Therefore, there are no rigid criteria applicable to all cities, but there are some basic recommendations that can be followed according to the case.

The Water Resources Council (1971) implements regulation on the basis of districts, each one defining the following: (a) a text setting out the regulations applying to each district, together with the administrative arrangements; (b) a map delimiting the various uses in the districts.

The zoning is complemented by the subdivision of the regulations, outlining the division of large plots of land into small ones, governing the development and sale of buildings. This is therefore the housing development control phase. The Building Code governs the construction of buildings in terms of structural, hydraulic, material and sealing aspects. The building regulations help to avoid future damage. We list below some of the general indicators that can be used in zoning.

Flood protection of dwellings depends on the owner’s financial capacity to carry it out. When a plan is implemented, the municipality may allow building in these areas, providing that it satisfies the following conditions (Tucci and Simões Lopes, 1985):

a. Establishment of at least one storey above the flood level delimiting the low-risk area;
b. Use of materials resistant to submersion or contact with water;
c. Prohibition of storage or handling and processing of flammable materials that could endanger human or animal life during flooding. Electrical appliances must be kept in a safe place;
d. Protection of landfills against erosion by means of vegetation cover, gabions or other systems;
e. Designs of storm drains and sewage systems must allow for the effects of flooding;
f. Structurally, buildings must be designed to withstand hydrostatic pressure, which can cause problems of overflows, among others, thrusts and moments that can require anchorages, and erosion that can destroy foundations;
g. Sealing of openings such as doors, windows and ventilation systems;
h. Basement walls are to be watertight and reinforced;
i. The floor slab of the upper storey must be reinforced or drained;
j. Piping must be fitted with valves;
k. Fixed equipment must be protected;

l. Walls must be anchored to prevent landslip.

The decision on the compulsory protection of new buildings in the flood plain is a process that must involve an in-depth discussion within the community concerned. Therefore, it must be borne in mind that, at the time of the last floods, property values fell in the areas at risk. With the passage of time, these areas will gradually acquire real-estate value, due to the natural spacing of floods over time, and in this way the implementation of a zoning plan may lead to higher costs of any necessary expropriation or difficulties in enforcing the regulations. This situation will change only when flooding recurs, bringing with it more damage. These conditions are more serious in the flood belt, where the municipality has to gradually remove structures obstructing runoff.

In order to preserve the memory of flooding in the streets, the lamp posts can be painted various colours. This spreads information about flooding and avoids problems with real-estate transactions in risk areas.

As for buildings already existing in areas liable to flooding, a complete inventory of them will have to be carried out and a plan established to reduce losses in the area, including those caused by the backwater resulting from obstructions to runoff. The existing conditions may vary and so have to be analysed case-by-case. Examples of such situations are: (a) for public works such as schools, hospitals and administrative buildings, check the viability of protecting them or removing them to safe areas in the medium term; (b) sub-dwellings such as emergency housing and dwellings of low-income population must be negotiated for transfer to safer areas; (c) for industrial and commercial areas, incentives can be offered for protecting the buildings and, where necessary, the whole area at the expense of the beneficiaries.

When removals or transfers are carried out, the authorities must be prepared with urban plans to allocate these areas for other uses or recreation, such as parks, preventing them being settled again for sub-dwellings.

Some government action is essential in this process, such as:

a. Preventing the construction of any public structure in risk areas, such as schools, hospitals and buildings in general. For existing buildings there should be a removal plan to be carried out over time;
b. Plan to gradually move the city’s main core to low-risk areas.
c. Financial institutions should avoid financing works in risk

areas.

d. Use economic mechanisms for the process of granting incentives and controlling risk areas: (1) offer property tax exemptions to owners who keep risk areas free from building and use them for example for farming, recreation, etc; (2) try and create a market for risk areas so that they return to public ownership over time;
e. Plan for immediate settlement of public risk areas when they become unoccupied, with a plan signalling the presence of the municipality or the State.

2.6.3. Flood-proof construction

Flood-proof construction is defined as a set of measures designed to reduce losses from flooding of buildings located in flood plains. These measures are:

- Temporary or permanent sealing of openings in structures;
- Increasing the height of existing structures;
- Construction of new structures on piles;
- Construction of low walls or dykes surrounding the structure; removal or protection of items that could be damaged inside the existing structure;
- Removal of the structure outside the area liable to flooding;
- Use of water-resistant material or new structures;
- Regulation of settlement by enclosing the area liable to flooding;
- Regulation of subdivision and building code, purchase of areas liable to flooding, flood insurance, setting up of flood forecasting and warning service with evacuation plan, adoption of tax incentives for prudent use of areas liable to flooding; installation of warning systems in the area and adoption of development policies. Non-structural flooding management measures can be grouped into: regulation of land use, flood-proof construction, flood insurance, flood forecasting and warning.

2.6.4. Flood insurance

Flood insurance is a viable preventive measure for projects with a high added value whose owners have the financial capacity to pay the cost of the insurance. Moreover, not all companies are prepared to offer flood insurance unless there is a system of reinsurance to spread the risk. Where the population settling the area liable to flooding is of low income, this type of solution becomes unviable.

2.7. Evaluating flood damage

According to the U.S. Army Corps of Engineers (1976), flood damage can be classified as tangible and intangible. Tangible losses comprise material damage, emergency costs and financial losses.

Material damage includes the costs of removals and cleaning buildings, loss of objects, furniture, equipment, decorations, stores and unfinished products. Emergency costs refer to evacuation, resettlement, temporary housing such as camps, warnings, etc. Financial costs are those due to the interruption of business and industrial production, and loss of profits. Intangible costs refer to flood damage that has no market or monetary value, such as loss of life or of historical works and buildings.

The methods used to evaluate flood damage are (Simons *et al.*, 1977): a) the level-damage curve; b) the historical curve method; and c) the aggregate-damage equation.

2.7.1. Level-damage curve

This method is described in U.S. Army Corps of Engineers (1976). It consists of plotting the curve of damage against probability or return time. To plot this curve the following relations have to be obtained: a) discharge curve; b) probability curve of peak flows; c) curve of level versus damage.

The discharge curve is the relationship between flow and water level in the section being measured. The flow probability frequency curve indicates the risk of the occurrence of flooding. To obtain the ratio between the level in the gauge section and the probability, just combine the two curves.

The main difficulty lies in determining the relationship between level and loss. Therefore, there is a need for a survey of flood plain settlement and an estimate of the loss for the various components of the settlement. This estimate can be made for standard buildings such as dwellings, any industrial or commercial settlement, and farming and livestock use. In the United States, bodies such as the Soil Conservation Service, Corps of Engineers and Federal Insurance Administration try to relate, for each basic type of building, the height above the first floor to the percentage of damage of the total value of the building. Figure 2.19 and Figure 2.20 respectively show examples of the comparison of the curves proposed by the three organizations for the cases of a single-storey house and a two-storey house, both without basements. The breakdown of costs for each area of the city, by sampling, allows an overall assessment of the damage involved. Individually, an industrial or business establishment may inventory its potential losses according to the water level.

Having established the ratio between depth and loss it is possible to establish the ratio between loss and probability, by using the last two curves (Figure 2.21). The damage-probability curve enables us to estimate the mean cost of flooding for a city or for an individual industry without a commercial or residential establishment. The curve also indicates the financial risks involved in settling areas liable to flooding. The mean cost of flooding is obtained by integrating the curve of damage versus probability.

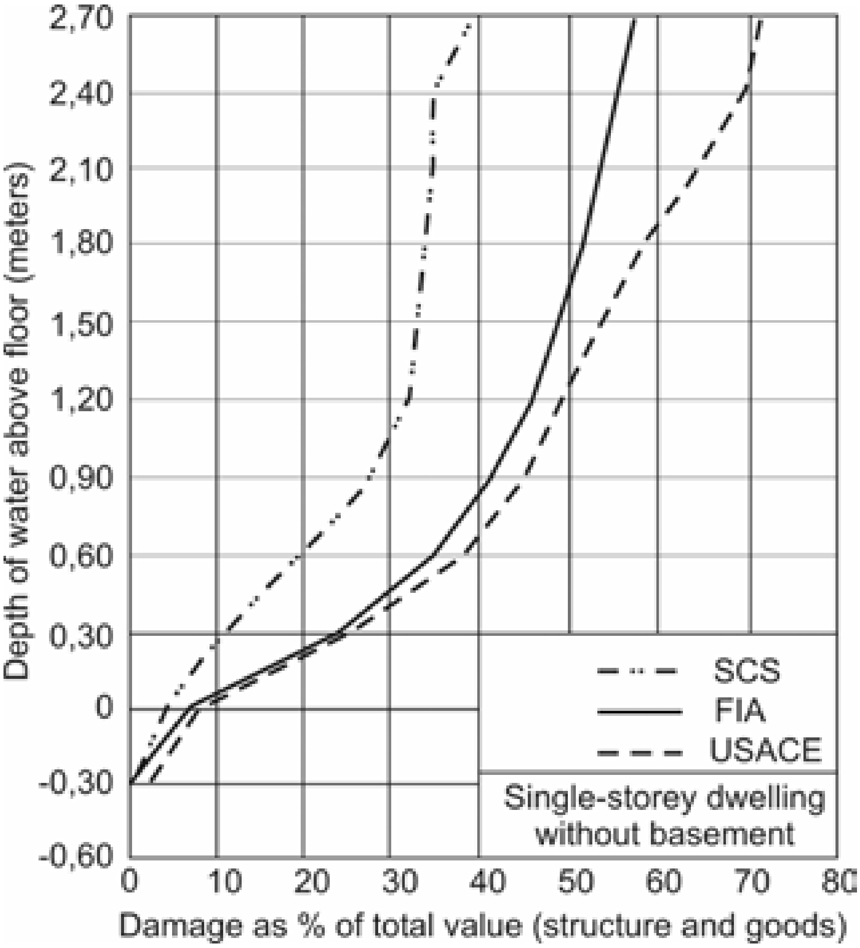


Figure 2.19. Depth-damage curves for a single-storey house without basement (Simons *et al.*, 1977).

2.7.2. Historical damage curve method

This type of methodology was proposed by Echstein (1958) and is based on a determination of the losses from flooding occurring in recent years. Plotting this loss against the levels gives a level-damage curve. This procedure has the following limitations: a) the method assumes that in recent years, growth in the region has been practically zero in the flooding area and that there have been no transfers; b) it assumes that the losses caused by flooding have been replaced; c) the values of the losses must be uniform, namely, it must take account of the inflation for the periods; d) the procedure for evaluating the losses must be the same for different floods, to avoid any biased valuations.

2.7.3. Aggregate-damage equation

James (1972) proposed the aggregate-damage equation, based on linear growth between the damage and the mean level of flooding of the flood plain. The equation is as follows:

$$C_D = K_D \cdot h \cdot M \cdot U \cdot A \tag{2.4}$$

where C_D is the total damage from flooding for one event; K_D is the damage index of the flood event, in monetary units per unit of depth of flooding; h = mean flooding depth; M = index of market value of development of the flooded area, in monetary units per units of development; U = settlement factor, i.e. the proportion of the developed flooded area in relation to the total flooded area; A = total flooded area.

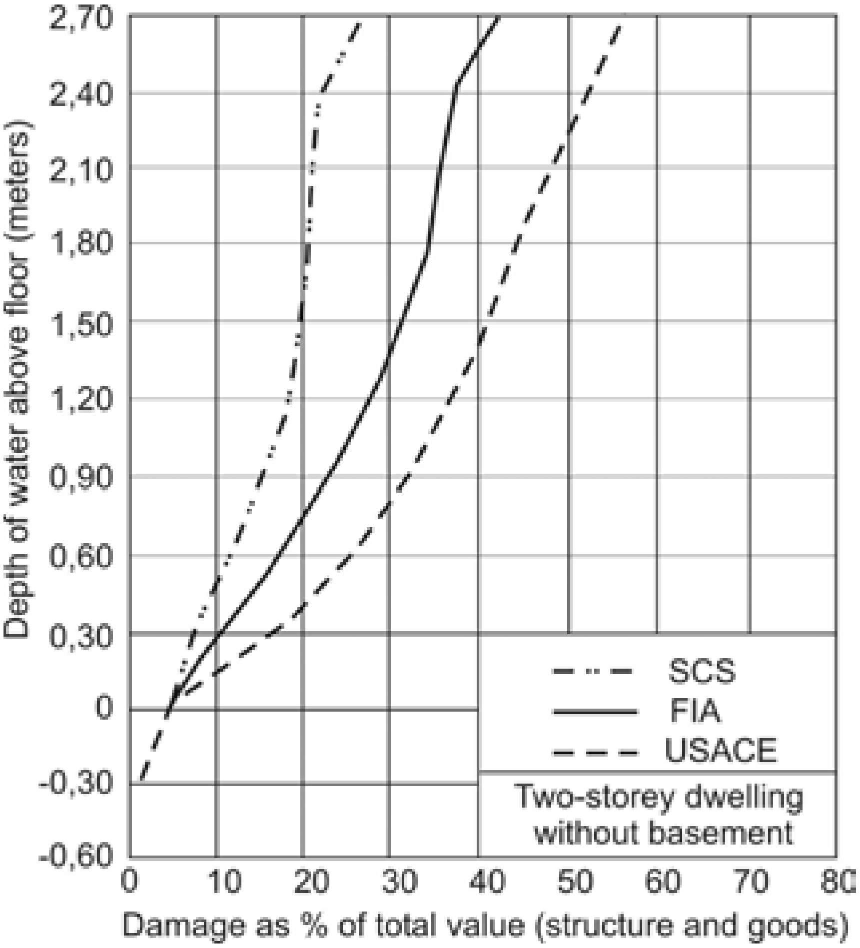


Figure 2.20. Depth-damage curves for a two-storey house without basement (Simons *et al.*, 1977).

The index K_D is defined as:

$$K_D = \frac{dD}{dy} \tag{2.5}$$

where dD is the damage and dy is the depth. This differential is obtained on the basis of the ratio between damage and depth. Homan and Waybur (1960) determined this value for floods of around 5 feet (1.5 m) in depth, obtaining K_D = 0.052. James (1964) presented a mean value of 0.044. When the flood water contains a large quantity of sediments or is of high velocity, the value of K_D increases. The mean flood level and the index of the market value are obtained for each place. The factor U is also obtained from local data.

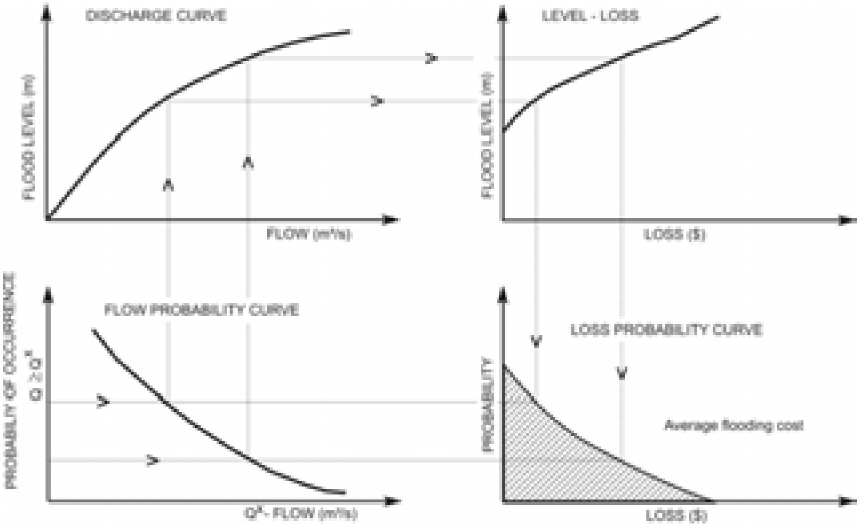


Figure 2.21. Level-damage method

Kates (1965) proposed a sequence of procedures for assessing the losses of flooding areas with growth, or changes in potential damage over time. The sequence is as follows: a) use a regional economy model to project regional urban growth over the analysis period; b) define these limits of the flooded areas on the basis of the hydrological analysis and allocate urban growth in that area; c) specify each structure in the flooded area by location, type, content and financial value, as a function of time; d) plot appropriate graphs of structural damage with level against time; e) aggregate the individual damage curves to enable the whole flood to be evaluated, reflecting changes over time.

Problems

1. Why does flooding occur?
2. What causes the problems of river flooding?
3. What is the difference between structural and non-structural measures?When should each type of measure be used?
5. What are the types of structural measures? What are extensive restrictions?
6. When are intensive measures used?
7. What are the types of non-structural measures? What difficulties are involved in implementing them?
8. How would you produce a flooding map of a city?
9. Is it possible to map without historical data?
10. How can the resulting map be used to plan urban settlement? If you had to advise the city administration, what recommendations would you make?
11. You have been asked to study an alternative for an industry located in an area liable to flooding. What financial alternatives should be evaluated?
12. What are the alternatives for controlling flooding in a watershed of 100 000 km^2? Analyse these alternatives.
13. What are the criteria for determining the area to be left unobstructed in the zoning of an area liable to flooding?
14. What are the criteria for zoning of the areas liable to flooding in association with the urban master plan?
15. Why are structural measures more expensive than non-structural measures?
16. What are the main impacts of cutting off meanders to control flooding in a section of river?
17. When is it viable to canalize a river to control flooding?
    What are the benefits of doing so?
18. How would you devise a plan for determining the flood levels of a place in the absence of data?
19. What measures complement zoning of a flood plain?

References

ECKSTEIN, O. 1958. Water resources development, the economics of project damage in urban areas. Water Resources Bulletin. Minneapolis, v. 11, No 2, Apr.

HOMAN, G.A., WAYBUR, B. 1960. A study of procedure in estimating flood damage to residential, commercial and industrial properties in California. Stanford Research Institute.

HOYT, W.G., LANGBEIN, W.B. 1955. Floods. Princeton: Princeton University Press, Princeton. 469p.

JAMES, L.D. 1964. A time-dependent planning process for combining structural measures, land use and flood proofing to minimize the economic cost of flood. Stanford University, Institute in Engineering Economic Systems.

JAMES, L.D. 1972. Role of economics in planning flood plain land use. Journal of the Hydraulics Division, American Society of Civil Engineers. New York, v. 98, n.6, p. 981-92.

JOHNSON, W. 1978. Physical and economic feasibility of non-structural flood plain management measures. Davis: Hydrologic Engineer Center.

KATES, R.W. 1965. Industrial flood losses: damage estimation in the Lehigh Valley. University of Chicago, Department of Geography. (Research Paper 98).

PRISCOLLI, J. 2001. Flood Management experiences in USA. Presented at a workshop in Santiago de Chile, January 2001. SAMTAC.

REZENDE, B. and TUCCI, C.E. M., 1979. Análise hidráulica e hidrológica dos problemas de inundação urbana na cidade de Estrela, RS. Technical report, p.29.

SIMONS, D.B. et al. 1977. Flood flows, stages and damages. Fort Collins: Colorado State University.

TASK, 1962. Guide for the development of flood plain regulation. Journal of the Hydraulics Division. American Society of Civil Engineers. New York, v.88, No 5, p. 73-119, Sept.

TUCCI, C. and SIMÕES LOPES, M. 1985. Zoneamento das áreas de inundação: rio Uruguai. Revista Brasileira de Engenharia Caderno de Recursos Hídricos. Rio de Janeiro, v.3, No 1, p.19-45, maio.

U. S. ARMY. CORPS OF ENGINEERS. 1976. Guidelines for flood damage reduction. Sacramento.

WATER RESOURCES COUNCIL, 1971. Regulation of flood hazard areas to reduce flood losses. Washington. Unpaginated.

Chapter

3

3. Management of floods in urban drainage

The control of urban drainage involves managing the urban area to control the impact of impermeabilization and to avoid canalization.

3.1. Impact of urban development on the water cycle

Urban Development alters the vegetation cover, affecting the elements of the natural water cycle in a number of ways. Roofs, streets, paved areas and patios make the ground impervious; the water that previously soaked in now runs through the drains, so increasing surface runoff. The volume that ran off slowly over the surface of the ground and was retained by plants, with urbanization now runs through canals, requiring sections with a higher runoff capacity.

Figure 3.1 shows the effect of urbanization on the variables of the water cycle. The typical hydrograph of a natural watershed is the one resulting from urbanization (Figure 3.2).

Urbanization alters the water cycle as follows:

- Reduced infiltration into the ground.
- The volume that does not infiltrate remains on the surface, increasing surface runoff. In addition, since storm drains have been built for the surface runoff, this is accelerated and the transit time is reduced. The peak flows also have higher peaks over time (Figure 3.2). The peak average flow can increase six or seven times. In the watershed of the river Belém in Curitiba, Brazil, with a drainage area of 42 km^3 and impervious areas of the order 60%, the average flood flow increased six times with the change from rural

conditions to the present urbanized state. Figure 3.3 plots flood flow against drainage area for rural watersheds and for the watershed of the river Belém. The trend of the values of the rural watersheds allowed us to estimate the average flood flow for the pre-developed situation and compare it with the current value (see [Figure 3.1).

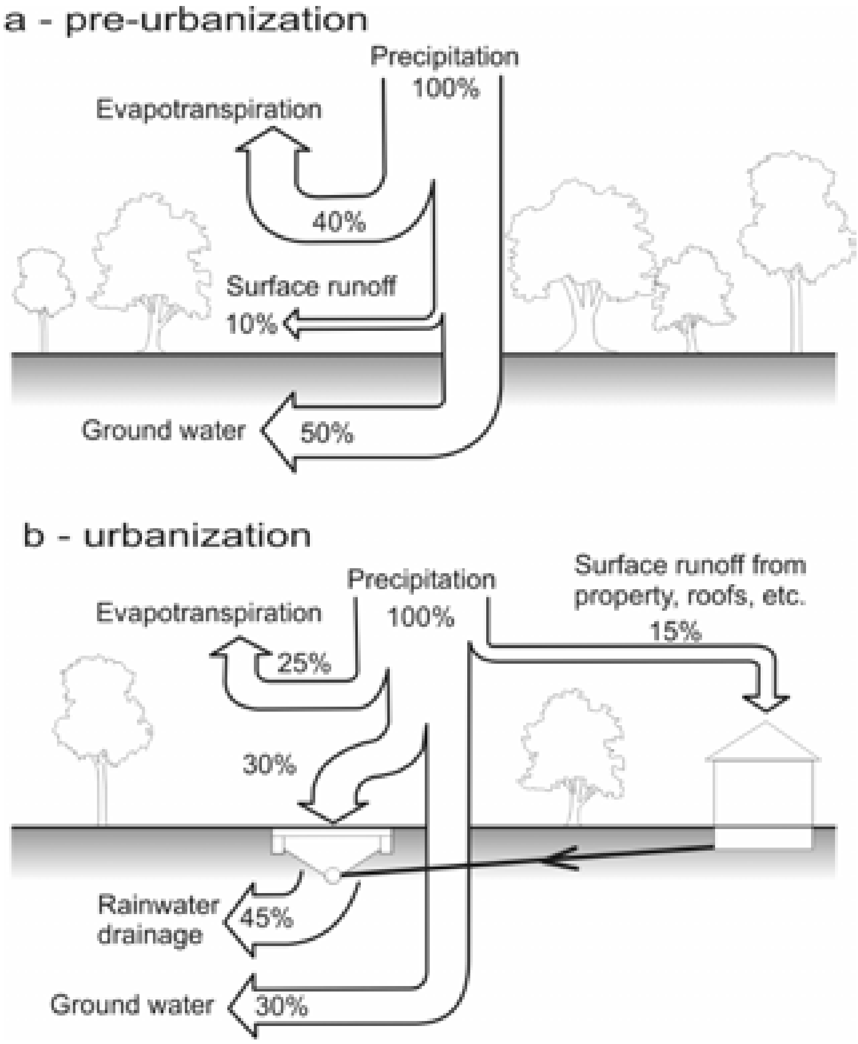


Figure 3.1. Water balance characteristics in an urban watershed (OECD, 1986)

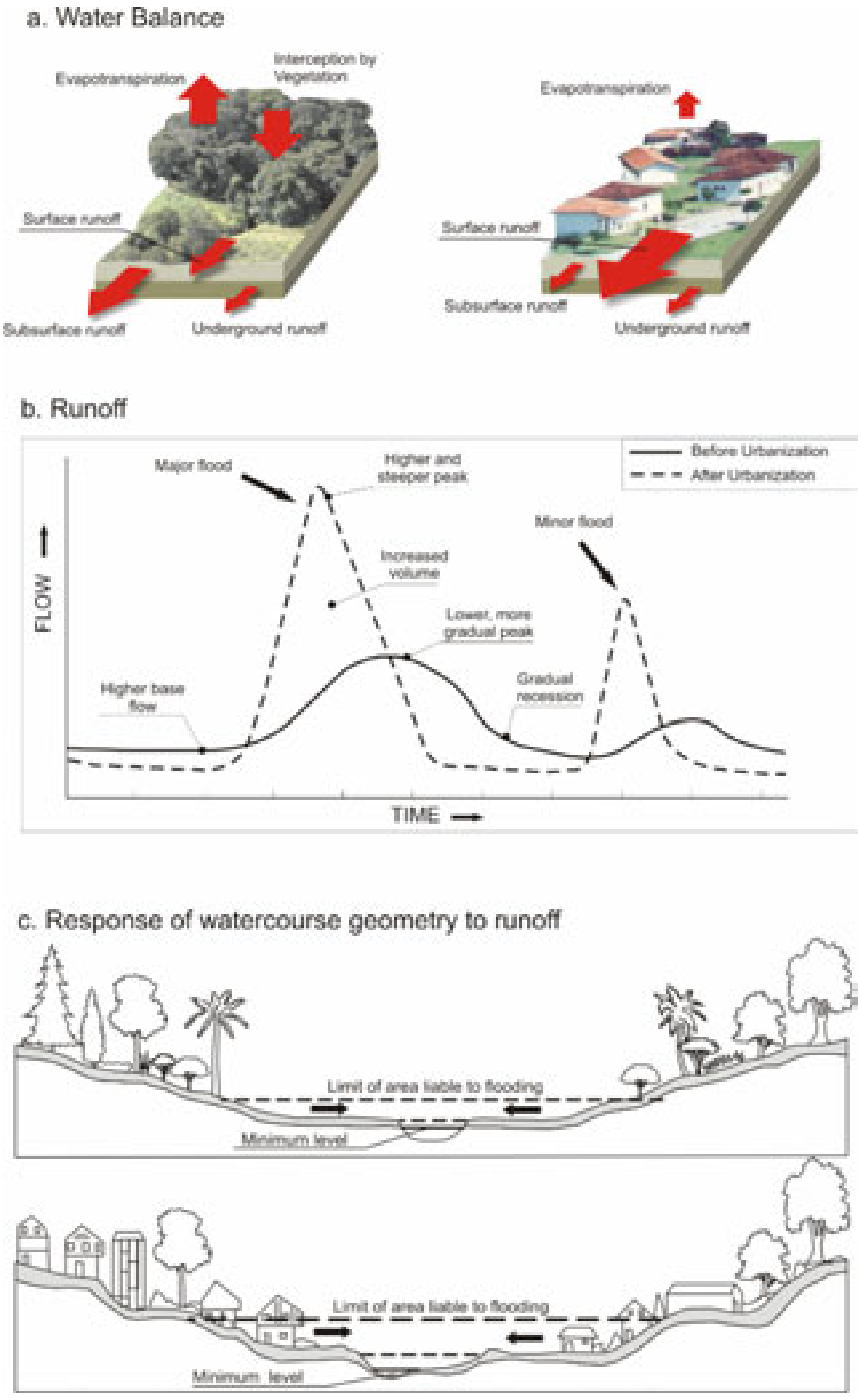


Figure 3.2. Impact of urbanization (Schueler, 1987)

- With reduced infiltration, the aquifer tends to lower the water table owing to a lack of feed water (mainly when the urban area is very extensive), thereby reducing underground flow. Water mains and sewage systems suffer leaks that can feed the aquifer, with the opposite effect to the above.

- The replacement of the natural cover reduces evapotranspiration, as the urban surface does not retain water as vegetation cover does and does not allow evapotranspiration from foliage and the ground. Despite this, urban surfaces in cities heat up which can cause greater evaporation of light rainfall.

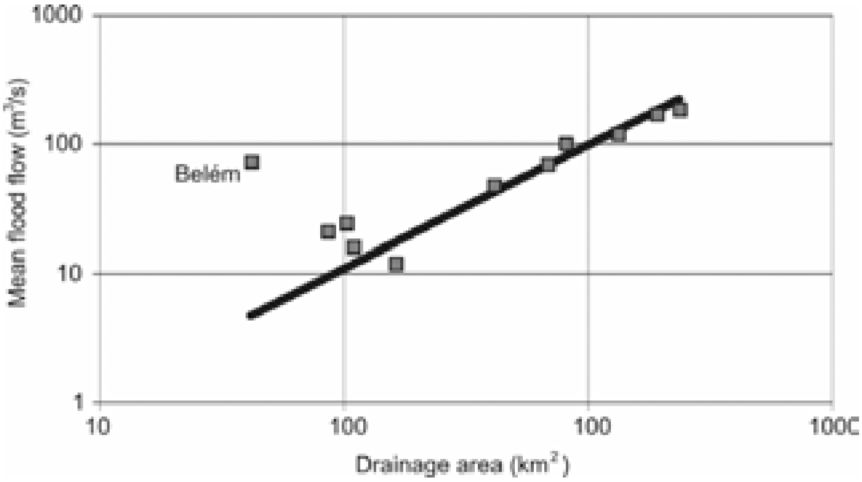


Figure 3.3. Mean flood flow as a function of drainage area in the Curitiba Metropolitan Region

3.2. Environmental impact on the aquatic ecosystem

With urban development, various human elements are introduced into the watershed and affect the environment. We discuss some of the main problems below.

Temperature rise: Impervious surfaces absorb part of the solar energy and increase the ambient temperature, creating islands of heat in the central part of urban areas, where the surfaces are predominantly concrete and asphalt. Asphalt, on account of its colour, absorbs more heat than natural surfaces or concrete. As the surface ages, it darkens, so increasing the amount or solar radiation absorbed. This temperature rise at the surface increases radiated heat into the environment, so generating more heat. The temperature rise also creates upward air currents which can increase precipitation. Silvera (1997) demonstrates that the central area of Porto Alegre has higher rainfall than the surroundings, attributing this tendency to urbanization.

Increase in sediment and solid material: During urban development, the watershed produces a significant increase in sediment owing among other things to building, clearing of land for new housing developments, building of streets, avenues and highways. Figure 3.4 illustrates a watershed’s tendency to produce sediment at its various stages of development.

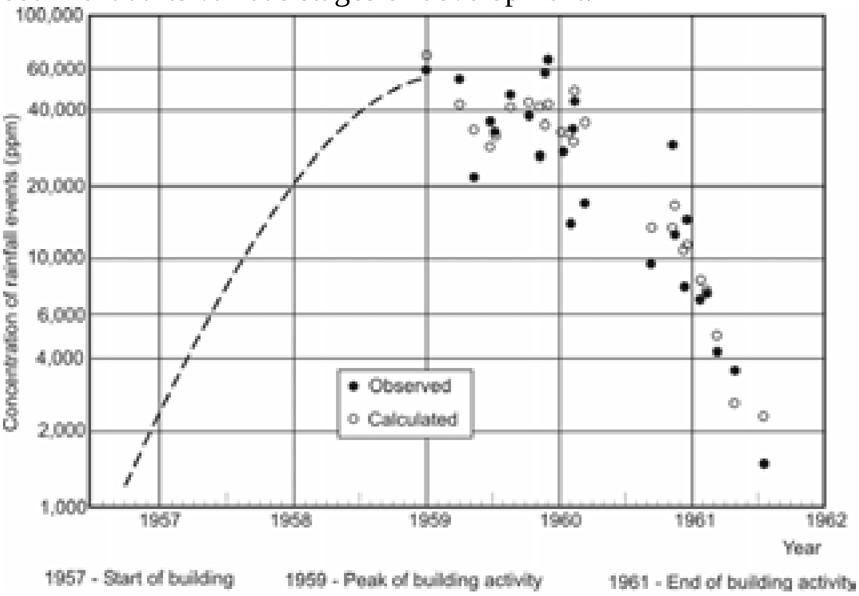


Figure 3.4. Variation in sediment production due to urban development (Dawdy, 1967)

The main environmental consequences of sediment production are as follows:

- Erosion of surfaces, leading to seriously degraded areas. Figure 3.5 and Figure 3.6 show the effect of erosion on unprotected urban surfaces. The photograph shows erosion caused by the increase in runoff from *upstream* drainage. The increase in energy and the quality of runoff can produce real ravines that can be up to 30m deep and 50m wide in fragile soils;
- Clogging of sections of drainage channels, thereby reducing the discharge capacity of urban conduits, rivers and lakes. The lagoon of Pampulha (in Belo Horizonte) is an example of an urban lake that has been clogged. Since it is very wide and shallow, in the dry season the Diluvio stream in Porto Alegre has deposited sediment from the watershed in the canal, leading to growth of vegetation and reducing runoff capacity during flooding.
- The sediment carries pollutants that contaminate the storm water.

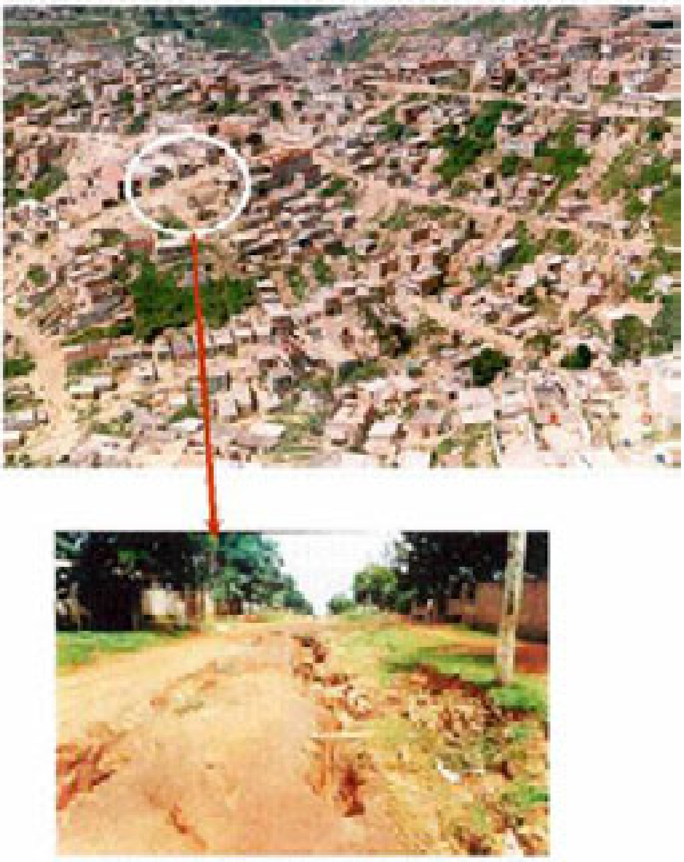


Figure 3.5. Erosion of unprotected urban area (Campana, 2004)

Figure 3.6. Erosion of unprotected urban area (Campana, 2004)

Obstructions to runoff: Runoff may be obstructed by bridge backfilling and piles, inadequate drains and obstructions of all kinds combined with clogged conduits.

Some examples of runoff obstruction are documented below:

a. *Solid refuse obstructing runoff:* the production of solid material that besides reducing runoff capacity obstructs the urban retention systems for local control of runoff. Figure 3.7 illustrates systems obstructed by solid material and piping passing through drains;
b. *Solid refuse in the detention system:* As the watershed is urbanized and densification consolidates, less sediment may be produced (Figure 3.4), but then another problem arises – refuse production. Refuse obstructs drainage even more, thereby creating very poor environmental conditions. This problem is minimized only by regular refuse collection and education of the population with heavy fines for infringements. Figure 3.8 shows the quantity of urban refuse in the drainage system. As can be seen, much of it is plastics, with a high concentration of bottles and supermarket bags;
c. *Maintenance problems with the drainage system:* In the drainage system various problems can occur with the normal water runoff, as a result of a lack of maintenance of the drainage system and poor design that does not take account of the clogging of the very narrow sections and with a single bore (Figure 3.9);
d. *Obstruction of runoff by buildings and risk:* Urban development tends to occupy areas of natural runoff of excess storm water, leaving little space for it, which in turn leads to risks to inhabitants and areas upstream (Figure 3.10).

Figure 3.7. Obstructions and refuse in the drainage (Belo Horizonte and São Paulo – cities in Brazil)

Figure 3.8. Refuse accumulating in drainage (São Paulo - Brazil)

Hillside risk areas: The settlement of hillsides in cities is one of the main causes of death in the rainy season owing to landslips caused by excess storm water runoff on low-sustainability soils, whose natural structure is damaged by uncontrolled urbanization (Figure 3.11).

Figure 3.9. Obstructions to flow in canals (Porto Alegre, Brazil).

Figure 3.10. Building in drainage channels (Caxias do Sul, Brazil)

Figure 3.11. Settlement of risk areas

Storm water quality: Storm water is of no better quality than effluent from secondary treatment. There is more material suspended in storm water runoff than in an untreated sewer. The volume of this material in suspension is more significant at the onset of flooding. Figure 3.12 illustrates a sample of rainwater in the form of a clock. When precipitation begins, there is a low concentration of material in suspension, then the concentration rises and after some time it drops markedly. Generally, 95% of the load in suspension is concentrated in the first 25 mm of rainfall. The pollutogram generated by an urban area after a dry period has a concentration peak before the peak of the hydrograph, indicating that the initial concentration is high, though the flow is low.

Figure 3.12. Samples of storm water quality The brown bottle (at 9 o'clock) corresponds to the onset of precipitation.

Flows may be combined (sewage and storm water in the same conduit) or separate (separate storm water and sewage systems). In Brazil, most systems are of the second type; combined systems exist only in the old parts of some cities. Nowadays, owing to a lack of financial resources to expand the sewage system, some municipalities have allowed sewage to be discharged into the storm drains, which can be an inappropriate solution since the sewage is untreated, and it rules out some solutions for controlling the quantity of storm water.

There is a wide variety of pollutants generated in the urban area, ranging from organic compounds to highly toxic metals. Some pollutants are used for various functions within the urban environment, such as insecticides, fertilizers, lead from motor vehicle emissions and oil leaking from trucks, buses and cars, all resulting from normal activities in the urban environment. Soot in emissions generated in the urban environment by vehicles, industry and the burning of refuse is deposited on surfaces and washed away by storm water. The resulting polluted water finds its way into the rivers.

The main pollutants found in urban surface runoff are: sediments, nutrients, oxygen-consuming substances, heavy metals, hydrocarbons, bacteria and pathogenic viruses. The mean values established for North America are presented in Table 3.1.

Table 3.1. Concentration for mean runoff for some urban land uses based on the (American) Nationwide Urban Runoff Program by Whalen and Cullum (1989).

Parameter	**Residential**	**Commercial**	**Industrial**
TKN (mg/1)	0.23	1.5	1.6
$NO_3 + NO_2$ (mg/1)	1.8	0.8	0.93
Total P (mg/1)	0.62	2.29	0,42
Copper (mg/l)	56	50	32
Zinc (mg/l)	254	416	1 063
Lead (mg/1)	293	203	115
COD (mg/1)	102	84	62
TSS (mg/1)	228	168	106
DBO (mg/1)	13	14	62

The quality of the water in the storm drains depends on a number of factors: the type and frequency of urban cleaning; the precipitation intensity and its distribution in time and space, the time of year and the use made of the urban area. The main indicators of water quality are the parameters for organic pollution and quantity of metals.

Contamination of aquifers: The main causes of contamination of urban aquifers are as follows:

- Sanitary landfills that contaminate groundwater via the natural processes of precipitation and infiltration. These landfills should not be sited in catchment areas; areas of low permeability should be chosen where possible. The effects of groundwater contamination should be examined when the landfill site is chosen.
- Most Brazilian cities discharge sewage into septic tanks. This system tends to contaminate the top of the aquifer. This pollution can compromise the urban water supply when there is communication between various strata of the aquifers by percolation and incorrectly bored artesian wells.
- The storm drain system can pollute the ground by volume lost in transit and also through obstructed sections of the system that force the contaminated water out of the conduit system.

3.3. Management of macrodrainage, impacts generated

3.3.1. Management of urban drainage

Current control of urban runoff has been established on an incorrect basis, causing serious harm to the population. These adverse impacts have been caused principally by two kinds of error:

a. *Drainage design principle:* Urban drainage has been developed on the basis of the incorrect principle that *the best drainage system is one that carries the excess water as quickly as possible away from its place of origin.*
b. *Evaluation and control in sections:* Microdrainage designs increase flow and transfer all their volume *downstream*. In Macrodrainage, urban drainage tends to be controlled by canalizing the critical sections. This type of solution is based on the particular perspective of a section of the watershed, without taking account of the consequences for the other sections or other aspects of urban settlement. Canalizing the critical points only transfers the flooding from one place to another in the watershed.

Combining these two types of error in microdrainage management has impacts on macrodrainage of cities, which occur in the following sequence:

- **Stage 1:** the watershed starts to be urbanized in a distributed way, with a higher density downstream, flooding appearing in the natural bed at natural bottlenecks along its course (Figure 3.13);
- **Stage 2:** the first canalizations are carried out downstream, based on the current level of urbanization; this increases the downstream hydrograph, but it is still contained by the areas that flood upstream and because not all the watershed is built up. (Figure 3.13).
- **Stage 3:** as density rises, public pressure encourages administrators to continue canalizing upstream. When the process is completed, and even before that, flooding returns downstream, owing to the increase in the peak flow, when no further widening is possible. The upstream

> areas function as attenuating basins. At this stage, canalization simply transfers flooding downstream (Figure 3.13). There is no more space to widen the canals downstream, and the solutions are based on deepening the canal, at extremely high cost (up to US$ 50 million/km, depending on the subsoil, width, lining, etc.).

This process is contrary to the public interest and represents an extremely high loss for the whole of society over time. Society loses twice and pays around 1000% or more for canalization, in relation to an attenuation solution, and still flooding gets much worse for the *downstream* population. Unfortunately, many engineers maintain this biased view of technical knowledge or an interest in costlier structures on the pretext that "*there is no space for attenuation*". The space required for attenuation is of the order of 1% of the watershed, and may be spread across several areas. It may be possible to expropriate these, although they are sometimes difficult to identify. Nonetheless, with the necessary commitment by technical staff it is possible to identify the combinations of runoff transfer and attenuation without transferring impacts *downstream*. The important thing is not to get too attached to a preconceived idea, but to look for a combined solution, based on the fundamental principle that no project may transfer its impact to another point in the watershed.

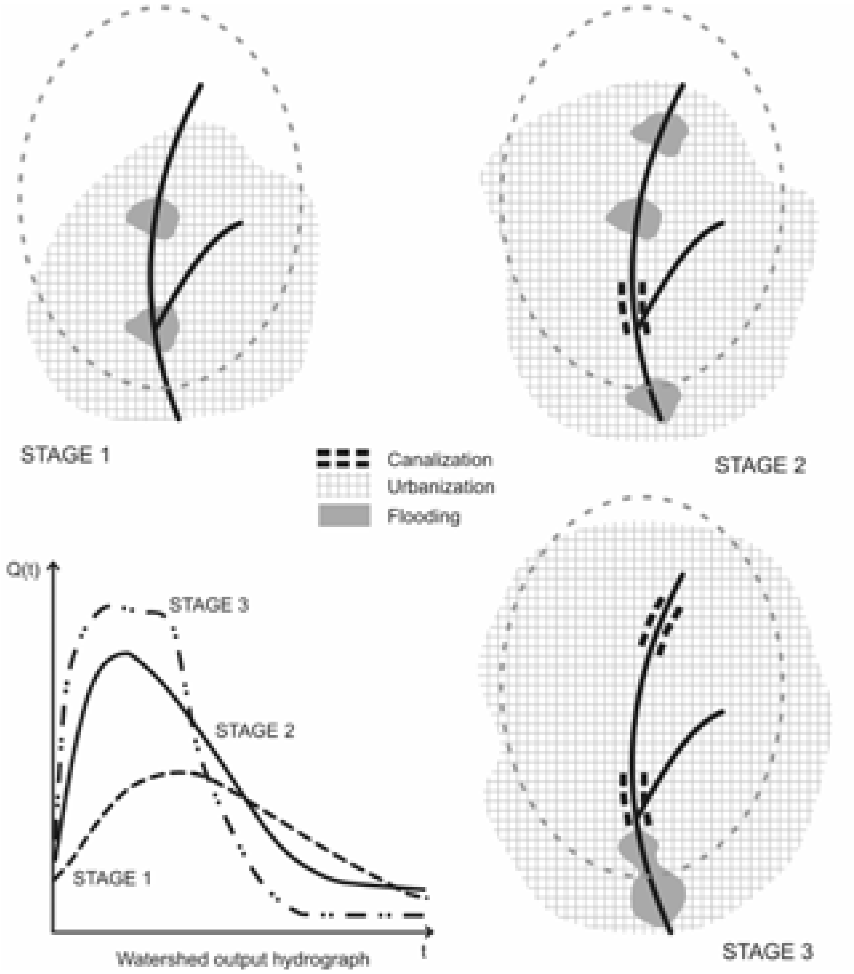
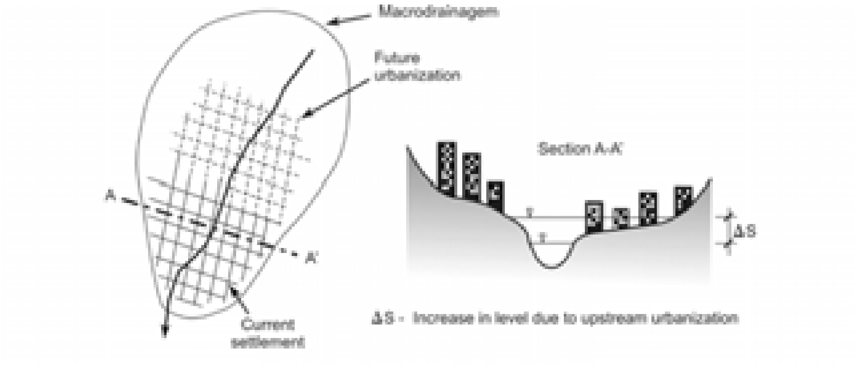


Figure 3.13. Stages of urban development

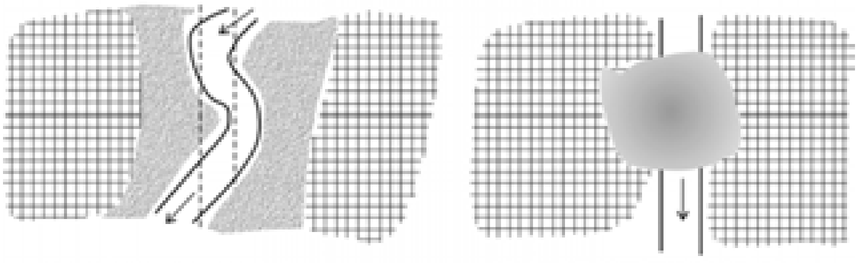
3.3.2. Mismanagement of riverside areas in combination with urban drainage

As we pointed out in the previous chapter, urban development tends to encourage settlement of riverside areas. The administration has been inclined to increase the capacity of the river, enabling the population to settle the flood plain of water courses (stage 1 of mismanagement, described in Figure 3.14). Over time, the watershed develops *upstream*, broadening the flood peak and increasing flooding frequency due to increased impermeabilization, canalization and conduits. The project to increase the runoff capacity of the downstream reaches only took account of the urban scenario that existed at the time it was carried out, and did not assess the potential future impacts; upstream urbanization led to renewed flooding of the flood plain now occupied by residential areas, leading to high-cost structural solutions, such as deepening the water course, reducing roughness, diversion tunnels, etc. These structures are economically unviable, reducing property values and increasing losses. This scenario was observed on the river Tietê in São Paulo, Brazil (Figure 3.15).

Figure 3.16 illustrates the set of processes originating with land use (settlement of the river flood plain, impermeabilization and canalization of runoff), drainage and the resulting impacts.



a) Tendency of urban growth into the watershed



b) Section A-A' at start of urbanization

c) Section A-A' future impact of urbanization

Figure 3.14. Increased urbanization, settlement of riverside areas and increased flooding frequency

Figure 3.15. Flooding of the river Tietê at the Bandeiras bridge as a result of urbanization of the city of São Paulo.

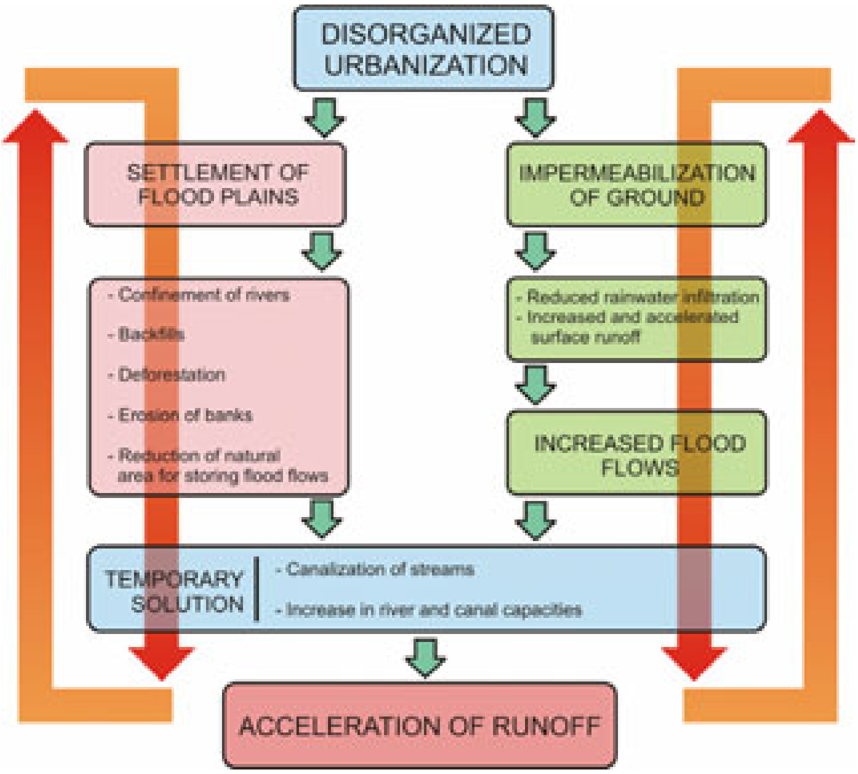


Figure 3.16. Progressive impact of urban drainage (Sudersha, 2002)

3.4. Principles of sustainable management

The basic principles of controlling storm water runoff due to natural flooding of the flood plain and urbanization are as follows:

The watershed as a system: A storm water control plan for a city or metropolitan area must take account of the watersheds in which urbanization is taking place. The measures may not reduce impact in one area to the detriment of another, in other words, impacts may not be transferred.

Control measures for the whole watershed: Flood control involves structural and non-structural measures that cannot readily be treated separately. Structural measures involve costs that most cities cannot afford. Also, unless a programme is set up for the whole watershed or urban region concerned, only specific problems are solved. This does not mean that this kind of measure is to be totally ruled out. The flood-control policy will be able to provide structural solutions for some places, but as part of an overall approach to the whole watershed, in which they are rationally integrated with other preventive (non-structural) measures and compatible with urban development.

Means: Flood control can be introduced with the following means: the urban master plan, municipal/provincial legislation and the drainage manual. The first sets out the main policies, the second controls implementation and the third offers guidance.

Expansion horizon: Once the watershed or part of it has been settled, the authorities will find it difficult to make those who are increasing runoff accountable, so unless the authorities act beforehand in the form of management, there will be more serious future economic and social consequences for the whole municipality. The urban master plan should cover the planning of the areas to be developed and any increase in the density of the areas currently developed.

Sustainable criteria: (a) Natural runoff must not be increased by inhabitants of the watershed, either by new housing development or by structures in the urban environment. This applies to a simple urban backfill, construction of bridges, highways, and basically impermeabilization caused by new urbanization. The principle is that no urban user should increase the natural flood level, (b) settlement of urban areas and storm water drainage must give priority to natural runoff mechanisms, such as infiltration.

Ongoing control: Flood control is an ongoing process; it is not enough to lay down regulations and build protection structures, we must look out for potential infringements of the legislation and expanding settlement of the risk areas. It is therefore recommended that: (a) no risk area be cleared unless it is immediately occupied by the authorities to prevent it being invaded; (b) the community must be involved in planning, implementation and ongoing observance of flood control measures.

Education: It is essential to educate engineers, architects, agronomists, geologists and other professions, the public and public administrators so that everyone is aware of public decisions taken.

Administration: The administration of maintenance and control is a local process and depends on the municipalities, through the approval of projects for housing developments, public works and drainage. The implementation of the drainage system should also evaluate the environmental aspects.

3.5. Types of control measures

Runoff control measures can be classified according to their effect on the watershed, as follows:

- ***Distributed or at source,*** this is control over housing developments, public squares and paths;
- ***In the microdrainage***, this is control over the hydrograph resulting from one or more urban developments;
- ***In the macrodrainage,*** this is control of the main urban watercourses.

Control measures can be organized in accordance with their effect on the hydrograph in each of the parts of the watersheds mentioned above, as follows:

Infiltration and percolation: normally, this creates space to enable more water to infiltrate and penetrate into the ground, using underground storage and flow to delay surface runoff.

Storage: using reservoirs that can occupy open or covered spaces. The reservoir has the effect of retaining part of the surface runoff volume, reducing the peak and spreading the flow over time;

Increased runoff efficiency: through conduits and canals, draining flooded areas. This type of solution tends to transfer flooding from one area to another, but can be beneficial when used in conjunction with retention reservoirs.

Dykes and pumping stations: a traditional solution for local control of flooding in urban areas having no space for attenuating flooding.

3.5.1. Distributed control measures

The main measures for local control in housing developments, car parks, parks and public thoroughfares are normally termed “source control”. The main measures are as follows:

- Increasing areas for infiltration and percolation;
- Temporary storage in residential or covered reservoirs.

The main characteristics of local control of runoff are as follows (Urbonas and Stanhre, 1993):

- More efficient drainage system *downstream* of the controlled places;
- Systems have a greater capacity to control flooding;
- Difficulty of controlling, designing and maintaining a large number of systems;
- Operating and maintenance costs may be high.

This type of system has been adopted in many countries with the help of appropriate legislation, or through a global flood control programme, as described by Yoshimoto and Suetsugi (1990) for the watershed of the river Tsurumi, where some 500 detention basins of 1.3 m^3 were built.

One of the main criteria adopted by many cities (Seattle, Denver, Porto Alegre, etc.) is the peak flow than can enter the public drainage system from housing developments, and commercial and industrial installations. This limit generally corresponds to the natural flow from the housing development for a given return time (generally 10 years’ return time and 1 hour duration). This flow is restrictive and obliges the entrepreneur to use the systems mentioned within the area under development in order to maintain the downstream flow.

We list below the types and characteristics of systems that may be used.

Infiltration and percolation:

Urban systems, as mentioned above, create impervious surfaces that did not exist previously in the watershed, leading to increased runoff that is carried in conduits and canals. The costs of these hydraulic structures are directly related to their peak flows, rising with increasing impermeabilization. To reduce these costs and minimize downstream impacts, one of the measures is to allow more precipitation to infiltrate, creating conditions as close as possible to natural conditions.

The advantages and disadvantages of systems increasing infiltration and percolation are as follows (Urbonas and Stahre, 1993):

- Increased recharge; reduced settlement in areas with a low water table; preservation of natural vegetation; less pollution discharged into rivers; reduced maximum downstream flows; smaller conduit sizes;
- Soils in some areas may become impervious over time; lack of maintenance; rise in water table up to underground buildings.

Infiltration is the process of transfer of the flow from the surface underground. The infiltration capacity depends on the properties of the soil and the humidity of the top stratum of soil, also known as the unsaturated zone. The velocity of runoff through that unsaturated layer down to the water table (saturated zone) is known as *percolation*. Percolation also depends on the humidity and type of the top stratum of soil. Certain soil types are less prone to percolation and can store low volumes, making them unsuitable for use, since they may: (a) keep water on the surface for much longer; (b) do little to reduce the final volume of the hydrograph.

The main systems for creating more infiltration are discussed below.

Infiltration surfaces: these are of various types, depending on the local circumstances. In general, the infiltration area is an area of grass that receives precipitation from an impervious area, such as residential areas or buildings (Figure 3.17). During heavy rainfall, these areas may be submerged if the precipitation exceeds their capacity. Where the drainage carries a lot of fine material, the infiltration capacity may be reduced, requiring the surface to be cleaned to keep it working.

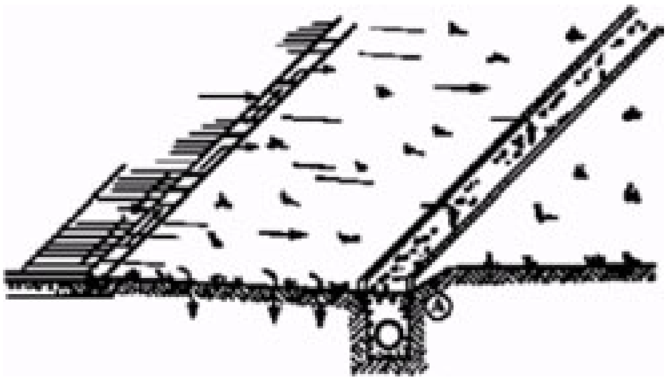


Figure 3.17. Infiltration surface with trenches

Infiltration trenches: these are lateral drainage mechanisms, often placed parallel to streets, highways, car parks, housing complexes, etc. (Figure 3.18). These trenches concentrate the flow from the adjacent areas and create conditions for infiltration over its whole length. After heavy precipitation, the level rises, and as infiltration is slow, they remain filled with water for some time. The volume should therefore be sufficient to prevent flooding. This system actually works as a detention basin when the drainage running into the trench exceeds the infiltration capacity. In periods of low rainfall or drought, it stays dry. This system also helps to reduce the quantity of pollution carried downstream.

Soakaways: soakaways within housing developments also help to increase recharging and reduce surface runoff. Storage takes place in the top layer of the soil and depends on porosity and percolation. The water table must therefore be low to allow space for storage. This type of system is not recommended for areas with a high water table. Soakaways are built to collect water from roofs and create conditions for runoff into the ground. They are made by digging out the soil and backfilling with gravel to create the storage space (Figure 3.19). Certain soil types require better drainage conditions to be created. In clay soils that have low percolation, the outlet needs to be drained. The main difficulty with using this type of system is that the spaces between the stones get clogged by the fine material entering the soakaway. It is therefore recommended to use a filter of geotextile material. In any case, it needs to be cleaned after some time (Urbonas and Stahre, 1993).

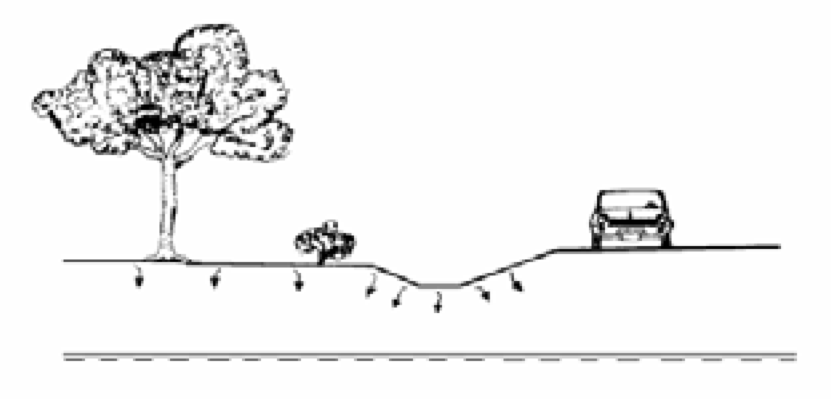


Figure 3.18. Infiltration trenches (Urbonas and Stahre, 1993)

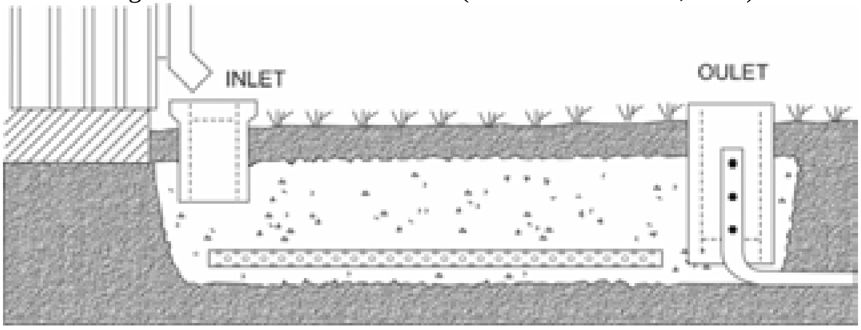


Figure 3.19. Example of a soakaway (Holmstrand, 1984)

Pervious hydraulic structures: there are various types of system that drain runoff and can be constructed to allow infiltration. Examples are:

- *Pervious inlets to the drainage system:* Figure 3.20 a shows a filter in the top of the chamber to prevent obstruction;
- *Pervious trench:* this is a special type of soakaway consisting of a chamber with gravel and a filter, with a porous or perforated pipe passing through (Figure 3.20 b);
- *Pervious kerb:* this system is used outside housing developments or inside condominiums, or industrial or commercial premises (Figure 3.20 c).

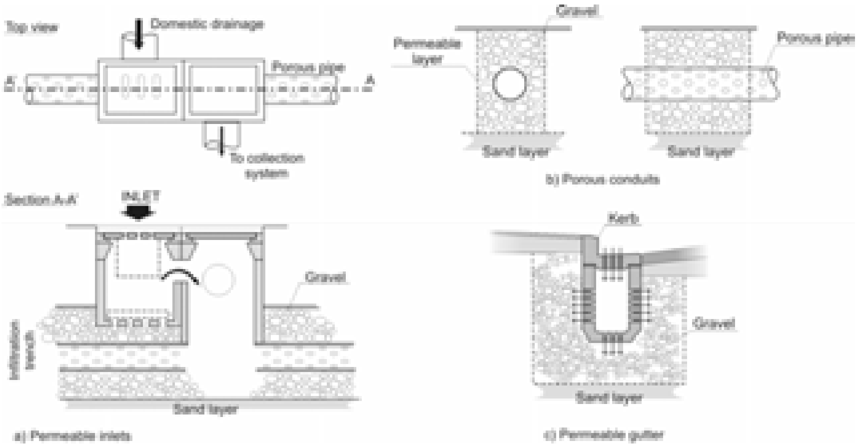


Figure 3.20. Pervious hydraulic systems

Pervious paving: pervious paving can be used for public thoroughfares, car parks, sports fields and streets with light traffic. In streets with heavy traffic, this paving can be deformed or blocked, thereby becoming impervious.

This type of paving can be made of perforated concrete or asphalt blocks (Figure 3.21). The concrete and asphalt are made in the same way as conventional paving, except that the fine material is left out of the mixture.

When this paving is designed to hold part of the drainage, its base must be at least 1.2 m above the water table in the rainy season. The base is drained with perforated tubes spaced 3 to 8 m apart. The drainage system has to be designed to absorb the volume held in the soil layer in a period of 6 to 12 hours (Urbonas and Stahre, 1993). This system is viable when the soil has an infiltration capacity of more than 7mm/h. It is not recommended for use in soils with more than 30% of clay or 40% of silica and clay combined. This type of control can have the following advantages: reduction in planned surface runoff in relation to an impervious surface; reduction of storm drain diameters; reduction of storm drain costs and of standing water on car parks and public thoroughfares. The disadvantages are: maintenance of the system to prevent clogging over time; higher direct cost of construction (without taking account of the benefit of smaller pipe sizes); contamination of aquifers.

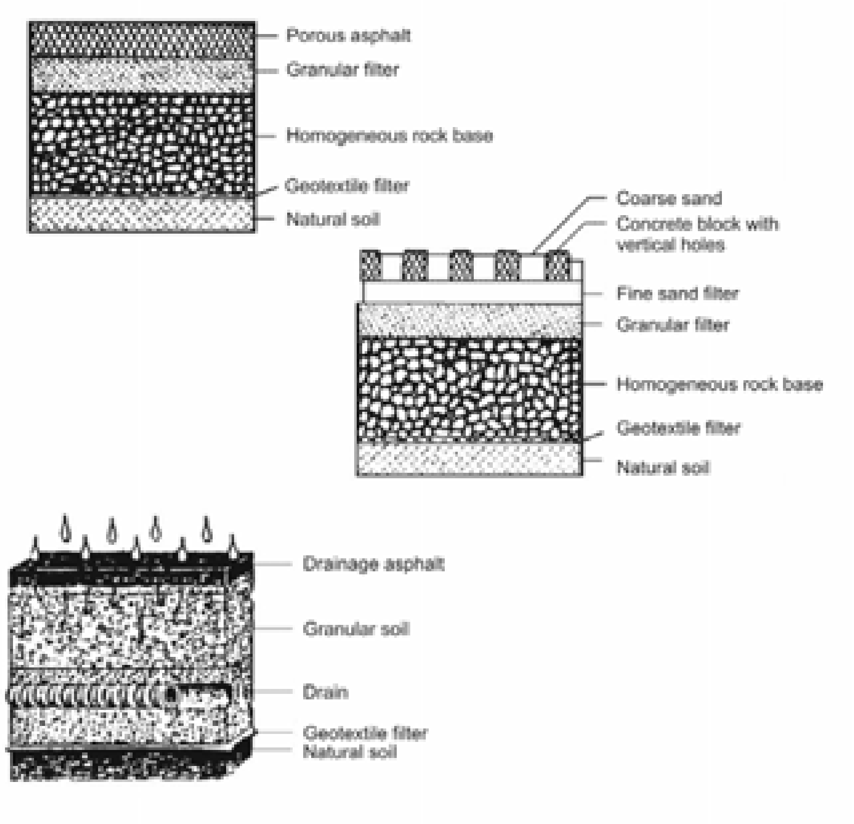


Figure 3.21. Pervious paving

Araújo *et al* (2001) carried out experiments with a variety of surfaces: (a) *Compacted earth* having a gradient of 1 to 3 %; (b) *Impervious paving:* an area of ordinary concrete, made of cement, sand and gravel, having a gradient of 4%; (c) *Semi-pervious paving:* an area of regular parallelepiped granite slabs, with sand joints, having a gradient of 4%; and another area laid with machine-made concrete blocks type "pavi S[1]", also with sand joints, known as blockets, having a gradient of 2%; (d) *Pervious paving:* an area of concrete blocks with vertical orifices filled with granular material (sand) having a gradient of 2% and an area of porous concrete having a gradient of 2%. The experiments were conducted with precipitation of 110 mm/h, equivalent to a 5-year return time for a duration of 10 minutes. The results of the experiments are presented in Table 3.2 which shows that parallelepipeds absorb part of the precipitation when it is very heavy and pervious paving produces practically no runoff. Note that the experiment was conducted with a rain simulator over a surface of 1 m^2, where the storage on the surface and in the

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[1] "pavi S" – Trade name given in Brazil to a type of industrial concrete paving.

reservoir of pervious paving is most effective. Pervious paving may cost 30% more than conventional paving as it has to be laid on a base. The figures in Table 3.2 show that parallelepipeds or blocks, when not jointed with cement, can store a substantial proportion of frequent precipitation or allow it to infiltrate. Therefore, streets paved in this way should be preserved to avoid aggravating localized drainage problems in cities. When laying asphalt or paving, an unpaved strip should be left at least in the middle of the area to allow part of the volume to infiltrate and accumulate.

Table 3.2. Runoff coefficients for simulated rain with an intensity of 110 mm/h on a variety of surfaces

Surface	C
Compacted earth	0.66
Concrete	0.95
Concrete blocks	0.78
Slabs	0.60
Perforated blocks	0.03
Pervious concrete	0.03

Figure 3.22 to Figure 3.25 depict various systems that favour infiltration of runoff, in addition to having a structural function in building. The advantages and disadvantages of the infiltration systems used for distributed runoff control are set out in Table 3.3.

Figure 3.22. Use of systems for retaining water from impervious areas (a) the left-hand photo shows drainage from paved areas onto grass and from roofs into gravel reservoirs; (b) paths with grass alongside to increase infiltration.

Figure 3.23. The photos show (left) an example of infiltration trenches and (right) pervious paving with perforated blocks for car parking

Figure 3.24. The photo (left) shows a street without a kerb allowing part of the runoff to infiltrate into the grass alongside. The photo (right) depicts an infiltration area in a flower bed.

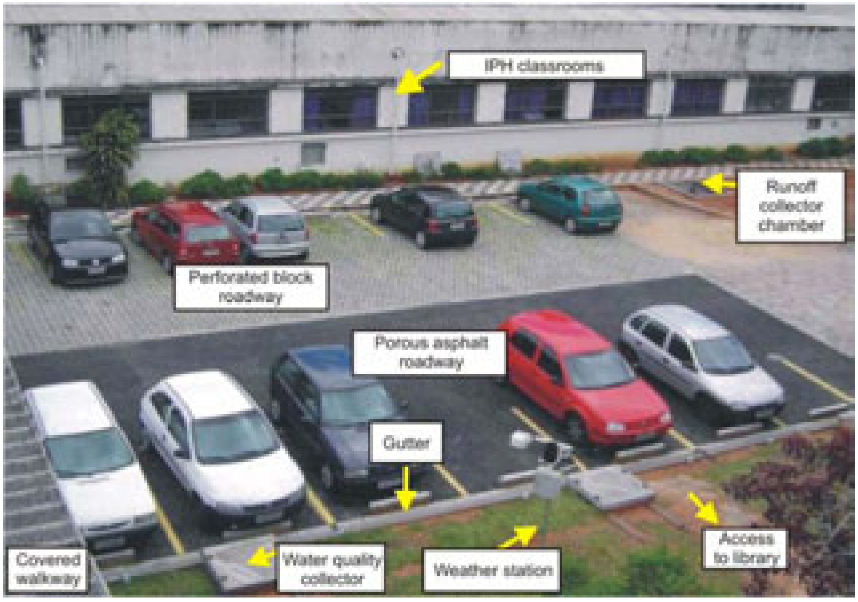


Figure 3.25. Two experimental areas of the car park at the Instituto de Pesquisas Hidráulicas (Porto Alegre – Brazil) with perforated blocks and porous asphalt.

Storage:

Storage can take place on roofs, in small residential reservoirs, car parks, sports fields, etc. We present below the main characteristics of some storage systems:

Roofs: rooftop storage involves some difficulties, namely maintenance and reinforcement of structures. Given the characteristics of the Brazilian climate and the type of roofing materials usually used, it would be difficult to apply this kind of control to our circumstances.

Urban housing developments: storage in a housing development can be used to attenuate runoff in combination with other uses, such as water supply, lawn irrigation and washing of surfaces or vehicles. Figure 3.26 depicts a reservoir of this type.

In areas with a low water distribution capacity, precipitation on roofs runs directly into an underground well and is then chlorinated for domestic use. Water collected on rooftops of sports centres can be collected directly for use in cleaning. An area of 120 m^2, with annual precipitation of 1 500 mm, can produce 360 m^3 a year, or nearly 15 m^3 a month, which is more than enough to supply a house. Obviously the more water is kept in the reservoir, the lower its attenuation capacity.

Table 3.3. Infiltration systems

System	Characteristics	Advantages	Disadvantages
Infiltration surfaces and trenches with drainage	Grass, areas of pebbles or other material allowing natural infiltration	Allows water to infiltrate into the subsoil	Surfaces with gradients > 0.1% should not be used; solid material carried to the infiltration area can reduce the infiltration capacity.
Infiltration surfaces and trenches without drainage	Grass, areas of pebbles or other material allowing natural infiltration	Allows water to infiltrate into the subsoil	The accumulation of surface water in the rainy season does not allow traffic in the area. Sloping surfaces that allow runoff away from them.
Pervious paving	concrete, asphalt or perforated blocks with high infiltration capacity	Allows water to infiltrate	Should not be used for streets with heavy traffic as this may reduce their

			effectiveness
Infiltration pits and trenches and soakaways	Volume accumulating underground that allows water to be stored and infiltrate	Reduction of surface runoff and attenuation depending on storage	Effectiveness can drop over time, depending on the amount of solid material draining into the area

(1) Physical constraints: Depth of water table in rainy season > 1.20 m. The impervious layer must be > 1.20 m in depth. Rate of infiltration into saturated ground > 7.60 mm/h. Saturated hydraulic conductivity of soakaways > 2.10-5 m/s.

There are various possible configurations for putting reservoirs into urban housing developments and projects, as shown in Figure 3.27 and Figure 3.28. The volume is generally estimated on the basis of the limits set by the public authorities for input to the storm drains. In Porto Alegre the limit is 20.8 1/(s.ha) which gives a reservoir size based on the following equation:

$$V = 4.15 \cdot AI \cdot A \qquad (3.1)$$

where: *AI* is the impervious area as a %, *A* is the area of the housing development or project in hectares and *V* is the required volume in m^3. For a building project on a site of 1000 m^2, with a total impervious area of 80% the required volume is 33 m^3. For a depth of 1.5 m, an area of 22 m^2 would be required. The legislation states that if the water from pervious surfaces is drained onto surfaces that allow infiltration but have no drainage, the impervious area in the calculation may be reduced by 80%, giving AI = 16% and V = 6.8 m^3 and 4.5 m^2. This type of management encourages all contractors to develop distributed infiltration techniques.

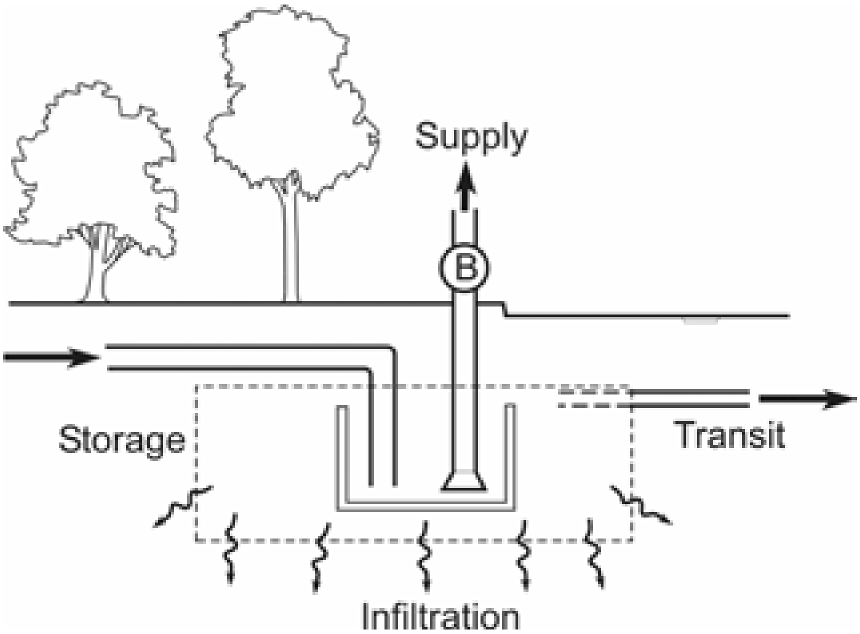


Figure 3.26. Multi-purpose reservoirs (Fujita, 1993)

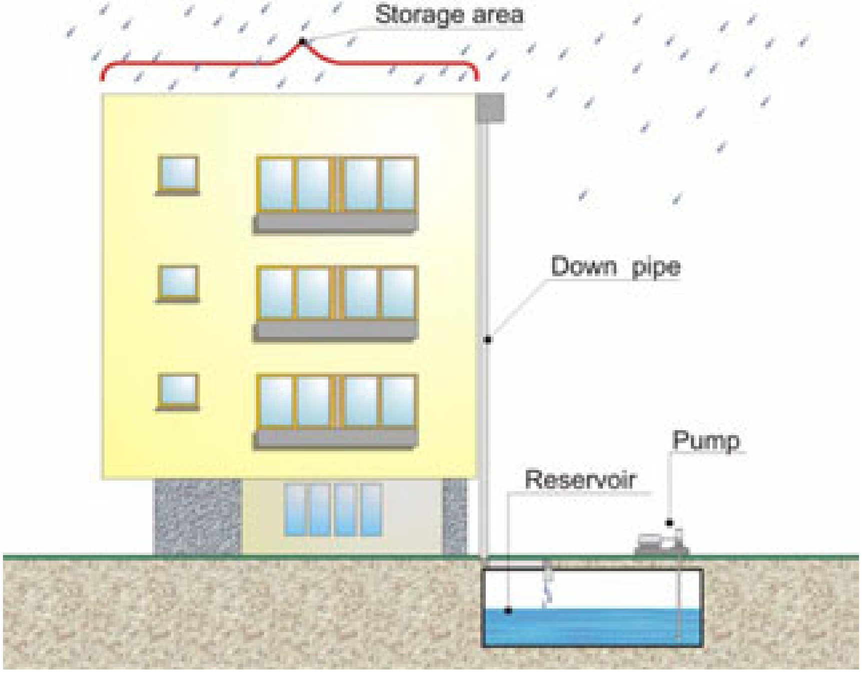


Figure 3.27. Reservoirs in a building (Campana, 2004)

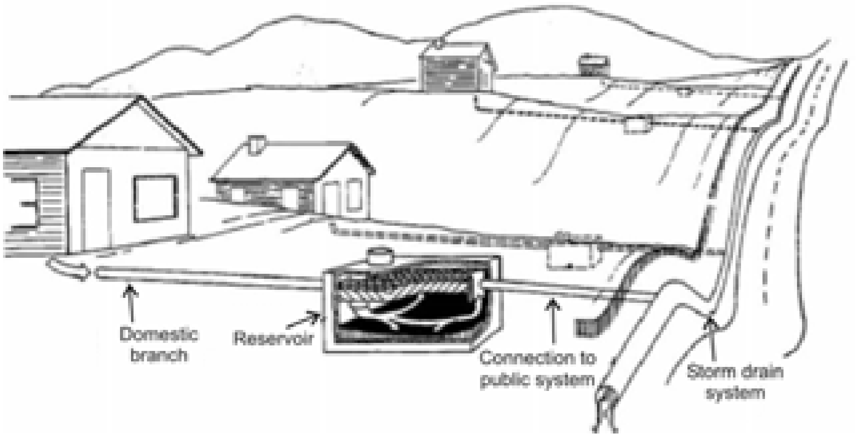


Figure 3.28. Reservoir in a residential area (Campana, 2004)

Figure 3.29. Storage in a condominium (left) and in the car park of a shopping centre (right)

3.5.2. Control measures in microdrainage and macrodrainage

In microdrainage, the conventional means of controlling runoff is to drain the urbanized area through storm drains to a main sewer or urban river. This type of solution has the effect of transferring the increase in surface runoff downstream at a higher velocity, as the runoff takes less time to move than in the pre-existing conditions. This causes flooding in the main trunk lines or actually in the macrodrainage.

As we explained above, impermeabilization and canalization increase the peak flow and surface runoff. To prevent this increase in flow from being transferred downstream, the volume generated is attenuated using retention systems such as: tanks, lakes and small open-air or covered basins. These are termed downstream control measures.

The purpose of detention basins is to minimize the hydrological impact of urbanization, attenuating the reduction in the watershed's natural storage capacity.

This type of control has the following advantages and disadvantages (Urbonas and Stahre, 1993): reduced costs, compared with a large number of distributed control devices; lower operating and maintenance costs; easy administration of construction; difficulty in finding suitable sites; cost of purchasing area to be used; large reservoirs encounter opposition from the population.

This control has been used where the municipal authorities impose restrictions in increases of peak flow due to urban development, and has accordingly been used in many cities in a variety of countries. The usual criterion is that *the peak flow of the area, with urban development, must not exceed the peak flow in the pre-existing conditions for a given return time.*

Characteristics and functions of reservoirs

Retention reservoirs are used according to the desired control objective. They can be used for:

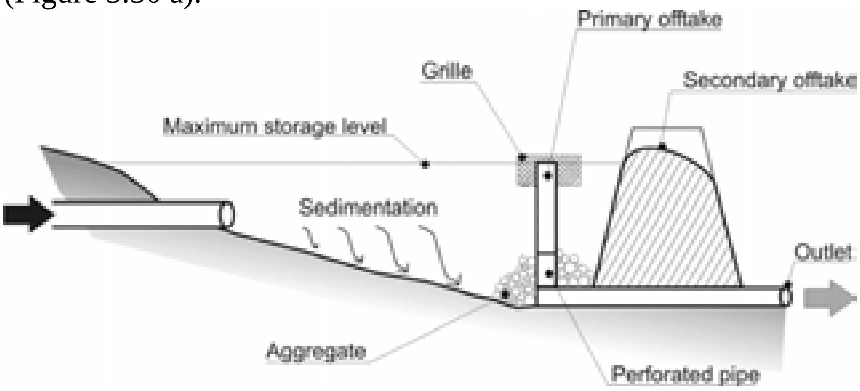
Controlling peak flow: This is the typical application for controlling the effects of flooding in urban areas. The reservoir is used to attenuate the upstream peak, reducing the hydraulic section of the conduits and maintaining the flow conditions pre-existing in the developed area.

Control of volume: this type of control is usually used when sewage and storm water runoff are carried in combined conduits or when the water comes from an area liable to contamination. As a treatment plant has a limited capacity, the volume for treatment must be stored. The reservoir is also used for the deposition of sediments and treatment of water quality, keeping its volume in the reservoir for longer. The detention time, which is the difference between the centre of gravity of the inlet and outlet hydrographs, is one of the indicators of the reservoir's treatment capacity.

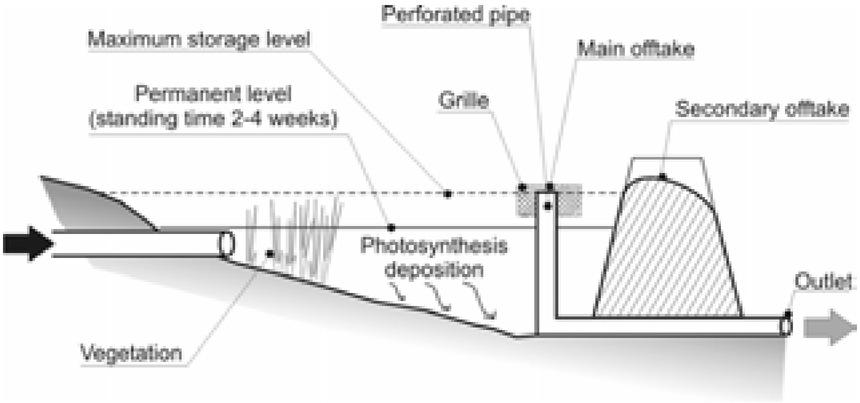
Control of solid material: when a significant quantity of sediment is produced, a detention basin can retain part of the sediment so that it can be removed from the drainage system.

Reservoir types

The reservoirs can be designed to be of such a size that they always hold a certain amount of water, known as *retention* basins, or so that they dry out after use, during heavy rainfall, and then used for other purposes. This type is known as a *detention basin* (Figure 3.30 a).



a – Detention basin



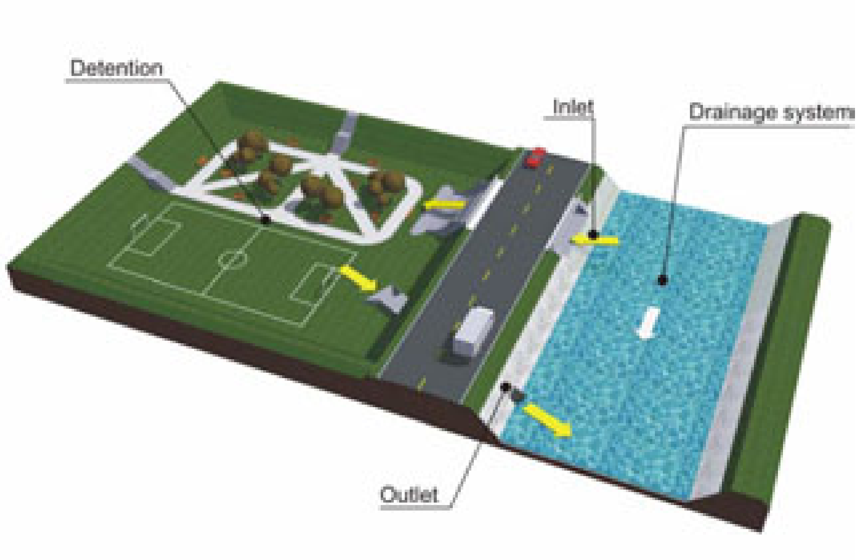
b – Retention basin

Figure 3.30. Reservoirs for controlling solid material (Maidment, 1993)

Retention basins that keep a quantity of water in them are designed to stop undesirable vegetation growing on the bottom and to reduce downstream pollution, and the reservoir becomes more effective at controlling water quality. Their use as an integral part of parks can create a pleasant leisure area. The advantage of this type of dry system is that it can used for other purposes. One common practice is to specify a wet area to be large enough to absorb frequent flooding, such as a two-year flood, and design the overflow area with landscaping and sports fields to handle flooding above the level corresponding to the selected risk. When this occurs, it will only be necessary to clean up the area that flooded, without further damage upstream or downstream. The main disadvantages of retention basins are the need for a larger reservoir volume and to control water quality.

Figure 3.30 is a schematic representation of dry and wet reservoir types. Dry reservoirs or basins are most commonly used in the United States, Canada and Australia. When designed to control flow, they empty rapidly in up to six hours and are not very effective at removing pollutants. Increasing detention to between 24 and 60 hours can improve pollutant removal (Urbonas and Roesner, 1994). This type of system retains a substantial proportion of solid material.

When drainage uses the system’s extra capacity for attenuation, and they are connected directly to the drainage system, this is known as an *on-line system* (Figure 3.31). When runoff above a certain flow level is transferred to the attenuation area, and receives only the excess from the drainage system, it is termed off-line (Figure 3.32 and Figure 3.34).



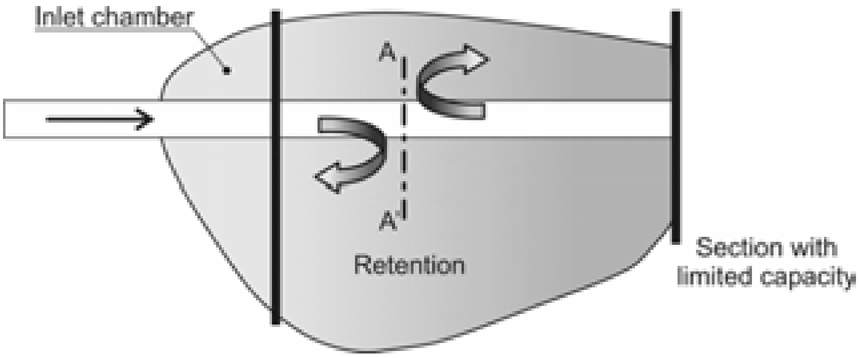


Figure 3.31. On-line detention system

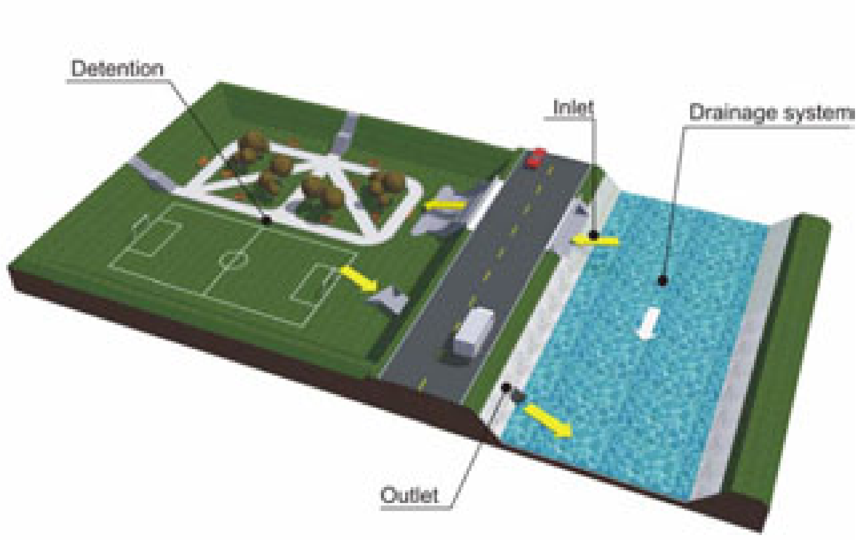


Figure 3.32. Offline detention system (left) connected with conduits and on-line system (right)

With on-line detention systems there are problems for drainage with mixed storm water flows when there is a large number of clandestine connections to the drainage system, on account of the serious contamination it produces in the reservoir, mainly in the dry season. In this case, it should have a concrete bottom to facilitate cleaning.

This type of reservoir can have a natural, excavated or concrete bottom. Concrete reservoirs are more expensive, but they can have vertical walls and hence a higher volume. This is useful where space is costly.

Reservoirs may be open or covered. The first generally cost less and are easier to maintain. The second cost more (up to seven times higher) and are very difficult to maintain. They are generally used when it is wished to use the space on top, owing to the topography or pressure from neighbouring population who have fears about refuse and the quality of the system.

Off-line reservoirs can operate automatically by gravity (Figure 3.33) or pumping systems when more volume is required for a given space (Figure 3.34). The difference is that in the first case the flow floods the area to the side and returns to the drainage system by gravity of its own accord. While in the second case, owing to the need to increase the volume, it is necessary to excavate below the level of the drainage system, and to extract all the volume. Pumping is required.

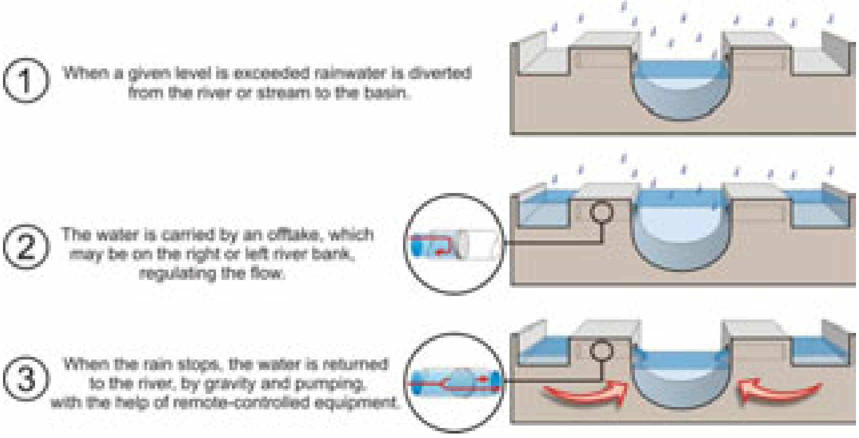


Figure 3.33. Off-line detention system with lateral volume (DAEE)

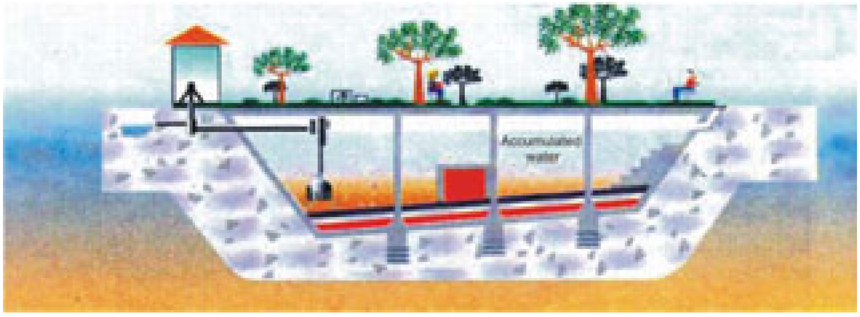


Figure 3.34. Covered detention system (DAEE)

Figure 3.35. Detention basins used as sports fields in Curitiba (left) and Porto Alegre (right)

ASCE (1985) mentions that the most successful detention installations of this type were those that also had other uses, such as leisure, as they are used by the community on a daily basis for recreation. The system design should therefore be integrated into the planning of the use of the area.

Location

As we said above, reservoirs may be open or buried (Figure 3.33) according to the conditions at the site. Where space is limited or it is necessary to keep the top surface for other uses as well, underground reservoirs may be used; however, these cost more than open ones.

Their siting depends on the following factors:

- In highly urbanized areas, siting depends on the available space and the ability to attenuate flow. If the only available space is upstream, draining low volume, the effect will be reduced;
- In areas to be developed, the reservoir should be sited on land of low value, taking advantage of natural depressions or existing parks. A good indicator for siting are the natural areas where small lakes or ponds form before development.

3.5.3. Compatibility of systems – sewage effluent

There are scenarios in which the drainage system is a mixed one, receiving both sewage and storm water; a separator system is where almost all the runoff is storm water.

Mixed system: Some drainage systems contain sewage that is carried to a treatment plant: this is the scenario used in old cities in Europe and the United States. The detention systems are of the off-line type. In this case the liquid sewage and part of the storm water are collected and sent to the sewage treatment plant. When the flow exceeds the design value during flooding, the excess is discharged to the drainage and detention systems. In this case a single, mixed system is used, but it has the disadvantage of unpleasant odours in hot climates, during the summer, and the risk of proliferating disease during flooding that exceeds the capacity of the whole system.

Separator system: This has independent sewage and drainage and systems (Figure 3.36). On-line detention systems are used that control the solid residue and manage the pollutant load. Advantages: proper management of urban detention and retention basins with a longer holding time allows water quality to be controlled, prevents contaminated water in flooding exceeding the design level, prevents odours in the dry season, and prevents the collapse of drainage systems through corrosion. Disadvantages: high initial cost in the case of a transition to a separator sewage system.

Transition system: When the city has an extensive storm drainage system but a small sewage system it may be costly to upgrade from a mixed system to a separator system. To spread the costs over time it is possible to adopt a strategy of a mixed macrodrainage system (Figure 3.37). Later, the project may implement a sewage system using secondary systems, eventually covering the whole city. When the separator system covers the city the connections may be removed.

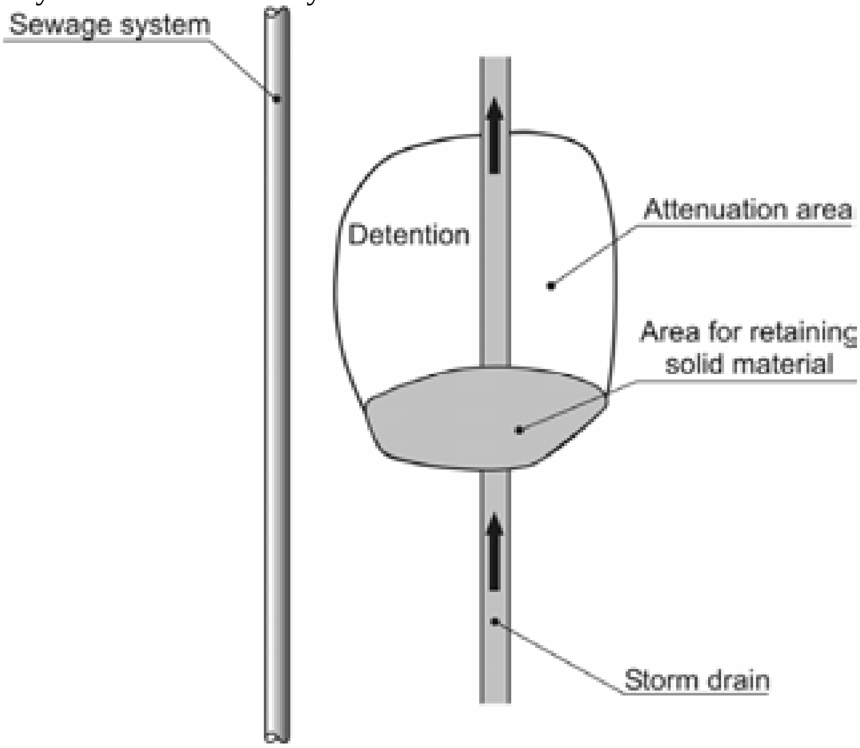


Figure 3.36. Characteristics of a separator system

3.5.4. Planning macrodrainage control

In Brazil the impact of runoff due to urbanization in the macrodrainage has been controlled in practice by canalization. The canal is designed to handle a flow for return times varying between 10 and 100 years. To prevent flooding from drainage only, the city as a whole should have its conduits expanded to allow for the urbanization of the whole watershed, which would be financially unsustainable. The solution for control in an urban watershed is a combination of distributed measures, but especially the combination of an increase in capacity by means of attenuation.

There are two development scenarios: (a) developed watershed with various flooding areas; (b) watershed with a small settled area and a tendency towards urbanization.

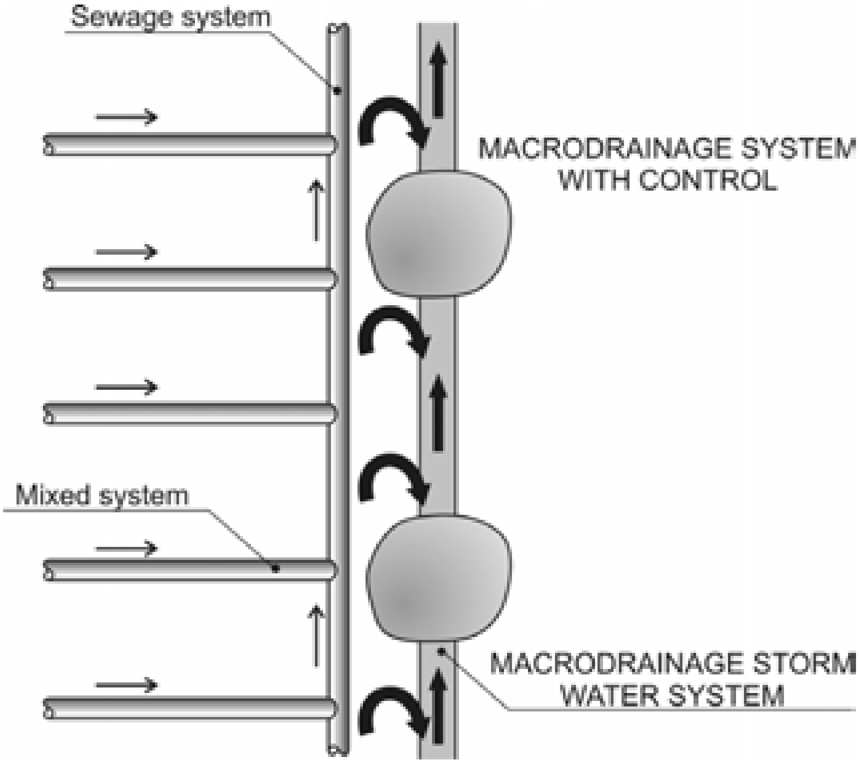


Figure 3.37. Transition system

Developed watershed

In this scenario, for each of the critical points detected, one has to try and identify the flooding areas and look for suitable areas for attenuating runoff rather than transferring it downstream. The ideal combination would be to have the lowest cost reservoirs and increase runoff in a way that is best suited to the urban area, i.e. low cost and environmentally appropriate.

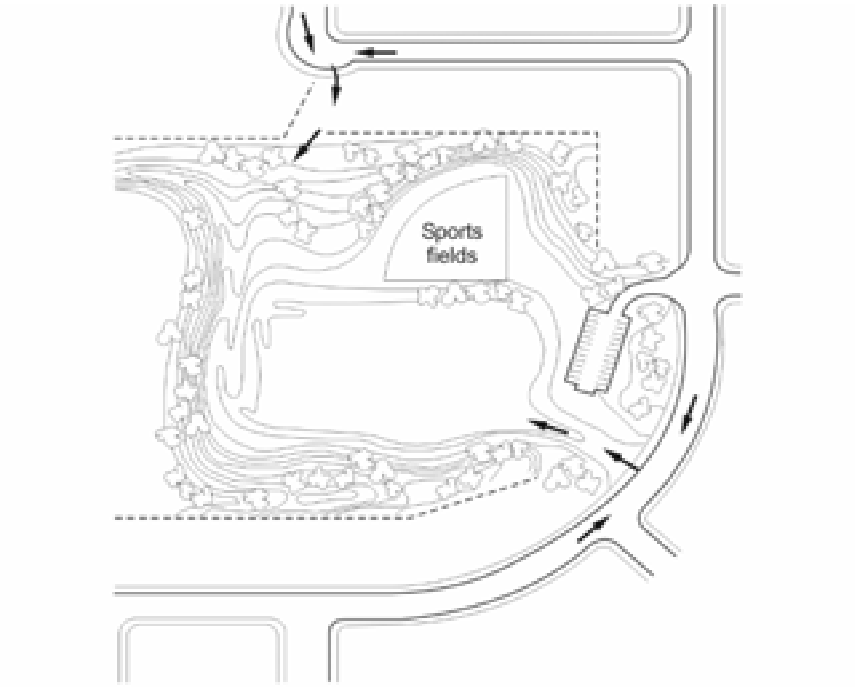
Wisner and Cheung (1982) presented, as per Table 3.4, a comparison of other alternatives and the use of parks for attenuation.

Figure 3.38 illustrates the park and flows in the urban area.

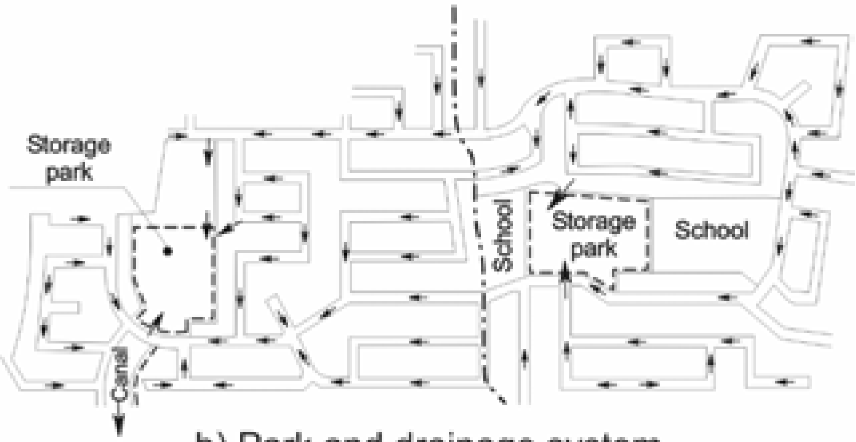
Table 3.4. Comparison between storage in park and other alternatives (Wisner and Cheung, 1982).

Type	**Downstream storage**	**Wet detention system**	**Dry detention system**	**Storage in park**
Storage	Continuous	Continuous	Frequent	Rare
Aesthetics	Unimportant	Very	Very	Less important

		important	important	
Maintenance	Low	High	Moderate	Very low
Likelihood of accident	Low	Moderate	Low	Very low
Cost	High	Moderate	Moderate	Low
Cost of land	None	High	High	None
Cost of landscaping	Low	High	Medium	Medium
Planning	Not very important	Very important	Very important	Very important



a) Park



b) Park and drainage system

Figure 3.38. Storage park (Wisner and Cheung, 1982).

Developing watershed

Consider the watershed in Figure 3.39. In the first stage the watershed is not completely urbanized, and flooding occurs in the urbanized reaches, where some areas are not settled because of frequent flooding. When the watershed reaches an advanced stage of development, expensive structural measures tend to predominate. However, these costs can be minimized by increasing the attenuation capacity in the urban watershed, endeavouring to recover as far as possible the natural attenuation by exploiting all the possible areas. Yoshimoto and Suetsugi (1990) described the measures taken to reduce the frequency of flooding in the river Tsurumi, within the Tokyo district. The watershed was divided into three: retention, retardation and lower areas, and the control flow was defined. In the retention area, municipal action managed to obtain 2.2 million m^3 for attenuation, plus other retardation measures. This action reduced losses in recent floods.

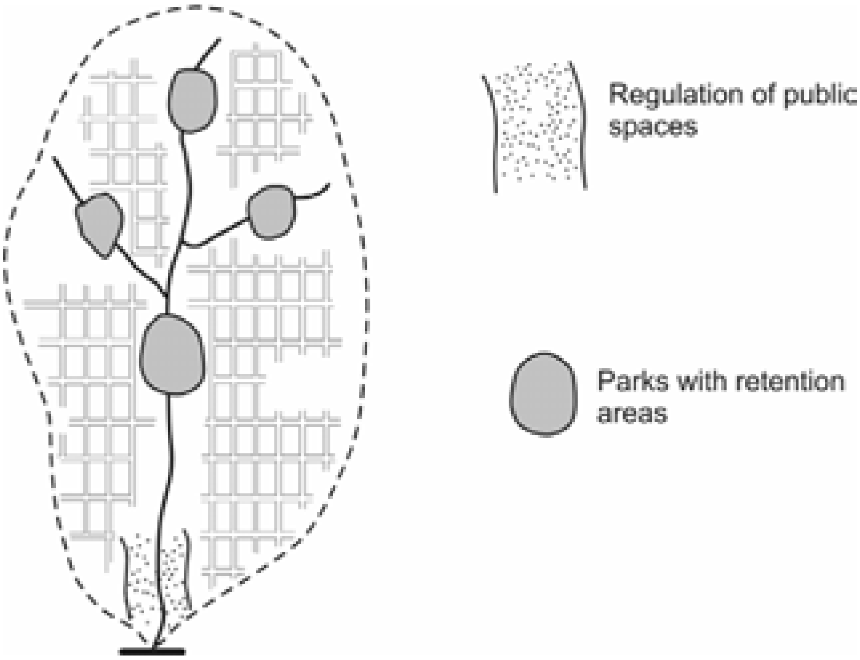


Figure 3.39. Planning of watershed control in the initial stage of urbanization

Problems

1. Analyse the types of measures for controlling runoff at source for urban drainage and describe its uses, advantages and disadvantages.
2. What is porous paving used for in a drainage project? What are its advantages and disadvantages?
3. What is the difference between detention and retention in controlling flooding resulting from the urbanization process? What impacts do these systems have on flooding?
4. What types of flooding are there and what are their respective impacts?
5. With reference to the previous question, when are impacts transferred?
6. What are the main strategies for managing urban drainage for an existing city and for future development?
7. What are the advantages and disadvantages of control at source? Which are more sustainable?
8. What should be the relationships between an urban master plan and the drainage plan and between the latter and the discharge of sewage and solid waste?
9. Many cities implement control of impervious areas but do not succeed in preventing the impact on drainage. Why? What is the problem and how can it be solved using non-structural measures?
10. What are the advantages and disadvantages of control measures in microdrainage and macrodrainage?
11. Describe the stages of an urban drainage master plan. What are non-structural measures?
12. Describe the principles of an urban drainage master plan.
13. When making a financial evaluation of flood losses, how should the costs be spread among the population?

References

APWA, 1969. Water pollution aspects of urban runoff. Water Quality Administration. (Water Pollution Control Research Series. Report N. WP-20-15).

ASCE, 1985. Storm water Detention Outlet Control Structures. Task Committee on the Design of Outlet Structures. American Society of Civil Engineers, New York.

ASCE, 1992. Design and construction of storm water management systems. The urban water resources research council of the American Society of Civil Engineers (ASCE) and the Water Environmental Federation. New York, NY.

AVCO, 1970. Storm water pollution from urban activity. Water Quality Administration. (Water Pollution Control Research Series. Report No 11034 FKL).

BOYD, M.J., 1981. Preliminary Design Procedures for Detention Basins. in: Second International Conference on Urban Drainage, Urbana, pp. 370-378. (Water Resources Publications).

BRAS, R. L.; PERKINS, F.E., 1975. Effects of urbanization on catchment response. J. Hydr. Div. ASCE, 101(HY3), 451-466

COLLISCHONN, W. TUCCI, C. E.M. 1998. Drenagem urbana e Controle de Erosão. VI Simpósio nacional de controle da erosão. 29/3 to 1⁄4 1998, Presidente Prudente, São Paulo.

COLSON, N.V., 1974. Characterization and treatment of urban land runoff. EPA. 670/2-74-096.

EPA, 1985. Methodology for analysis of detention basins for control of urban runoff quality. Washington. (Environmental Protection Agency 440/5-87-001).

FUJITA, S., 1984. Experimental Sewer Systems for Reduction of Urban Storm Runoff. In: International Conference On Urban Storm Drainage, 3, 1984, Göteborg, Proceedings. Göterburg: Chalmers University of Technology, 4v. v3., p. 1211-1220.

FUJITA, S., 1993. Storm water goes to ground as Japan chooses infiltration. *Water Quality International*. London, No 3, p. 18-19.

GUARULHOS, 2000. *Código de Obras do Município de Guarulhos* Law 5617 of 9 November 2000, Municipality of Guarulhos.

HOGLAND, W.; NIEMCZYNOWICZ, J., 1986. The unit Superstructure - A New Construction to prevent groundwater depletion. In: BUDAPEST SYMPOSIUM, 1986. Conjunctive Water Use: Proceedings. Wallingford: IAHS. 547p. 512-522 (International Association of Hydrological Sciences. Publication No 156)

HOLMSTRAND, O. 1984. Infiltration of Storm water: research at Chalmers University of Technology. Results and examples of Application. In: International Conference On Urban Storm Drainage, 3, 1984, Göteborg. Proceedings. Göteborg: Chalmers University of Technology. 4v. v3, p1057-1066.

HOYT, W.G., LANGBEIN, W.B. 1955. Floods. Princeton: Princeton University Press, Princeton. 469p.

IBGE, 1998 “Anuário Estatístico do Brasil – 1997”, Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, 1998 (CD-ROM)

IDE, C., 1984. Qualidade da drenagem pluvial urbana. Porto Alegre: UFRGS-Curso de Pós-Graduação em recursos Hídricos e Saneamento 137f. Dissertation (masters).

JACOBSEN, P.; HARREMOˇES, P. 1981. Significance of Semi-Pervious Surfaces in Urban Hydrology. In: International Conference On Urban Storm Drainage, 2, 1981, Urbana. Proceedings Urbana: University of Illinois, v.1, p 424-433.

JOHNSON, W. 1978. Physical and economic feasibility of non-strutural flood plain management measures. Davis: Hydrologic Engineer Center.

LARGER, J.A; SMITH, W.G.; LYNARD, W.G.; FINN, R.M.; FINNEMORE, E.J. 1977 Urban Storm water management and technology: update and user’s guide. US EPA Report – 600/8-77-014 NTIS N. PB 275654.

LEOPOLD, L.B.,1968. Hydrology for Urban Planning - A Guide Book on the Hydrologic Effects on Urban Land Use. USGS circ. 554, 18p.

LLORET RAMOS, C.; HELOU, G. C. N.; BRIGHETTI, G. 1993 Dinámica do transporte sólido nos rios Tietê e Pinheiros na região metropolitana de São Paulo. Anais. X Simpósio brasileiro de recursos hídricos. Gramado.

MAIDMENT, D.R. (ed.) 1993. Handbook of Hydrology. New York: McGraw-Hill.

NAKAE, T.; BRIGHETTI, G. 1993 Dragagem a longa distância aplicada ao desassoreamento da calha do rio Tietê. Anais. X Simpósio brasileiro de recursos hídricos. Gramado.

OLIVEIRA, M. G. B.; BAPTISTA, M. B. 1997 Análise da evolução temporal da produção de sedimentos na bacia hidrográfica da Pampulha e avaliação do assoreamento do reservatório. Anais. XII Simpósio Brasileiro de Recursos Hídricos - ABRH. Vitória.

PMBH, 1996 Plano Diretor Urbano. Prefeitura Municipal de Belo Horizonte.

PMPA, 2000. Segundo Plano de Desenvolvimento Urbano e Ambiental de Porto Alegre. Prefeitura Municipal de Porto Alegre.

RAMOS, M.M.G. 1998 Drenagem Urbana: Aspectos urbanísticos, legais e metodológicos em Belo Horizonte. Dissertation for Masters. Escola de Engenharia Universidade Federal de Minas Gerais.

REZENDE, B. and TUCCI, C.E. M., 1979. Análise hidráulica e hidrológica dos problemas de inundação urbana na cidade de Estrela, RS. Téchnical report, p. 29.

ROESNER, L.A; TRAINA, P. 1994. Overview of federal law and USEPA regulations for urban runoff. Water Science & Technology V29 n 1-2 p. 445-454

SCHUELLER, T. 1987. Controlling Urban Runoff : A Practical Manual for Planning and Designing Urban BMPs.

SILVEIRA, A L. L., 1999. Impactos Hidrológicos da urbanização em Porto Alegre. 4o Seminário de Hidrologia Urbana e Drenagem. Belo Horizonte ABRH.

SIMONS, D.B. et al. 1977. Flood flows, stages and damages. Fort Collins: Colorado State University

SUDERSHA, 2002. Medidas não-estruturais. Plano Diretor de Drenagem Urbana da Região Metropolitana de Curitiba. CH2MHILL Engenharia do Brasil Lt.da

TASK, 1962. Guide for the development of flood plain regulation. Journal of the Hydraulics Division. American Society of Civil Engineers. New York, v.88, n.5, p.73-119, Sept.

TUCCI, C.E.M. 1993. Hidrologia: Ciência e Aplicação. EDUSP, Editora da UFRGS, ABRH, 952p.

TUCCI, C.E.M., 1998. Modelos Hidrológicos. ABRH Editora da Universidade, 652p.

TUCCI, C.E.M. 2000 a. Plano Diretor de Drenagem Urbana da Região Metropolitana de Curitiba Memorando n. 8. CHMHill / SUDHERSA.

TUCCI, C.E.M., GENZ, F., 1994. Medidas de controle de inundações in: Estudos Hidrossedimentológicos do Alto Paraguai, IPH/MMA.

TUCCI, C. E. M.; PORTO, R. L. 2000. Storm hydrology and urban drainage. In: Tucci, C. Humid Tropics Urban Drainage, chapter 4. UNESCO.

TUCCI, C. and SIMÕES LOPES, M. 1985. Zoneamento das áreas de inundação: rio Uruguai. Revista Brasileira de Engenharia Caderno de Recursos Hídricos. Rio de Janeiro, v.3, No 1, p.19-45, May.

UNITED STATES, Departament of transportation, 1979. *Design of urban highway drainage*. Washington: Federal Highway Administration.

URBONAS, B.; ROESNER, L.A., 1993. Hydrologic Design for Urban Drainage and Flood Control. In: Handbook of Hydrology. D.R. Maidment (ed.). Chap. 28.

URBONAS, B.; STAHRE, P., 1993. Storm Water Best Management Practices and Detention, Prentice Hall, Englewood Cliffs, New Jersey. 450p.

U. S. Army Corps of Engineers. 1976. Guidelines for flood damage reduction. Sacramento.

VEN, F.H.M., 1990. Water Balances of Urban Areas. in: DUISBERG SYMPOSIUM, 1988. Hydrological Processes and Water Management in Urban Areas, IAHS , p21-32 International Association of Hydrological Sciences Publication 198).

YOSHIMOTO, T.; SUETSUGI, T., 1990. Comprehensive Flood Disaster Prevention Measures in Japan. in: DUISBERG SYMPOSIUM, 1988. Hydrological Processes and Water Management in Urban Areas, IAHS, p175-183 International Association of Hydrological Sciences Publication 198).

WATER RESOURCES COUNCIL, 1971. Regulation of flood hazard areas to reduce flood losses. Washington.

WEIBEL, S.R., ANDERSON, R.J; WOODWARD,R.L.,1964. Urban Land Runoff as a factor in stream pollution. Journal Water Pollution Control Federation. Washington, V. 36, No 7, 914-924.

WILKEN, P., 1978 Engenharia de drenagem superficial. São Paulo: CETESB

WRI, 1992. World Resources 1992-1993. New York: Oxford University Press. 385p.

WRIGHT, A.M. 1997. Towards a Strategic Sanitation Approach: Improving the Sustainability of Urban Sanitation in Developing Countries.

Chapter

4

4. Integrated urban water management

Integrated management, in the sense of interdisciplinary and intersectoral integration of the components of urban water, is a necessary approach for achieving results in line with sustainable urban development.

In recent decades urban development has changed most of the concepts used in water infrastructure engineering in cities. The approach for developing these topics within engineering has been based on imparting knowledge in each discipline without an integrating solution.

The urban planner carries out his work aware that the engineers in transport, sanitation and other areas of infrastructure will find a solution for the planned or spontaneous land use that is found in cities. Following this approach, water is drawn from the upstream source (hopefully not contaminated) and discharged untreated downstream; drainage is designed to remove water as quickly as possible from any place, transferring the surplus downstream. The solid residue is deposited in a remote place so as not to disturb the city dwellers. This set of local solutions may be justified within a local project with all the equations devised over the years by hydraulic, hydrological and sanitation engineers to solve a "given problem".

What is the consequence of these projects for society? Unfortunately this approach has been quite disastrous. To make an analogy with medicine, it is as if a number of specialists were prescribing medicines for different symptoms in one person without taking account of the combined side effects suffered by the human body.

Today's problems are reflected in public health, frequent flooding, and the loss of a rich and diversified environment in many regions. With the transformation of a rural environment into an urban one, this problem is getting worse, and the longer the situation lasts, the greater will be the legacy of incompetence and liability for future generations.

What is wrong and what can be done to remedy the situation?

- *Urban development* must not take place without considering the sustainability of the place where people are settling. In order to achieve this rules for land use and settlement must be defined that preserve the natural conditions and enable the system to handle transport, water supplies, sanitation systems, effluent treatment, urban drainage, and refuse collection, processing and recycling;
- The *water supply* must be provided from reliable sources that are not contaminated by other sources upstream;
- Excess sewage must be treated so that the water used is not contaminated and the water system can recover;
- *Urban drainage* must preserve natural infiltration to avoid transferring downstream the increased flow, volume and contaminant load from storm water runoff and soil erosion;
- *Solid refuse* must be recycled to encourage sustainability, financial exploitation of this resource, and the disposal of the remaining material must be minimized.

These objectives cannot be pursued on an individual basis, but it must be a collective effort that begins with education. Unfortunately, the universities are still teaching inappropriate ideas and the public still has an inaccurate perception of the solutions. It is therefore necessary to change by proposing a more sustainable approach for humans and their living space.

4.1. Management phases

From the late 19th to the mid-20th century, the concept of *urban water* was simply a matter of supply, or providing water for the population and discharging the sewage as far away as possible in the environment without any kind of treatment. This is what can be termed the *public-health (or sanitation)* phase, based on the sanitation engineers' concern to prevent the proliferation of disease and reduce infection by water-borne diseases. In this period the solution was always to collect water upstream and discharge sewage downstream of the metropolis. Excess storm water was planned to run off freely through the streets to the rivers. This scenario was acceptable while cities had populations of up to 20 000 inhabitants and were far enough away from one another for the sewage from one city not to contaminate another.

The cities grew, becoming closer together and the development strategy remained in the public-health phase, leading to what we term the contamination cycle (see chapter 1, Tucci, 2003), in which the upstream city contaminated the downstream city, which in turn contaminated the next one along.

Decision makers in many cities considered that the investments needed for sewage treatment were very high, and opted to invest in sectors that were considered more important, without understanding that they were failing to tackle the origin of the "cancer". Now, the system is beset by pollution and the cost of fixing it is extremely high.

The developed countries emerged from what we have termed the public-health phase (Table 4.1) to enter the *corrective* phase, with the treatment of domestic sewage effluent and control of urban flooding with detention basins (attenuation). There was almost full domestic sewage treatment, so that the urban environment improved, but did not regain its natural state. It was also observed that in addition to sewage effluent there was the storm water load and poor distribution of solid refuse, processes that are fully interdependent in the day-to-day routine. Refuse that is not collected ends up in the drainage system. Developed countries are taking action to solve this type of problem. This impact has an even higher cost as it is widespread throughout the whole city. While seeking solutions it was discovered that it was not sufficient to tackle the problem at the "end of pipe", i.e. after it had occurred and was in the pipes, but rather a preventive approach was needed right from the beginning of urban development. Likewise, modern medicine is starting to focus on prevention rather than the cure.

In order to find an environmentally sustainable solution the management of the urban infrastructure needs to be integrated, beginning with a definition of land use that aims to preserve the natural functions like infiltration and the natural drainage system. This kind of development has been termed LID (Low-Impact Development) in the United States (U.S. Department of Housing and Urban Development, 2003; NAHB Research Center, 2004 and U.S. Environmental Protection Agency, 2000) or Water-Sensitive Urban Design (WSUD) in Australia.

Despite representing the modern and environmental type of land use in developed countries, in Brazil this approach is not new, as Saturnino de Brito in the early 20th century planned some cities in accordance with this conception which was ahead of its time. Unfortunately, not all cities adopted this approach.

Developing countries are trying to emerge from the first phase to attempt corrective action but practically none of their development falls within the sustainable phase. The third phase involves integration between the layout design and the space, the architectural design and the functions of the water infrastructure in the urbanized environment and not merely the search for infiltration areas in the design of a project.

Table 4.1. Stages of sustainable urban development in developed countries.

Years	Period	Characteristics
Until 1970	Public health	Water supply with no sewage treatment, downstream disposal of storm water runoff by canalization
1970-1990	Corrective	Sewage treatment, quantitative attenuation of drainage and control of existing impact of storm water quality. Mainly involves tackling impacts.
1990* - ?	Sustainable	Planning of urban land use in line with natural runoff mechanisms; control of micropollutants and diffuse pollution, and sustainable development of storm water runoff by recovering infiltration.

* time when this type of approach began

4.2. Integrated and sustainable approach to urban development

4.2.1. Integrated approach to the urban environment

It is important to describe sustainable urban development, which involves minimizing the impact of disturbances of the natural environment consisting of the climate, soil, air, water, biota, etc. In order to attain that objective we first have to understand the impacts that each action has and find solutions where that impact is restricted to a minimum local area by planning measures that are sustainable over time.

The urban environment is too complex to be covered in an introductory text such as this one, so here we examine the environment relating to storm water that has been the basis of a new approach to land-use management.

In this scenario, traditional settlement does not try to understand how the soil, water and plants are integrated into nature in an attempt to mitigate the adverse effects of introducing impervious surfaces such as roofs, public thoroughfares, streets, etc. In nature, precipitation that does not infiltrate tends to form natural runoff in accordance with the intensity and frequency of the precipitation, vegetation cover and resistance of the ground. The water infiltrates, runs into the subsoil and aquifer and ends up in the rivers. With the destruction caused by urban drainage, the new system is formed of streets, storm water outlets, conduits and canals that accelerate runoff and increase peak flows several times over, as well as washing surfaces carrying contaminants produced by emissions from cars, trucks, buses, industry and hospitals.

So what is the solution? In the beginning attempts were made to restore attenuation capacity by using detention basins, but the surface volume still increased on account of the impervious areas and the public objected to the area used for detention owing to the pollution generated and conflicts over the use of the space. Therefore, attempts were made to recover infiltration capacity through local measures in residences and buildings, using infiltration trenches, but still within a localized "end-of-pipe" approach designed to find a solution for a specific project or impact.

In this case, the integrated approach starts with the planning of subdivision and settlement of the space in the housing development phase, the point at which the scheme should be adjusted to preserve the existing natural runoff. This design should be the opposite of current schemes, since they are based entirely on maximum exploitation of the space regardless of the natural drainage system. A sustainable scheme preserves the natural system and breaks the settlement down into smaller plots, conserves a large common green area, removes the kerbs from the less busy streets, complementing the asphalt by other natural vegetation systems to enable the water to infiltrate. A scheme of this kind removes divisions between properties (as in rural properties when planning for small watersheds and soil conservation). In this way, runoff is reduced to the pre-existing conditions for frequent rainfall; the water infiltrates and does not affect the downstream quantity or quality. This applies to a residential scheme, while industrial and commercial areas require specific control schemes, though still within an integrated approach by the designers.

Sustainable infrastructure tends to cost less than a corrective system, and even less than the traditional infrastructure due to the removal of certain systems, such as the elimination of piped drainage systems, kerbs, etc., which are replaced by grass for infiltration, grass gutters and protected natural systems.

The reader may imagine that this is a utopian view of reality; nevertheless contractors are sensitive to cost and to a public willing to pay for a better environment and quality of life. These factors are very important for decision-making.

It is difficult for developing countries to miss out these stages owing to the serious problems existing in the cities with regard to storm water runoff (never mind all the others yet to be solved). It is therefore necessary to devise strategies in two main areas.

a. Control existing impacts through the scenario of structural corrective action that handles management by urban sub-watersheds;
b. Non-structural measures encouraging new projects to adopt development that has less impact and is more sustainable.

These two measures can be implemented through the master plan for storm water (or urban drainage as it is sometimes called), or better still an urban master plan that includes these elements plus sewage disposal, solid refuse, transport and land use (Figure 4.1).

Figure 4.2 shows how the various city plans integrate and seek ways in which to interact to solve these aspects in an integrated way.

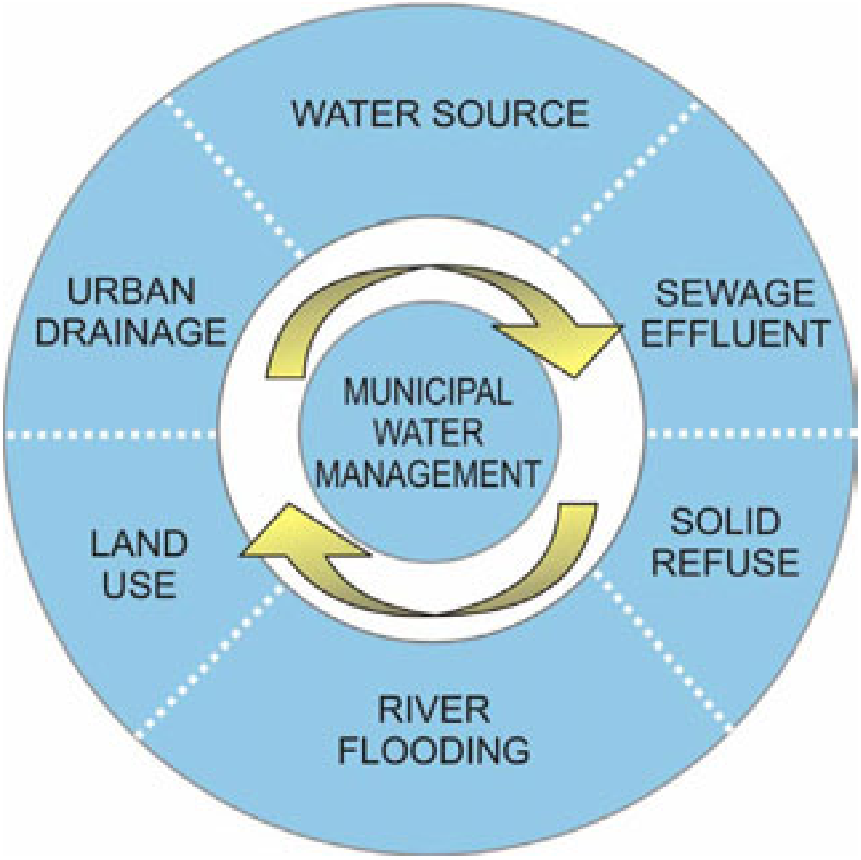


Figure 4.1. Integrated approach (Tucci, 2003)

Preventive action in urban development reduces the cost of solver water-related problems. Planning the city with residential areas and control of drainage at source, the distribution of areas at risk and the development of supply and drainage systems, the costs will be lower than those of a crisis where the remedy costs the municipality more than it can afford.

The development of planning of urban areas mainly involves:

- planning of urban development;
- transport;
- water supply and sanitation;
- urban drainage, and flood and erosion control;
- solid refuse;
- environmental control.

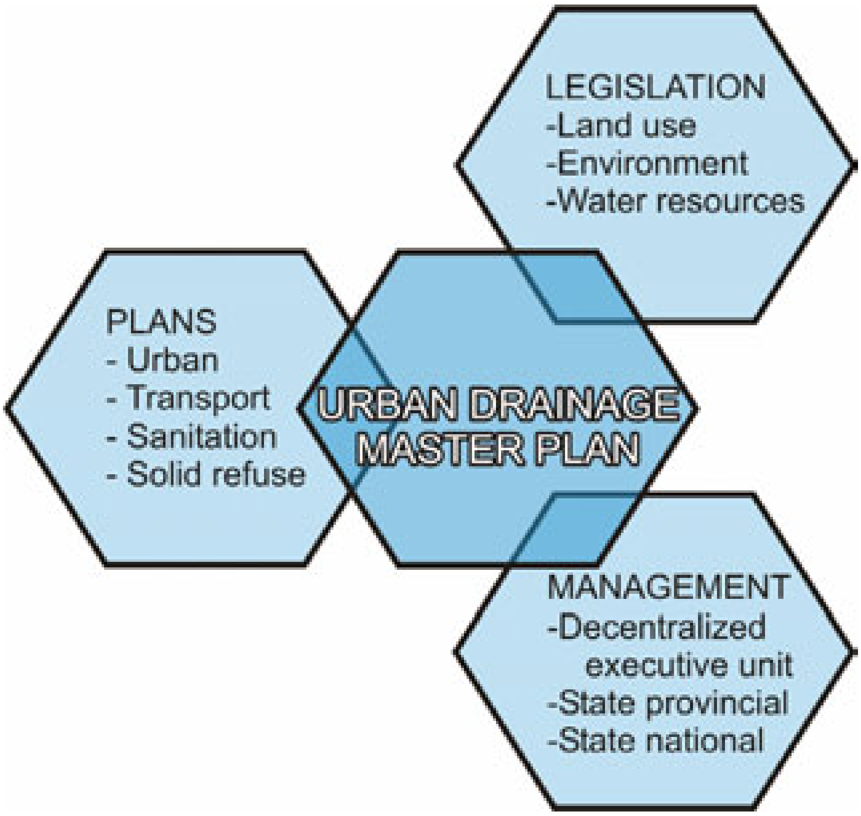


Figure 4.2. Interface between the city plans and the storm water or urban drainage master plan

Urban planning must consider aspects relating to water, land use and the definition of the trends of the city's expansion vectors. The water-related aspects are closely interrelated, as shown by the following examples:

- The water supply is obtained from sources that may be contaminated by sewage, rainwater or refuse tips;
- The solution for controlling storm water runoff depends on the existence of a sewage collection and treatment system and the removal of the connections between the systems;
- Soil erosion leads to clogging and affects land use, streets, sewage systems, etc.;
- Street cleaning, and collection and disposal of refuse affect the quantity and quality of storm water.

The main difficulty for implementing integrated planning lies in the limited ability of the municipalities' institutions to tackle complex, interdisciplinary problems and in the sectoral organization of municipal management.

4.2.2. Institutional aspects:

The institutional structure is the basis for the management of urban water resources and its policy for controlling them. The institutional definition depends on the division of responsibilities in a country's organization, and the relationship between the law and management regarding water, land use and the environment. To establish the mechanism for managing these elements it is necessary to define the geographical areas connected with the problem.

Geographical area of management

The impact of sewage and storm water effluent can be analysed within two different spatial contexts, analysed below:

Impacts extrapolated by the municipality: increasing flooding and contaminating downstream watercourses such as rivers, lakes and reservoirs. This contamination is known as *point-source* or *diffuse urban pollution*. This type of impact arises from action within the city that is transferred to the rest of the watershed. To control it, objectives can be established and these are generally regulated by means of federal and provincial legislation on the environment and water resources;

Impact within the cities: these impacts are disseminated within the city, affecting its population. In this case, control takes the form of measures implemented in the municipality under municipal legislation and specific structural measures.

Experience

The American experience of the process took the form of a national programme implemented by the Environmental Protection Agency (EPA) that requires all cities with over 100 000 inhabitants to set up a Best Management Practices (BMP) programme. Phase two of the programme recently began for cities with a smaller population (Roesner and Traina, 1994). The BMPs involve the control of the quality and quantity of water by the municipality using structural and non-structural measures. The municipality has to demonstrate that it is progressing and endeavouring to achieve these objectives under a plan. This process helps to reduce diffuse pollution in rivers near to cities. The penalty that may be applied is legal action by the EPA against the municipality.

The French experience involves management of the impacts and controls by the watershed committee, the basic decision-making forum. The targets to be achieved by the municipalities and other players are decided by this committee.

Legislation

Legislation on urban water relates to water resources, land use and environmental licences. There follows an analysis of the Brazilian situation, comprising the following levels: Federal (national), State (State or Province) and Municipal (Figure 4.3).

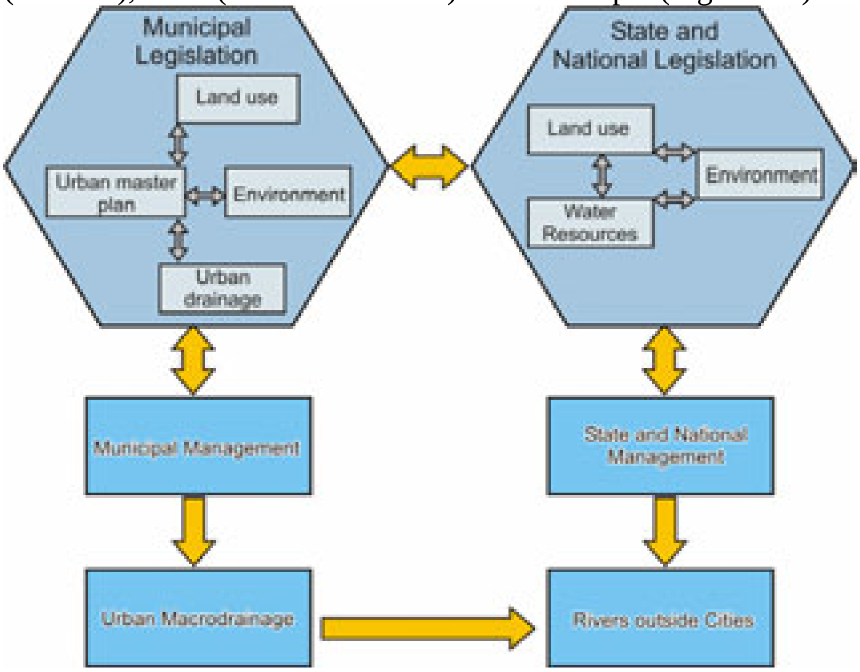


Figure 4.3. Management spaces (Tucci, 2003)

Regarding **water resources**, the Federal Constitution defines responsibilities for rivers, and the federal legislation on water resources lays down the basic principles of management by watersheds. Watersheds may be a provincial or federal responsibility.

Some provincial laws on water resources lay down criteria to regulate the use of water, but they do not make any provisions for the control of the discharge of drainage effluent. Environmental legislation lays down rules and standards for the quality of river water by means of classes, but it does not impose restrictions on urban effluent discharges into rivers. Action by provincial environmental control bodies is limited owing to the municipalities' limited investment capacity to carry out such controls. Therefore, there is no requirement and no pressure to invest in the sector.

In this context, storm water runoff from cities should be regulated or controlled by provisions of the watershed plan. As these procedures are not yet being enforced by the States, for the time being there is no direct pressure to reduce the impacts of urbanization.

Land use: Article 30 of the Brazilian Federal Constitution states that land use is a municipal responsibility. However, the Provinces and the Union may lay down rules governing land use on grounds of environmental protection, pollution control, public health and security. This means that urban drainage, involving environment and pollution control, is a joint municipal, provincial and national responsibility. The municipalities tend to introduce urban macro-zoning guidelines in urban development master plans, encouraged by the provinces.

We observe that the municipalities have not considered zoning for land use, or the aspects of urban water such as sewage effluent, solid refuse, drainage and flooding. On the other hand, there has been restrictive legislation to protect water sources and settlement of environmental areas. Highly restrictive legislation merely leads to negative reactions and disobedience. The desired environmental control objectives are not therefore met. This takes the form of the invasion of protected areas, unlawful housing developments, etc.

When introducing restrictions on land use, the legislation must offer financial alternatives to the landowner, or the municipality must buy the property. In a democratic society, prevention of use of private space in the public interest must be compensated, and the space structured for the use of society, otherwise it amounts to confiscation. Current land-use legislation allows appropriation of private property and even requires payment of taxes by the owner, who has no financial alternative. The immediate consequence in most situations is civil disobedience.

Environmental licence: this licence sets limits on building and operating drainage canals, pursuant to Law 6938/81 and CONAMA resolution No 237/97. Likewise, Article 2, VII of CONAMA resolution 1/86 requires an environmental licence for *“water drainage works”*.

4.3. Urban and watershed management

Management of action within the urban environment can be defined in accordance with the dependent relationship on water throughout the watershed or the municipal, provincial or national administrative jurisdiction. Water resources have tended to be managed by watershed, though land use is managed by the municipality or group of municipalities in a metropolitan area. Management can be carried out on the basis of the demarcation of the geographical area within and outside the city.

Watershed plans have been devised for large watersheds (>3 000 km^2). In this scenario there are several cities, each affecting and transferring impacts to the others. It is difficult for the watershed plan to cover all the necessary measures in each city, but it must establish the cities’ outputs such as effluent quality and changes in quantities that can be transferred as impacts.

The environment within a city is managed by the municipality to attain the output conditions laid down in the watershed plan to avoid impacts and seek to improve water quantity and quality throughout the watershed, as well as the internal constraints aimed at avoiding impacts on the city’s own population.

These two main spaces define the administrators, instruments and management targets for these instruments, as described in Table 4.2. This overall management structure faces some difficulties:

- The limited management capability of the municipalities;

- The watershed management system has yet to be consolidated in most South American countries;
- Limited ability to fund municipal action and a high level of indebtedness on the part of the municipalities.

In the first case, the solution is to provide provincial and federal support through technical offices that help the least capable cities to devise and implement their plans. The second will depend on the transition and evolution of the country's administration. The third will basically depend on setting up a federal and provincial programme with funding to enable the planned measures to be implemented.

Table 4.2. Urban water management space

Space	**Field**	**Administrators**	**Instrument**	**Characteristic**
Watershed[1]	Province or Federal Government	Committee and agencies	Watershed plan	Management of the quantity and quality of the water in the river system forming the watershed, avoiding the transfer of impacts
Municipality[2]	Municipalities or metropolitan area	Municipality	Urban master plan and integrated plan for runoff, urban drainage and solid refuse	Minimize impacts on quantity and quality within the city, in the small urban watersheds and avoid transferring impacts to the river system.

1 – large watersheds (>1000 km^2); 2 – coverage by municipality and its small macrodrainage watersheds (<50 km^2). Area values are indicative and may change for large cities.

Management of urban watersheds shared by two or more municipalities: Many cities share watersheds with other municipalities. The main scenarios are as follows: (a) one municipality is *upstream* of the other; (b) the river runs between the municipalities.

Institutional control of urban water that involves at least two municipalities may be achieved by means of:

- municipal legislation appropriate to each municipality;
- provincial legislation setting standards to be maintained in the municipalities so that no impacts are transferred;
- both of the above procedures.

These procedures can take place in a watershed committee and when the provincial plans implement the sectoral regulations. Therefore, when watershed plans are devised that involve more than one municipality, attempts should be made to agree on joint action between the municipalities in order to achieve planning of the whole watershed.

Potential control measures outside urban areas: The mechanism provided for in Brazilian law for management outside the cities is the watershed water resources plan. Nevertheless, it is too much to expect such a plan to cover drainage and sewage and refuse disposal for each city in the watershed. The plan should set targets for the cities to ensure that the water quality in the main river and its tributaries is maintained at environmentally acceptable levels. The integrated plan for urban drainage, sewage and refuse disposal must satisfy the controls laid down in the watershed plan of which it is a part.

The basic mechanisms for introducing this process are: (a) institutional and (b) economic and financial.

Legislation: The law currently provides for approval of effluents. Accordingly, two basic mechanisms could be established:

> *(a) laying down standards and criteria to regulate effluents affecting the quality and quantity of water from urban areas; for example:*
> *“Article (??) (…) shall be responsible for laying down criteria and standards regarding impairment of the quantity and quality of rainwater from urban areas.*

The second component relates to the mechanism for achieving these objectives. This mechanism should be an integrated plan for sewage, urban drainage and solid refuse disposal. Sectoral planning will not work since the aspects mentioned are closely linked. For instance:

> *Article (??) The regulation of sewage and storm water discharge and refuse disposal by the municipalities shall be based on integrated municipal sewage, solid refuse and*

> *urban drainage plans in accordance with the requirements of Article (??) of this decree.*
>
> *Paragraph 1 – For cities with populations exceeding 200 000 (to be specified in more detail) the plan shall be completed within no more than five years. For other cities, the plan shall be completed within ten years.*
>
> *Paragraph 2 – The watersheds committee shall be responsible for monitoring the implementation of the plans.*

The text quoted in these paragraphs has not been properly revised by a lawyer and should be used merely as a guide to the technical content.

Funding: Figure 4.4 shows an example of the configuration of interaction between the staff of the watershed and the municipalities provided for in the urban drainage master plan for the metropolitan region of Curitiba (Brazil).

The potential introductory procedures for the municipalities would be as follows:

- The subsidiary watershed committee starts to devise the plans based on the resources;
- Set up a funding for the measures in the plan for cities. The investments would be obtained from specific municipal charges for disposal of sewage, refuse and urban drainage, the latter being based on the impervious area of the properties. The plan should make these mechanisms transparent within the municipality, aiming for the long-term sustainability of the payment system by means of appropriate charges.

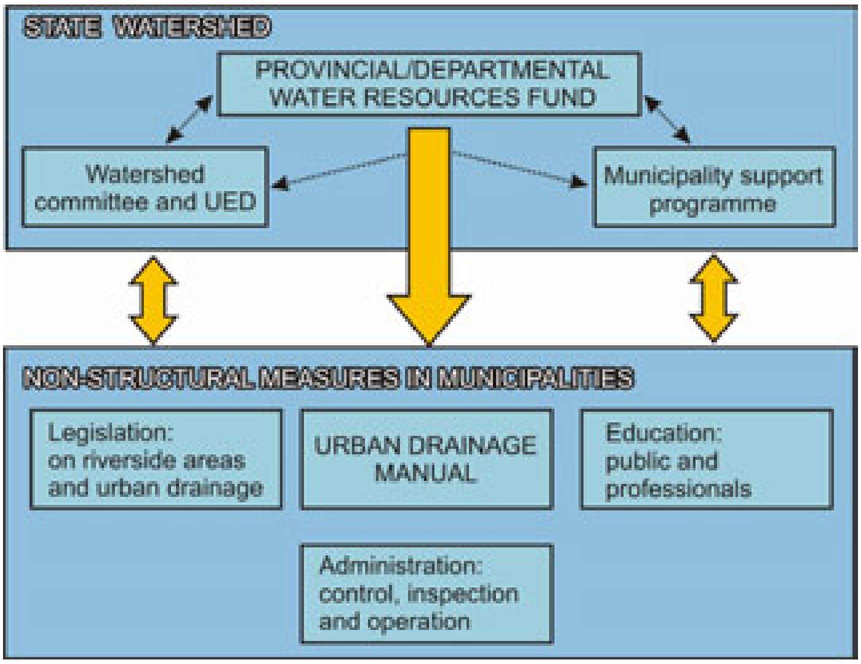


Figure 4.4 Example of technical and financial interaction (SUDHERSA, 2002)

Potential control measures within urban areas: The measures adopted for the management of urban water are in the integrated environmental sanitation plan. Having observed the interfaces in the larger municipalities, this plan can be devised in a fully integrated way for smaller cities with the agreement of the agencies concerned. The next chapter describes the features of the rainwater plan and its interfaces within the environmental sanitation plan.

References

CRUZ, M. 2004. Otimização do controle do escoamento na bacia hidrográfica urbana. Doctoral thesis. IPH – UFRGS.

NAHB RESEARCH CENTER. 2004. Municipal Guide to Low Impact-Development. Maryland. Available online at http://www.lowimpactdevelopment.org

ROESNER, L.A; TRAINA, P. 1994. Overview of federal law and USEPA regulations for urban runoff. *Water Science & Technology* V29 No 1-2 p 445-454.

SUDERSHA, 2002. Medidas não-estruturais. Plano Diretor de Drenagem Urbana da Região Metropolitana de Curitiba. CH2MHILL Engenharia do Brasil Lt.da.

TUCCI, C. E. M. (2002). Gerenciamento da Drenagem Urbana. Revista Brasileira de Recursos Hídricos. Volume 7, No 1. Jan/Mar, 5-27.

TUCCI, C. E. M. (2003). Águas urbanas. In: Inundações urbanas da América do Sul GWP ABRH.

U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT. 2003. The practice of Low-Impact Development. 119p. Washington, D.C. Available online at <http://www.lowimpactdevelopment.org>

U.S. ENVIRONMENTAL PROTECTION AGENCY. 2000. Low-Impact Development (LID): A Literature Review. 35p. Washington D.C. Available online at <ftp://lowimpactdevelopment.org/pub>

Chapter

5

5. Storm water plan

Storm water within the municipality is managed under the storm water plan and should be subordinate to the cities' urban master plan.

The rainwater plan is the mechanism for managing river flooding and urban drainage in cities. This plan must be integrated with the city's various infrastructure plans, mainly those relating to environmental sanitation: water, sewage, refuse and environment, and subordinate to the urban master plan that brings together all the city's planning.

5.1. Interfaces between plans

The main aspects relating to the interfaces of the sanitation and refuse plans are as follows:

5.1.1. Management

The management of the urban water services, i.e. basic water and sanitation, urban drainage and solid refuse should be implemented by a single municipal structure in order to achieve synergy and economies of scale for the services.

In some countries such as Brazil, the water and sanitation services have been provided over time by provincial enterprises, while all the other services remained at municipal level. In those municipalities where this is difficult to achieve this configuration may change in the short term, even though it is the municipality's responsibility to grant concessions for water and sanitation services. In this case, the other services have to be brought together into a single institution and institutional management mechanisms devised.

5.1.2. Sanitation and urban drainage

The scenarios for managing these services vary according to the circumstances of each city. In South America the tradition is to develop systems that separate sewage and storm water; however, the reality is very different from this type of planning owing to institutional disorganization. The main scenarios are as follows:

a. *No drainage or sewage system:* this applies to the poorer countries or poor cities in the region's countries. When the city is small the ground has the capacity to absorb material from septic tanks, the main problems will be in urban drainage, with increased flooding and soil erosion (e.g. some cities in Paraguay and areas of poor cities in Brazil, and other countries of the region). When the ground has low permeability, we return to a scenario similar to the early 19th century where sewage flows through the streets along with the drainage, creating unsatisfactory health conditions.
b. *Sewage system but no drainage:* A sewage system does not have the capacity to receive storm water runoff from the streets. The main problem is the increase in flooding, as the cities become unsustainable again when it rains. When it rains in Barranquilla, Colombia, going out into the street can be fatal. The city is fully covered by water supplies and sanitation, however.
c. *Drainage, but no sewage system:* This is the most common case in Brazil; where the drainage has a greater capacity, the sewage and storm water systems flow together. This scenario enables the foul water to be carried far from the population, but it has a high environmental impact on the river system. In the rainy season there is a high risk of disease proliferation and in the dry season there is the problem of offensive odours in the city. In this case management must be integrated because there is a high level of integration between the systems. In cities with practically no sewage system it is hard to implement a separate system for the whole city in the first plan. There will have to be a transitional period between the mixed and separate systems.

An example of this is the case of Caxias do Sul (RS, Brazil), (IPH, 2003). During the first phase of the system the strategy was to implement sewage collectors alongside the macrodrainage system to collect domestic sewage being discharged into the secondary and primary drainage together with dry-weather runoff. This volume is conveyed to the treatment plant. The excess runs into the macrodrainage and is attenuated and discharged by the urban drainage controls. This provides a solution for the quality and quantity of water downstream of the city. Over time, and depending on its investment capacity, the city can introduce a separator system for the secondary and primary systems (see Chapter 4).

5.1.3. Urban drainage, erosion and solid waste

This interface has two components:

a. *Erosion:* Urban development accelerates runoff, causing erosion in fragile soils and significant impacts on the urban environment. This problem can be managed by training professionals and regulating new projects to reduce the energy of runoff downstream of the projects;
b. *Solid refuse production:* solid refuse passing into the drainage has environmental impacts downstream and reduces runoff capacity, thereby increasing the frequency of flooding. The less efficient a city's refuse collection system, the greater the load on the drainage system. It is therefore necessary to devise an efficient system that integrates drainage with refuse collection and urban cleaning. Refuse enters the drainage mainly after a few days without rain. When it rains the load is very high. Planning urban cleaning before the rainy season is therefore essential for reducing the quantity of solid material in the drainage.

5.1.4. Environmental restoration

All the elements of the environmental sanitation plan are directly related with urban environmental conservation. Urban effluent and refuse contaminate the water and soil, as well as leading to degradation spread throughout the city. The city's environmental plan is linked to the environmental sanitation plan in the following main ways:

- water quality in urban rivers;
- area of degradation due to erosion;
- control of refuse tipping areas;
- contamination of urban watersheds.

5.2. Structure

The structure of the urban drainage master plan is shown in Figure 5.1 (Tucci, 2001). The main groups are:

- storm water policy,
- measures: non-structural and structural,
- products,
- programmes,
- information.

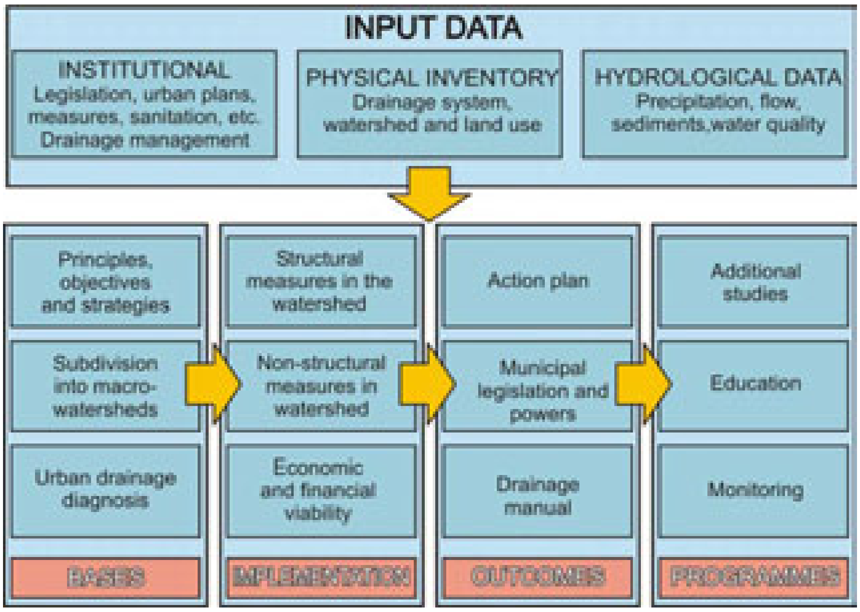


Figure 5.1. Structure of storm water plan (adapted from Tucci, 2001)

Note that this structure contains a group of inputs to the plan that is the basic information for its implementation, namely: storm drain inventory (watersheds and their physical characteristics), hydrological data (precipitation, flow and sediment), urban and environmental master plan, sewage and refuse plan and current urban management.

The plan’s policy is based on the following:

- Principles and objectives of storm water control;
- Strategies for implementing the plan such as compatibility between plans devised for the city;
- Definition of urban development scenarios and flooding risks.

5.2.1. Principles

The following principles are designed to avoid the problems described in the previous chapter. These principles are essential to the smooth operation of a sustainable storm water programme.

1. *The urban drainage master plan is part of the city's urban development and environmental plan.* Drainage is part of the urban infrastructure and must therefore be planned in conjunction with the other systems, mainly environmental control, sewage collection and disposal of solid material and transit;
2. Runoff during rainfall events may not be increased by the settlement of the watershed, whether in a simple housing development or in macrodrainage structures in the urban environment. This applies to a simple urban backfill, construction of bridges and highways, and the implementation of urban areas. *The principle is that no urban user should increase the natural flooding level;*
3. The storm water control plan must take account of the watersheds in which urbanization is taking place. The measures may not reduce impact in one area to the detriment of another, in other words, *impacts must not be transferred*. If it does happen, a measure must be taken that mitigates the effects;
4. The plan must *minimize the environmental impact of storm water runoff* by providing for compatibility with the planning of environmental sanitation, control of solid material and the reduction of the contaminant load in storm water entering the river system within or outside the city;
5. The *regulations* of the urban drainage master plan *should cover the planning of the areas to be developed and any increase in density of the areas currently developed*. Once the watershed, or part of it, is settled, it will be difficult for the public authorities to hold anyone to account for increasing flooding. Therefore, unless government action is taken in advance through management, the future economic and social consequences will be greater for the whole municipality;
6. In riverside areas, flood control is implemented through structural and non-structural measures that cannot readily be treated separately. Structural measures involve many resources and only solve specific local problems. This does not mean that this kind of measure is to be totally ruled out. The flood-control policy will certainly be able to provide structural solutions for some places, but as part of

an overall approach to the whole watershed, in which they are rationally integrated with other preventive (non-structural) measures and compatible with urban development;

7. Control should be exercised over the whole watershed, and not in isolated sections;
8. *Means for introducing flood control are the PDDUA, municipal and provincial legislation and the drainage manual.* The first sets out the main policies, the second implements the controls and the third offers guidance.
9. Ongoing control: *Flood control is an ongoing process*; it is not enough to lay down regulations and build protection structures; we must look out for potential infringements of the legislation and further settlement of the risk areas. It is therefore recommended that:

    - No risk area be expropriated unless it is to be immediately occupied by the authorities to avoid it being resettled;
    - The community be involved in the planning, implementation and ongoing enforcement of the flood-control measures.

10. Education: It is essential to educate engineers, architects, agronomists, geologists and other professions, the population and public administrators so that *everyone is aware of public decisions taken*.
11. The cost of implementing structural measures and the operation and maintenance of urban drainage must be transferred to the owners of the plots, calculated on the basis of the impervious area, which is what generates the additional volume in relation to natural conditions;
12. This set of principles covers the *control of urban runoff at source*, laying down measures for those that increase runoff and contaminate storm water;
13. Efficient management is essential for maintaining drainage and enforcing the regulations.

5.2.2. Objectives of the plan

The urban drainage master plan aims to create mechanisms for managing urban infrastructure relating to storm water runoff and rivers in the urban area. This plan aims to avoid financial losses and improve health and environmental conditions in the city, in line with economic, social and environmental principles laid down by the city's urban development and environmental master plan.

The goals of the urban drainage plan are:

- To plan and distribute storm water over time and space, based on the urban settlement trend, matching infrastructure to this development to prevent financial losses and environmental damage;
- To control the settlement of flooding risk areas by means of regulation;
- To live with flooding in low-risk areas.

Urban constraints are the result of a number of factors that will not be discussed in this text, as we work on the assumption that they have been defined in the urban and environmental development master plan. However, owing to the interference of land use with drainage, there are elements of the drainage plan that are used to regulate the articles of the urban and environmental development master plan.

5.2.3. Strategies

Strategies can be established in line with the preparation of the plan and environmental control:

Preparing the plan

The urban drainage master plan can be prepared in line with two basic strategies:

For unsettled areas: devise non-structural measures relating to regulations on urban drainage and settlement of risk area, endeavouring to contain the impacts of future developments. These measures are designed to transfer the cost of controlling hydrological changes due to urbanization to whoever makes those changes;

For settled areas: the plan devises specific studies for urban macro-watersheds with the aim of planning the measures necessary to control the impacts within those watersheds, without their transferring the existing impacts downstream. This planning gives priority to using temporary storage in detention basins.

Environmental control

As regards environmental controls, covering the quality of storm water runoff, solid material in transit and contamination of groundwater, the strategies are as follows:

1. For areas having no sewage systems or a large number of sewage connections to the storm drains, control measures give priority to quantitative control. This type of measure uses detention only for the volume exceeding the current drainage capacity, so preventing runoff in dry seasons and the volume of the first part of the hydrograph contaminating the detention basins. These storage areas are kept dry during the year and are used only for events with a return time exceeding 2 years. In some cases they have to be used for lower risks owing to the low capacity of the existing system.
2. When the sewage system is implemented, the plan can move into a second stage in which the runoff system is modified together with the detention basins so that they can also help to control storm water quality.
3. To control contamination of aquifers and control solid material, medium-term programmes will have to be set up with the goal of reducing such contamination by means of measures distributed throughout the city.

5.2.4. Scenarios

The scenarios for devising the plan must take account of two aspects: (a) urban development scenario; (b) control measures adopted in the scenarios. The main urban development scenarios identified in this study are as follows:

i. *Present:* Present urbanization conditions, obtained by means of population estimates and satellite images;
ii. *Present scenario + PDDUA:* This scenario involves the present settlement for the parts of the watershed where the plan’s forecasts were exceeded, together with the plan’s guidelines for the areas in which the plan was not exceeded;
iii. *Maximum settlement scenario:* This plan relates to the maximum settlement in accordance with the situation observed in various parts of the city that are at this stage. This scenario represents the situation that would occur without disciplined land use.

The first scenario represents the next stage after the present, the second is the scenario planned for the city in the

PDUA. The second scenario represents the most realistic situation, since it accepts development carried out outside the master plan and the guidelines of the plan for the parts being developed. The third scenario is the one associated with no control measures, i.e. if nothing is done to change the trend.

Regarding the control measures adopted in each scenario of the plan, the following should be taken into account:

1. The planning for the present scenario with non-structural measures presupposes that they come into effect on the date of the survey in the watershed. This is not correct, as some time will pass between the end of the studies and the approval of the regulations;
2. It is possible to adopt the future scenario as a higher level of action, as it presupposes that the regulation measures can be applied with some delay; when the proposed regulations are approved the scope of the alternative will have to reviewed at project level.

Generally the second alternative is chosen. The 10-year return time risk can be chosen to specify the capacity of the macrodrainage, because structural control measures are not generally economically viable above this level of risk. Flooding losses are more costly for high-risk flooding (short return times) since they occur more often. In this way, the benefit of using control measures for low risks (long return times) can be very costly but they are not of great benefit on average. The risk must be assessed on the basis of the risk to human life and financial losses. The 10-year risk is often used but it must be assessed in every case.

5.3. Measures

5.3.1. Non-structural measures

The main non-structural measures are as follows:

- Legislation and regulations on increases in flow due to urbanization and the settlement of riverside risk areas;
- Management of urban services relating to storm water.

Legislation and regulations

Urban drainage regulations: use of regulations to control urban drainage for sites to be developed in terms of both housing developments and densification, involving the approval of works in existing housing development sites. The evaluation of the Porto Alegre master plan and the decree presented in Annex A is an example of regulation that can be used in the urban master plan.

Regulation of riverside areas: this component attempts to define the areas liable to flooding and the areas to be regulated, and the use of definitions discussed in Chapter 2, with the aim of avoiding densification of the population in areas at risk of riverside flooding.

Storm water management

This management is the task of the institutions in the municipality that will have to implement the various aspects of the storm water master plan. This implementation involves: devising the action plan, inspecting services, evaluating and inspecting housing development implementation and works relating to legislation and regulations, plus implementing the planned programmes.

The ideal scenario is for storm water management, sewage system and solid refuse to be managed with the same agency, to achieve economies of scale and a clear hierarchy in the services at the interface between these components. However, in practice, water and sewage are often administered by one agency, and storm water and refuse by another two independent agencies, along with land use. In the absence of technical and political coordination, this tends to lead to conflicts within the city.

5.3.2. Structural measures

As described in the strategy, structural measures involve the plan for each significant sub-watershed within its flow geography, plus any structural protection measures against river flooding. Figure 5.2 illustrates the stages of the plan for each watershed.

The definition of the urban watersheds is the first action under the plan in terms of structural measures. This definition is based on a subdivision of rivers running into a larger system (lake, river, reservoir or estuary), beyond the city limits. Since a plan will be devised for each sub-watershed, it is acknowledged that they must not export impacts, but there may be some interference between them through runoff. Where necessary, an urban macro-watershed may be subdivided according to development and size.

Watershed plan

The structure of the study of plan alternatives is shown in Figure 5.3. Note the three main groups: input data, watershed plans and development of outcomes. Once the plan has been drafted, action focuses on implementing the structures.

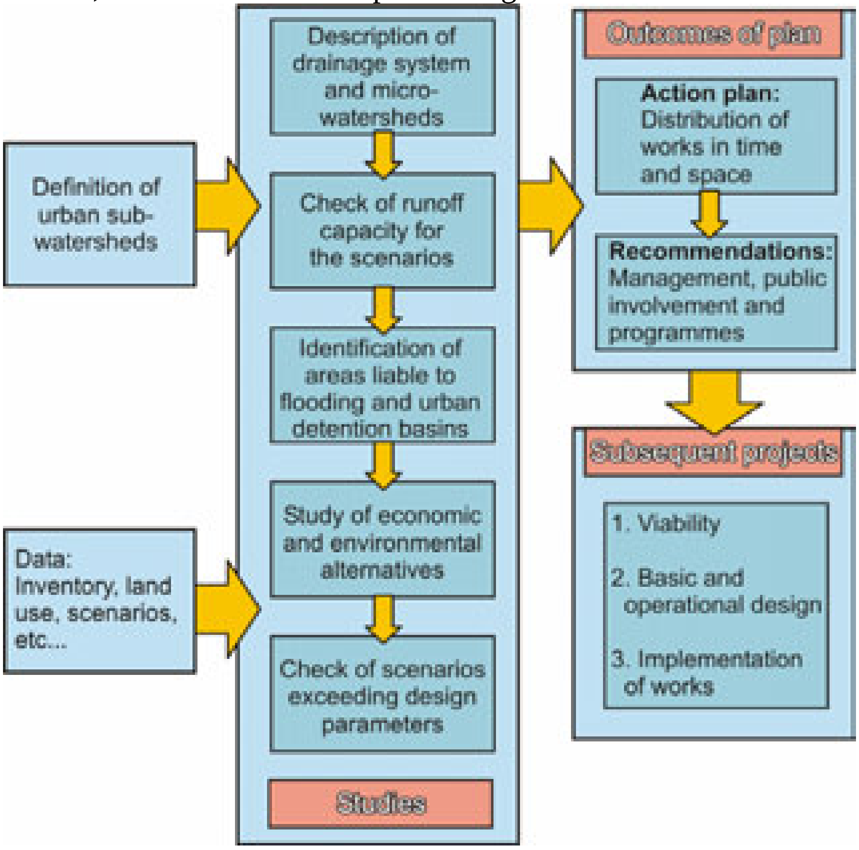


Figure 5.2. Structural measures

Input data: The following input data are needed to study the plan's structural alternatives: (a) current physical urban characteristics such as geology, soil type and topography; (c) hydrology: precipitation data for plotting intensity-duration-frequency curves and events with precipitation and flow data for adjustment of the hydrological models; (d) topography, preferably at a scale of 1:2 000; inventory of constructed storm drain system: conduit or tunnel sections, map position and top or bottom level of tunnels and their condition in terms of clogging or obstruction; natural sections representing the rivers of the urban area concerned; (e) location of any sewage system and information on the refuse-collection and urban-cleaning system.

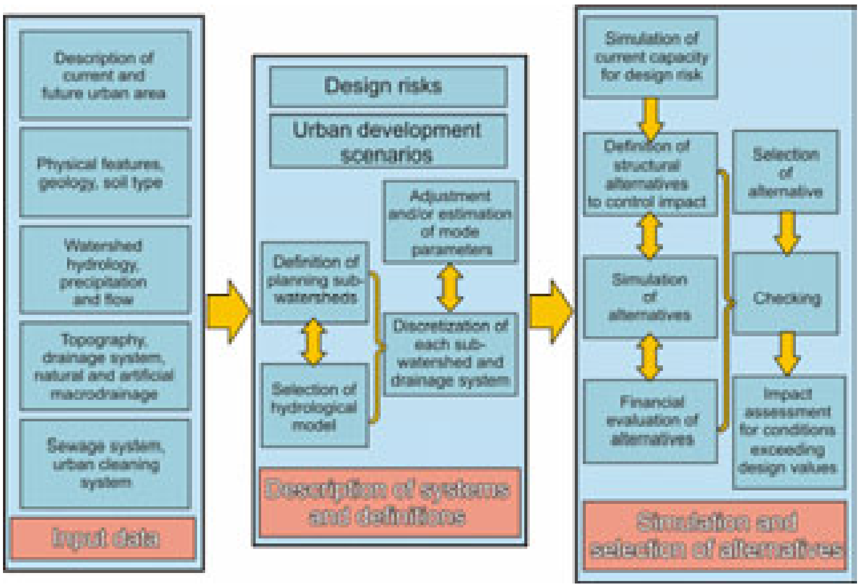


Figure 5.3. Stages of the plan by watershed

Description of systems and definitions: This module covers project definitions relating to: (a) analysis scenarios: present and future; (b) design risk: chosen return time for the project; (c) subdivision of city watersheds where the plans will be carried out and internal subdivision of these for simulation purposes; (d) adjustment of model or definition of simulation parameters (more details in next section).

The scenarios for quantitative analysis of an urban watershed are:

> *Present scenario* (capacity of existing system): this is the scenario in which the present system is analysed for floods with a risk similar to the one considered in planning; mainly for the scenarios of current settlement and for the short term, and for any future settlement in the urban master plan;
>
> *Future scenario* (study of control alternatives): in this scenario the combined conditions are investigated for control of the system for the planning horizons, based on the measures for controlling and increasing the runoff capacity.

Simulation and choice of alternatives: The stages of this analysis involve:

Existing runoff capacity: analysis of the conditions of runoff into the system, determining the runoff capacity in each defined discrete section of the drainage system in the watershed. In this phase it is possible to identify the critical places due to the variability of the runoff capacity that generally occurs in urban areas. It is common for there to be sections with a lower runoff capacity downstream than upstream of the section.

Simulation of present state of urbanization and future state of the storm water runoff system for the present and future scenarios. In this simulation it is possible to identify the critical sections or reaches where the existing capacity is insufficient to handle the simulated flow. Generally, this simulation is carried out with a model for an open surface, ignoring processes occurring under pressure.

Definition of control alternatives: formulation of possible control measures by means of the following: (a) identification in the field of possible sites for detention basins; (b) evaluation of available volumes on the basis of water levels; (c) sections that can be widened and associated constraints.

To determine the optimum combination, the planner can check the available alternatives: (a) reduction of surface runoff by means of measures at the source (generally for future scenarios); (b) detention basins in places where there are available areas or even on buried sites where no open areas can be found; (c) increasing the system’s runoff capacity.

Simulation of alternatives: simulation of the selected alternatives, checking their effectiveness for the various scenarios. Various layouts are defined with the physical alterations that control existing flooding. The best economic solution is the one that costs the least to install. This can be achieved by trial and error, varying certain combinations, or using an optimization model in combination with a hydrological model.

Financial evaluation of the alternatives: assessment of the costs of implementing the alternatives and choice of project alternative and plan of action for implementing the measures.

Checking of design with a hydrodynamic model that takes account of runoff under pressure. Check for conditions of higher risk than that adopted for the project. Assuming, for example, that a return time of 10 years has been selected for the project, the plan must assess the impacts on the drainage for risks of more than 10 years, proposing preventive measures for the various most critical places.

Characteristics of models: The models used in urban watersheds generally have two modules: (a) watershed module: that calculates from precipitation the resulting flow entering tunnels and canals; (b) modules for rivers, canals, tunnels and reservoirs; transporting runoff in canals, tunnels and detention basins.

Generally, the algorithms used vary with the chosen level of detail for representing the watershed and its characteristics, and with the effects of runoff to be taken into account. Two types of models can be used:

a. *Hydrological model:* in this case, the watershed module only is available and possibly also the canal (tunnel) module. The watershed module comprises hydrological functions for determining runoff into the macrodrainage conduits by means of algorithms such as initial losses, infiltration and propagation of surface runoff. Examples of models that handle this module only are IPH-II (Tucci *et al*., 1981) and SCS (SCS, 1975). The IPHS1 model (Tucci *et al*. 1988), includes watershed and canal algorithms.

   In the tunnel module the flow is transported by storage equations such as Muskingum, or modified versions of it, such as Muskingum-Cunge. In detention basins, the Puls method is used.

   This type of model identifies the places where flooding occurs owing to flows exceeding the runoff capacity, or to high water, with the help of height-flow curves for the sections.

b. *Hydrological-hydraulic model:* This type of model is generally used only in conditions of backwater and runoff under pressure, leading to flooding in various places that need specific solutions, or when there is a major interaction in the system. In this case, the tunnel module is represented by the dynamic equations (by Saint Venant) for open surfaces or runoff under pressure, adapted to the “Preissman slot” scheme. This model is also used for design checking and assessing the impact for risks exceeding the design values.

Elements of the simulation: The simulation of alternatives is one of the main stages in devising an urban drainage master plan. The simulations to be carried out cover such situations as:

- Various phenomena, such as rainfall-flow transformations and runoff into canals;

- Runoff into canals may happen according to various regimes: free, under pressure, subcritical, supercritical; and combinations of and transitions between them;
- Simulation of special structures such as detention basins or pump houses;
- Various scenarios for the settlement of the watershed, relating to present and future urbanization; or various watershed settlement patterns.

In addition to this variety of conditions there are other constraints:

- The need to represent interactions in the conduit system (e.g. backwater effects);
- It must be possible to estimate the parameters of the methods on the basis of physical characteristics of the watershed or drainage system, whether in the absence of adjustment data or for simulating future situations;
- Since the urban drainage master plans generally analyse the macrodrainage only, detailed designs and microdrainage designs are carried out separately. The parameters and criteria adopted in these projects must therefore be consistent with those used in the plan. This implies using accessible methods and criteria that are readily spread, to the extent that may even be included in products such as drainage manuals;
- In order to be able to spread the criteria, parameters and methods used, it is best to avoid the use of specific software methodologies, on which it is not easy to find references, examples or other types of support for the application (the methods should not be "software-dependent");
- There is a very high volume of simulations to be carried out. Assuming that the macrodrainage piping is 1 m in diameter upwards or equivalent, the average size of "basic watersheds" is generally 0.5 to 1 km^2. The methods adopted must not involve excessive work, especially for determining the parameters.

When selecting the methodologies for simulating and estimating the parameters it is essential to observe the applicability conditions for each of them, as much in general terms as for the specific conditions of use. Most common rainfall-flow simulation techniques, and most parameters for this transformation, have been developed for rural areas. The use of these techniques should avoided, or they should be used when corrections can be introduced that take account of conditions in urban watersheds. For instance, the Kirpich formula for concentration time must be applied with the corrections applying to urbanization (Tucci, 1993).

The use of parameters from the literature is not a validation, although it is often inevitable owing to a lack of data on rainfall and especially flow. An alternative would be to calibrate the models for a similar watershed and transpose the parameters. In this case and where some data is missing, qualitative calibration (Cunge, 1980) has to be used. This technique consists of comparing the results of the simulations with the location and apparent magnitude of the flooding occurring in the watershed, and other phenomena such as: runoff conditions into open canals, water overflowing out of inspection pits or storm drains, etc. This procedure is easier to use with low-recurrence storms – 1 to 2 years – since they are more readily remembered by the population. Another alternative is to use historic high-impact floods, which are better identified by the population, as long as rainfall records are available.

The information that the municipality has on problems caused by flooding are vary valuable in this connection; it can enable storm drainage professionals to make at least a reasonable mapping of the places and frequency of flooding. Another interesting source of information are the transport authorities, as road traffic is affected by flooding.

Design rainfall: The most common method is alternate block, using intensity-duration-frequency curves. The other alternatives are the SCS triangular hietogram, very similar to the previous method, or methods based on the time distribution of rainfall in the region under study, such as those by Huff or Pilgrim and Cordery. For the duration of the rainfall, we must adopt as a reference the concentration time of the whole watershed rather than the sub-watersheds into which it is divided. A duration between 1.5 and 2 times the concentration time is advisable. Remember that control measures such as detention basins are usually planned; and for specifying them the runoff volume is as important as the peak flow. The calculation of small-scale measures (e.g. housing development reservoirs) must include at least one analysis for long-duration rainfall.

It should be stressed that using the design rainfall and a rainfall-flow model (the usual case when there are no flow data), the risk of the flow obtained is not necessarily the same as the precipitation. Therefore, the associated risk relates to the precipitation rather than the flow.

Effective rainfall: The rainfall-flow transformation has two components, the determination of effective precipitation (a quantity of rainfall that is transformed into runoff); and the propagation of that volume up to its entry into the macrodrainage system. The most commonly used alternatives for representing the first phenomenon are:

- SCS curve number (CN) method: this is a an extensively tabulated parameter, which helps to estimate it, and relationships can be constructed with the impervious area;
- Infiltration curve (Horton, Philips, etc.) combined with estimates of the impervious area.

The runoff coefficient, although very common and extensively tabulated in the literature, has the disadvantage that it does not take account of temporal variations in rainfall, and is not appropriate for calculating volumes. In addition, the runoff coefficient (and the Rational Method) are applicable to small areas; although the basic watersheds used in devising the plan are of the order of 0.5 to 1 km^2, the watersheds on which we work are generally larger.

The methodologies for runoff separation take soil type as a reference for determining the parameters. In areas that are urbanized or in the process of urbanization, the top layer of soil is removed, covered or substantially altered. One therefore has to be very careful when using soil maps, which normally describe only the natural situation before urbanization. In this case, the estimate of the impervious area is fundamental.

Campana and Tucci (1999) presented a curve relating population density to the impervious area of a watershed based on data from Curitiba, Sao Paulo and Porto Alegre. This curve enables us to study future urban settlement scenarios, as the population density is used as an indicator for urban planning.

Surface runoff: Once calculated (rainfall transformed into runoff) it must be propagated until it enters the macrodrainage system. There are various ways of calculating this in the literature. The methods used may depend on the availability of data. Prominent among the linear and non-linear methods are those of Clark, Nash, Kinematic Wave and the linear methods based on the synthetic unit hydrograph (UH) (Tucci, 1998).

Synthetic unit hydrographs, such as Snyder or the SCS triangle, were generally devised for rural areas, which is a very different application to an urban area. SCS (1975) was adapted for urban areas. Regionalized parameters for these models have been presented for various places, notably the work of Díaz and Tucci (1989) who regionalized the UH for Brazilian urban watersheds.

Methods such as Clark and Nash are better suited to urban areas, as their parameters can be estimated taking account of the characteristics of the area simulated. Germano *et al.* (1998) regionalized the parameters of the Clark model used in the IPH-II model for Brazilian urban watersheds.

The use of the kinematic wave depends on making a detailed analysis of the physical system, which is not always possible. Moreover, the representativeness depends on the actual runoff conditions and the scale of application. For instance, a kerb could be regarded as a triangular canal, but in practice there are parked cars, refuse bags and other similar objects that make the runoff behave more like a cascade of reservoirs than a canal. On the other hand, when the unit of representation is one or more blocks of houses, the definition of “roughness” or “gradient” of a complex of roofs, terraces, lawns, etc., taken as a whole require an adjustment of the observed data.

Runoff into the macrodrainage system: In the runoff of a macrodrainage system and the control alternatives, the interaction (both physical and operational) between the components of the system is fundamental. The development of efficient alternative solutions, and the guarantee that they will work properly, depends on taking account of existing interactions. Generally speaking, there are two classes of models like those mentioned above: hydrological and hydrodynamic. The first type is used for the phase of studying alternatives and the second for checking the chosen alternative and for scenarios that exceed the design values. Some of the main aspects relating to runoff models are highlighted below:

- In order to achieve a more accurate representation of the operation of the drainage system, the system models usually limit the entry of surface runoff into the system’s conduits, depending on the pipe capacity and the runoff conditions, as happens in practice. Most models store excess runoff, usually at the point where it reaches the public system, and may release it afterwards when conditions in the pipes allow runoff. The water running out of the system owing to excess pressure is treated in a similar way, usually being accumulated at the outlet point. In practice this is only one of the possibilities, though there are other possible behaviours. The water could run through the streets until it reaches another point where it enters the system, or accumulate, or continue running downstream, depending on the topography and conditions of the conduits at each point and at any moment in time. This problem is not critical in the design simulations, as the system must be capable of absorbing the water arriving at any point. Already in the quantitative or qualitative simulations for calibration, and diagnostic simulations in general, it is important not to confuse the bottlenecks in the system with the places where flooding would occur.

- There is an implicit assumption that all the runoff generated in the watershed will reach the macrodrainage system, in other words that the microdrainage is working perfectly. This type of reasoning can result in critical places that are not subject to flooding. This is not an error as there is a real shortcoming in the system, but it is being masked by the microdrainage constraints.

The cases mentioned above show that the analysis of the simulation cannot be limited to the results of the model of the drainage system. It is essential to take account in the analysis of the behaviour of the surface water in the watershed, until it reaches the macrodrainage, and what would happen to the water if it did not manage to enter the system.

Analysis of alternatives: When seeking alternative solutions it is essential to make an integrated analysis of the watershed. This allows account to be taken of interactions between components of the macrodrainage system and helps to optimize the solution. The limitations of the control measures in one region can be compensated in another, or expensive control measures in one region can be supplanted by less expensive measures in another region.

The criterion of control measures not increasing natural flooding is a basic principle of an urban development master plan. However, since in Brazil and most Latin American countries these plans were devised after urban settlement, it is generally the case that the increase has already taken place in most of the system, and it is possible to establish control through municipal legislation only in new building developments. In this way, when analysing alternatives, control amounts to not transferring the existing constraints downstream, using the installed drainage capacity, which in one way or another is greater than the capacity of the natural watershed. Therefore, the most important thing when studying alternatives is to assess the whole of a watershed where internal solutions avoid internal flooding, and maintain the design flow at no more than the conditions existing at the design stage.

Control at source: In the definition of the control measures and the evaluation of their impacts, one case that warrants special attention is control at source, applied at housing development level, such as micro-detention reservoirs or infiltration surfaces. The issues that may make evaluation difficult are: (a) uncertainty as to their installation, operation and maintenance; (b) uncertainty as to their real impact on runoff and the sustainability of that impact over time.

The actual implementation of control measures at housing development scale depends on the installation and proper functioning of a large number of individual components. These components often depend on the inhabitants rather than the public authorities, which are restricted to requiring installation and inspecting operation. In the case of control measures that operate on a larger scale (reservoirs in plots, districts, etc.), the installation depends on administrative decisions by the public authorities. This can therefore help to make the project more effective to implement since the responsibility for operation and maintenance of the structures is clearly defined.

In addition to the uncertainty regarding the implementation and operation of control measures at source, there is also uncertainty about their real impact. In other words, unless the measures are implemented and operated properly, it is quite difficult to quantify their real impact on the generation of runoff, as there is no proper monitoring that can evaluate this impact on the watershed. It seems unlikely that the impact of urbanization can be cancelled out completely, as control at source cannot readily cover 100% of the watershed surface (e.g. streets and public thoroughfares). In addition, some measures, such as those designed to promote infiltration, may prove quite vulnerable over time.

The doubts mentioned should not prevent such measures being adopted. On the other hand, two approaches are suggested:

(a) these measures should not be relied on entirely to manage urban drainage, and (b) medium- and long-term monitoring programmes should be launched to obtain data to enable this kind of approach to be adopted in the appropriate circumstances.

Detention reservoirs: Since it is a planning approach, it is not essential to present a full technical design study for these proposals, though this does not mean that it is sufficient to decide on the location and estimate the necessary volume, except when the available information does not allow a more detailed approach or when it is a very preliminary study. Besides estimating the necessary volume, it is essential to check the viability of operation. This means checking the input and outlet conditions of the reservoir, the operating levels and hydraulic structures. It may happen that a reservoir has sufficient volume but that there is no hydraulic structure that can achieve the desired effect of attenuating the hydrograph; or that the volume and hydraulic structures exist, but the levels do not allow it to function properly.

Conduit and canal dimensions: The usual practice in Brazil is to use a Manning roughness coefficient of 0.013 to calculate conduit and tunnel sizes. This value is suitable for new concrete pipes, but is not representative of the actual operating conditions of real conduits. After a few years' operation, the condition of the pipe and joints begins to deteriorate. Even in well maintained systems, sediment and other materials will inevitably accumulate, increasing the flow resistance. Accordingly, a Manning n of 0.015 or 0.016 is more appropriate for simulating the operating conditions of the drainage system over its working life.

Another issue to be highlighted is that, contrary to the recommendation of all the urban drainage manuals, losses from singular loads (manholes, bends, etc.) are customarily ignored. In the simulation of a macrodrainage system this can be justified depending on the working scale, but it must be compensated using techniques such as the equivalent length or an increase in the Manning n to values of around 0.02. For more detailed calculations, or localized projects, singular losses must be considered, and the energy line checked. Another important issue is that it is not always possible or efficient to adopt the criterion of free surface runoff.

An important phenomenon, when situations are analysed in which runoff takes place under pressure, is the reduction in hydraulic conductance. This happens when the water reaches the top of a conduit, especially a rectangular one.

Economic assessment of alternatives

One of the main elements involved in comparing alternatives is the cost of implementation. As this is the planning stage, no detailed designs are prepared for the components of each alternative. The cost estimates must therefore be prepared from schematic definitions of the solutions. In the case of extensions, there are two most frequent situations: (a) It is possible to define in the plan which conduit is to be laid and the characteristics of the extension (size and shape); (b) It is possible to evaluate that the extension is viable, but the choice of route and characteristics require work beyond the scope of the planning stage.

In the first case, the cost can be estimated by means of a calculation that takes account of the specific conditions of the construction of the extension; or a cost can be adopted per unit length, from tables, generally available in the municipality, of average construction cost according to the size and type of conduit.

Where it is not possible (or justified) to define the route and characteristics of the extension, one possibility is to plot, from a table of cost per unit length, a graph of cost against the necessary additional capacity K (hydraulic conductance). Figure 5.4 shows one of these graphs used in the urban drainage development master plan of Caxias do Sul, Brazil (IPH, 2001). Using this methodology, it is a simple matter to simulate alternatives, as the extension is defined on the basis of the increase in the capacity of the existing conduit. Some additional constraints for the extension, such as maximum water levels to avoid back-water effects, or specific constraints in certain sections or places, should and – where possible – must be considered.

When choosing which cost calculation methodology to use, one must take account of the importance of the structure in the context of the plan, and its total cost.

An additional issue to be taken into account in evaluating the costs of each alternative is the transfer of impacts downstream of the system under study. Solving the problems caused by this transfer generates costs, which have to be added to the costs generated within the system being planned.

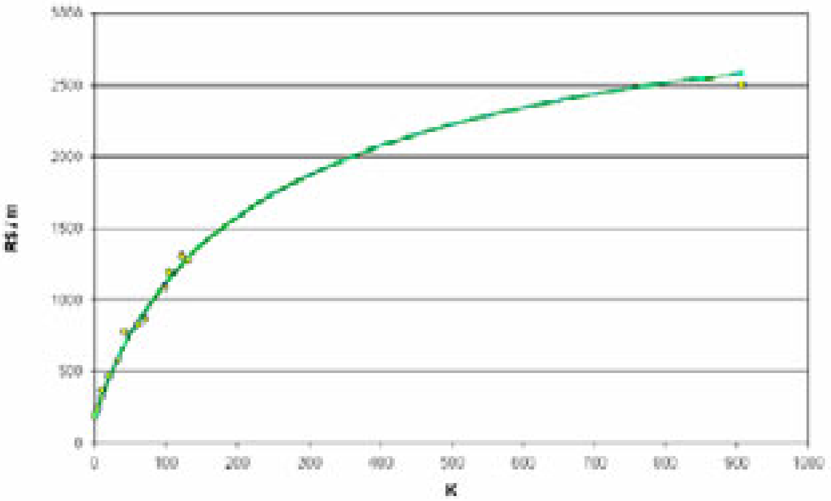


Figure 5.4. Graph of mean construction cost as a function of hydraulic conductance (Villanueva and Tucci, 2003).

Cruz (2004) estimated the cost of various Porto Alegre watersheds and devised an equation as a function of population and drainage area:

$$CT = 0{,}536 \cdot POP - 5{,}233 \cdot A \qquad (5.1)$$

where Ct is the cost in millions of reais, A is the area of the watershed in km^2 and Pop is the population in thousands of inhabitants. This equation should be used for watersheds with a low settlement density (< 20 inhab/ha). The equation was obtained with R2 = 0.98, but with only 8 watersheds.

An interval of 1 to 4 million $R\$/km^2$ is estimated, the lower value corresponding to less dense areas and the upper interval to more dense ones.

Economic viability

The economic assessment has two components in this plan: (a) economic assessment of the alternatives, as mentioned above, evaluating the cost of the works;(b) mechanisms for financing the works and the drainage operation highlighted at the end of this chapter.

The economic viability of implementing structural measures and long-term control of urban drainage depends on the financial capacity to implement the measures.

The costs relating to urban drainage and flood control in urban areas cover:

- Costs of implementing macrodrainage works and other structural measures for controlling impacts in the city. These costs are spread over the watersheds by means of the plan for each watershed. Besides this, this cost arises at implementation time;
- Costs of operating the existing drainage system in the storm drainage system, involving cleaning, maintenance of conduits and solving localized problems. This cost should be spread over the users of the drainage system.

The basic principle of funding urban drainage measures is to spread the costs in accordance with the uncontrolled impervious areas on a property. In urban drainage, anyone increasing the volume of surface runoff is responsible for flooding and should pay for increasing the impact. The fundamental factor in increasing volume is the impervious area. The costs of implementing the drainage proposed in this plan are spread on the following basis:

Control structures: For the control structures planned in each watershed, the implementation costs must be spread over each watershed in accordance with the impervious area of each property, from a total estimated charge levied for its installation or through financing. In this way, the population of the watersheds having more impervious areas and hence with more critical drainage conditions, will have to pay more.

Operation and maintenance: The cost relating to the operation and maintenance of the drainage system can be collected: (a) as part of the general budget of the municipality, without specific payments by users; (b) by means of a fixed charge for each property, regardless of the impervious area; (c) on the basis of the impervious area of each property. This last alternative is the fairest from several points of view, as whoever uses the system more has to pay in proportion to the runoff generated.

The main difficulty in the collection process is in estimating the real impervious area of each property. The following procedures can be used to do this:

1. Use the built-up area of each planned property for the plan of the area of land as the impervious area. This is not the real value, as the impervious area tends to be higher depending on the paved areas.
2. Set up a programme to assess the impervious area using satellite imaging and sample checks by visits to the area.

Costs should be divided up taking account of the following:

1. For each watershed and each city, the estimate of the total impervious area and the total cost of the work or of operation and maintenance;
2. The calculation of the cost of operation and maintenance calculated on the basis of the total operating cost of the city, since the geographical differences are not significant and it is more complex to calculate separate operating costs for each watershed.Annex B describes the methodology for sharing costs for uncontrolled areas based on the volume of runoff generated by each surface.

5.4. Outcomes

The outcomes of the plan are:

- Regulations of the urban and environmental master development plan in the articles relating to urban drainage;
- Action plan: control of the city’s urban watersheds;
- City management proposal;
- Drainage manual.

The first item was discussed earlier. The activities under the action plan are highlighted below. The management proposal involves assessing the current administration and a proposal for operation covering: implementation of the plan, inspection of the works, approval of projects taking account of the new regulations, operation and maintenance of the drainage system and risk areas and inspection of all activities.

The action plan lays down the following:

- Management of the implementation of the plan: involves identifying the agencies carrying out the planned activities;
- Funding: the funding mechanism proposed for the measures under the plan and for recovering costs;
- Implementation: the sequence of measures in time and space relating to the plan for each sub-watershed.

The drainage manual is the document that will guide the activities of the city planners and designers regarding the development of drainage and river flooding. The manual must be a support document.

5.5. Programmes

The programmes are additional medium- and long-term studies recommended by the plan to help offset the deficiencies encountered while implementing the plan. The programmes identified in this phase of the plan are presented in chapter 4 of this book and feature the following aspects:

- Monitoring programme;
- Additional studies needed to improve the plan;
- Maintenance;
- Inspection;
- Education.

The programmes under the urban drainage development plan were designed to be medium- and long-term activities required to improve the planning of urban drainage in every city.

In this context, programmes may be planned relating to the monitoring of data required for planning purposes, additional studies, maintenance and education. Inspection must be incorporated in management. Some examples of programmes are described below.

5.5.1. Monitoring programme

The planning of quantitative and qualitative control of urban drainage requires a knowledge of the behaviour of the processes involved in storm drainage.

There is limited hydrological and environmental data and planning at this stage is carried out on the basis of secondary information, which tends to lead to more uncertainty in relation to decisions on the choice of alternatives.

The Information System programme must attempt to make available information for managing urban development, linking producers and users, and laying down criteria to guarantee the quality of the information produced.

The monitoring programme proposed in this plan has the following components:

- Monitoring of the city’s representative watersheds;
- Monitoring of impervious areas;
- Monitoring of solid material in drainage.

Monitoring of the city’s representative watersheds

Evaluating the established hydrological system. The available information is generally scattered and limited, and is not necessarily in line with the interests of planning urban drainage in the city.

Justification: For determining flows in urban watersheds hydrological models are used that have parameters estimated on the basis of observed precipitation and flow data or estimated from information found in the literature. The studies carried out use some of the information already existing in the city. However, there is often a need for a more representative sample over a longer period of observation. Not all Brazilian cities have data on storm water quality. This information is important to find out the level of contamination resulting from runoff, the loads of the various components and for establishing appropriate control measures.

Objectives: The aims of the programme are to obtain more information on precipitation, flow, and water-quality parameters for some parameters representative of the city’s urban development, and to monitor any change in their behaviour under the plan.

Method: For conducting this programme it is recommended to:

Survey and review existing information on hydrological variables and water-quality parameters;

For the same places, identify the main indicators of urban settlement for the same periods as the data collected;

Prepare a plan for supplementing the existing system;

Set up a database to store the existing and collected information;

Implement the planned system and make it operational.

Monitoring impervious areas

The city’s urban development is dynamic and monitoring of urban densification is designed to evaluate the impact of the process on the city’s infrastructure. In hydrological studies carried out in recent years with data from Brazilian cities, Campana and Tucci (1994) presented a clearly defined relationship between urban densification and impervious areas (see Urban Drainage

Manual). Therefore, the increase in densification has a direct relationship with the increase in impervious ground area, which is the main cause of the increase in urban drainage flow.

Justification: During the implementation of the plan use is made for a future development scenario of the densification forecast in the urban master plan and, using the above-mentioned relationship, the impervious areas planned for various scenarios. Since the latter may deviate from the forecast, the actual change in impervious area in the watersheds covered by the plan must be monitored.

Objective: To monitor changes in the impervious area of the city's watersheds, checking any deviation from the planned conditions.

Method: This programme may be set up on the following basis:

- Obtain an annual satellite image of the city;
- Systematically determine the impervious areas for each of the city's watersheds;
- Check whether they are in line with the scenarios considered in the environmental and urban development master plan;

Whenever there are new population surveys, update the ratio of density vs. impervious area; Adjust this ratio for commercial and industrial areas.

Monitoring of solid material in drainage

There are great uncertainties regarding the quantity of solid material reaching the drainage system. Very little of this information has been evaluated in Brazil. It is generally known how much solid material is collected in the collection area, but not the actual amount that reaches the drains. The figures may differ significantly in magnitude.

Justification: Urban drainage studies are based on the principle that a conduit has the capacity to carry the flow reaching that section from upstream, but it is not possible to estimate the extent to which that conduit will be obstructed in relation to the production of solid material. Thus, flooding is often due not to an under-specified water pipe capacity, but to obstructions caused by the solid material. In order to be able to tackle this issue we need to know more about how the components of the production and transit of this material behave in urban watersheds.

Objective: To quantify the amount of solid material reaching the storm drains, as a basis for introducing mitigating measures.

Method: To quantify the components involved in the production and transit of solid material, one or more sampling areas have to be defined. The planned method is as follows:

- Define the goals of a programme for estimating the components of the process of generation and transit of solid material to the drains;
- Select one or more representative areas for sampling;
- Define the components;
- Quantify the components for the areas surveyed for a sufficiently representative period;
- Propose mitigating measures to reduce obstructions.

Revision of the inventory of the drainage system: The depths and diameters of the conduits in the current drainage system are recorded. The level is normally obtained on the basis of the available topography of the inventoried area in drawings existing in the city. Owing to the variability of existing city surveys, incompatibilities are usually observed when combining the information, and this has to be properly analysed.

Justification: The existing error can compromise the specification of the structures and the study of alternatives. In the design phase it is essential that the inventory be as accurate as possible.

Objective: To revise the inventory of the city's storm drains.

Method: The survey must endeavour to establish the topography in relation to a single reference point using GPS, checking the current level with the level obtained in the field. The analysis must be based on the places identified as problem areas in the simulation studies carried out.

5.5.2. Further studies

While studies are being carried out needs are generally identified for further studies to improve the planning of urban drainage in the city. These studies aim to provide information to improve future planning and design for the city's storm water.

Typically, these studies are:

- Financial evaluation of risks;
- Review of hydrological parameters;
- Method for estimating rainwater quality;
- Systems for retaining solid material in detention basins;
- Check of design conditions for structures for control at source.

Financial evaluation of risks

The urban drainage project has been drawn up on the basis of risks adopted in the literature, which are not always justified in relation to the circumstances of the place. The risk of a project (return time) can be chosen on the basis of social and/or economic factors. The conventional financial method gives special importance to the relationship between the benefit derived from the structure (reduction of losses from flooding) and the cost of building the protection structures. This procedure does not always accurately reflect the local circumstances, in that in some areas the benefit will be minimal when the population has a low income. Accordingly, there are other economic methods such as the valuation of the property on the basis of the reduction in the occurrence of flooding or the owner’s will to pay.

Justification: It is difficult to apply these methods to every project in a city; generally, standard planning and design risks are adopted, as these studies require a survey of a set of data for each place, representing a significant part of a project’s cost. Therefore, if it does prove necessary, check whether the risk adopted of ten years for the control of the city’s macrodrainage adequately represents the economic scenarios.

Objective: The objective of the study is to evaluate – using available financial methods – the risk adopted for the project in the city.

Method: The planned method is as follows:

- Define the financial procedures to be adopted and a specific sampling methodology;
- Define criteria for sampling the areas to be used for the study;
- Choose the areas in the study, preferably the city’s watersheds;
- Carry out a financial study for each area of the city;
- On the basis of the results obtained, analyse the variability

of the results and the impact of the plan devised.

Review of hydrological parameters

The areas studied were planned and designed using the Soil Conservation Service (SCS) model, which has two basic parameters relating to: (i) the separation of the runoff and impervious areas and (ii) the movement of runoff in the watershed. These parameters characterize the peak flow of a particular place on the basis of the physical characteristics of the soil, coverage and impervious areas.

Justification: These parameters are estimated on the basis of existing, generally limited data. With the collection of the hydrological data from the watersheds as planned in the monitoring programme and with those that can be implemented in new programmes, it is possible to check the relationship between the parameters and characteristics of the watersheds, so reducing the uncertainties of the estimates.

Objective: The objective of the study is to update the relationship between the parameters of the model used and the types of soil, coverage, drainage characteristics and impervious area.

Method: The planned stages of the methodology are:

- Selection of events for the watersheds, with data available in the city and under the planned monitoring programme;
- Determination of the physical characteristics of the watershed for the same period;
- Determination of the parameters on the basis of the observed precipitation and flow data;
- Check the relationships and adapt if necessary.

Method for estimating storm water quality

No methodology has been developed for estimating the quality of storm water using data from Brazilian urban scenarios. The estimates are based on water quality parameter data from American or European cities which have different development circumstances from Brazilian ones.

Justification: In view of the limitations highlighted in the previous item, we observe that to obtain consistent estimates of storm water quality, methods are required that are based on the data representing the situation in the watersheds subject to urban constraints.

Objectives: To devise a methodology for estimating the quality of storm water using data from watersheds. The data will be obtained from the monitoring programme referred to in the previous section.

Method: The proposed methodology is as follows:

- Analysis and selection of water quality data analysed in accordance with the programme set out in the previous section and other data obtained within the city;
- Evaluation of variability over time and space of the water quality parameters associated with urban cleaning practices, the sanitation system and other factors influencing those parameters;
- Definition of suitable estimating model and methodology for various levels of water quality.

Retaining solid residues in detention basins

The plan devised may use detention basins for attenuating runoff in urban areas, with the aim of containing the increase in flooding. The detention basins will be used to retain volumes of solid material from the drained watersheds. In the design of these structures refuse detention strategies have to be defined that do not obstruct runoff or cause flooding nearby.

Justification: There are various alternatives for designing detention basins; often, where a high volume of solid material is produced, a lot of it has to be collected before it obstructs the macrodrainage. Accordingly, it is important to use detention basins as places for concentrating and removing refuse. In order to do so, systems have to be designed that work with optimum efficiency to achieve this.

Objectives: To design systems for retaining solid material associated with detention projects.

Method: The procedures proposed are as follows:

- Identify and analyse existing systems for retaining solid material;
- Select a group of pre-existing and proposed alternatives

for experimental study;

- Develop a scale model to test the defects of the selected systems;
- Prepare a manual to support the project based on evaluating the experimental operation of the systems.

Checking of control systems

There are various control systems in the literature. The experience of operating these systems has been documented in a number of countries though Brazil has no experience in the field. These elements can represent changes in behaviour depending on the characteristics of use, production of solid material, climate, etc.

Justification: In the search for improved quantitative and environmental operation of urban drainage control systems, a sample of them has to be evaluated over time, to identify their operation and potential corrections for future designs.

Objectives: To evaluate the operation of control systems sited in the city as part of the plan.

Method: The planned stages of the methodology are:

- Inventorize all control systems, such as: pervious paving, detention and retention basins and infiltration areas. For this inventory the basic information for a database has to be defined;
- By sampling existing systems and monitoring by inspection officials, make an annual evaluation of the systems’ efficiency. In this case, the assessment criteria and information to be obtained from the selected systems will be defined;
- On the basis of at least one representative sample and of operation over a period of 3-5 years, the recommendations prepared in the urban drainage manual will be reviewed in relation to systems constructed. These evaluations must be continued for a reasonable period of time until the project ascertains that the potential improvements have been achieved.

Maintenance programme

The maintenance programme is essential to enable the planned structures to be effective over time. To that end, as we recommended in the previous chapter, the municipality should set up a group to manage and maintain the detention basins constructed, taking account of the following:

- Urban drainage;
- Control of solid refuse;
- Environmental protection;
- Urban landscaping and recreation.

Over time private detention basins may also be built, operated in this case by their owners. Experience in the United States and France has shown that with the passage of time private entrepreneurs do not carry out the maintenance and it tends to pass into the hands of the public authorities. In this situation the cost is paid by the entrepreneur with an increase in the above-mentioned operating charge.

Justification: Failure to carry out maintenance and remove solid material from detention basins can result in losses of efficiency, propagation of disease and environmental degradation.

Objective: To maintain the drainage system so that it operates in accordance with its design capacity over the long term.

Method:

- Set up a management group to maintain the systems being built in the municipality;
- Train maintenance teams;
- Set up a preventive support programme for solid refuse, with community support;
- Action programme for cleaning detention basins in the rainy seasons;
- Systematically quantify the volume generated and its relation to preventive programmes.

Education programme

Ignorance of the impacts of urbanization on drainage is very widespread, among both technical specialists and the general public. This impedes decision making, especially where the population is directly involved in taking the city’s investment decisions.

Justification: The viability of this plan depends on acceptance by the population and technical specialists, whatever the regulations say. Therefore, management can be viable only if everyone is properly informed.

Objectives:

- To impart concepts on the impact of urbanization on urban drainage for the public, engineers and architects;
- To train engineers from the municipality and private enterprise in urban drainage control techniques.

Method:

- Public information campaign through the media (newspapers and television);
- Talks with trade associations – architects, engineers, builders, etc.;
- Speaking at public budgeting meetings; (meeting at which the public decides on the structures to be built in the city, if such exists);
- Short training courses on urban drainage for municipality designers and technicians.

References

IPH, 2000. Plano Diretor de Drenagem Urbana de Porto Alegre. Volume III – Bacia do Arroio do Areia. Porto Alegre, RS.

IPH, 2001. Plano Diretor de Drenagem Urbana de Caxias do Sul.

SCS, 1975. Urban Hydrology for Small Watersheds. Washington. U.S. Dept. of Agriculture Technical Release No 55.

TUCCI, C.E.M.; ORDONEZ, J.S.; SIMÕES, M.L., 1981. Modelo Matemático Precipitação-Vazão IPH II Alguns Resultados. Anais IV Simpósio Brasileiro de Recursos Hídricos. ABRH Fortaleza.

TUCCI, C.E.M.; 1997. Plano Diretor de Drenagem Urbana: Princípios e Concepção. Revista Brasileira de Recursos Hídricos. ABRH. Vol. 2, No 2.

TUCCI, C.E.M., Zamanillo, E.A, Pasinato, H.D. 1989. Sistema de Simulação Precipitação-Vazão IPHS 1. Porto Alegre: UFRGS - Curso de Pós-Graduação em Recursos Hídricos e Saneamento Ambiental.

TUCCI, C. E. M., 1993. Hidrologia Ciência e Aplicação. Porto Alegre: Ed. da Universidade: ARBH: EDUSP, 943p.

TUCCI, C.E.M. 1998. Modelos Hidrológicos. Ed. da Universidade/UFRGS/ABRH. Porto Alegre. 669p.

TUCCI, C. E. M.; PORTO, R. L. 2001. Storm hydrology and urban drainage. In: Tucci, C. Humid Tropics Urban Drainage, Chapter4. UNESCO.

URBONAS, B., STAHRE, P., 1993. Storm water Best Management Practices and Detention. Englewood Cliffs, New Jersey, 440p.

Chapter

6

6. Case studies

Carlos E. M. Tucci and Juan Carlos Bertoni

The examples help to understand the problems and solutions matching each situation

En This chapter offers a selection of case studies illustrating aspects of flooding and studies relating to them. They help to assess the complexity and alternative solutions applying to each situation. The cases presented relate to various cities in Brazil and Argentina in South America, and El Salvador and Nicaragua in Central America. Other cases corresponding to various South American countries have been collected by Tucci and Bertoni (2004).

6.1. Urban flooding in Brazil

Brazil's total population is currently over 170 million. Less than a century ago Brazilian cities housed 10% of the country's population, whereas 82% of the population now lives in cities, some of which are very large. In these there is a variety of cases associated with urban drainage and flooding. Brazil is in fact one of the most advanced countries in Latin America in the analysis and treatment of the issue of urban drainage.

Socioeconomic problems typical of Latin America make the Brazilian examples relevant to the whole continent. Below we present the cases of the cities of Estrela, União da Vitoria/Porto União, Curitiba and Porto Alegre. We also analyse Brazil's storm water plan.

6.1.1. River flooding in Estrela (RS), Brazil

The city of Estrela (State of Rio Grande do Sul, Brazil; population 28 300) is located on the banks of the river Taquari, in a watershed of some 25 000 km^2, with varying flood levels that in extreme cases attain 18 m in a single day. Part of the area close to the city and the banks of the river is unsettled on account of that risk, but areas where the risk is less frequent are settled. In 1979, when the urban master plan was being prepared, it was realized that there was a need to prepare zoning of areas liable to flooding for inclusion in that plan. Rezende and Tucci (1979) conducted a technical study that took account of the probability of flooding in the city and proposed limits for urban settlement in the city. The following areas were defined: (a) limit of flooding regulation area: 26.00 m; (b) between 24 and 26 m: area that may be built on, subject to piles above a water level of 26 m; (b) area below 24 m: permanent reserve (established in 1981).

To avoid the invasion and recovery of the area liable to flooding already settled, under Municipal Law No 1970 of 1983 the municipality stipulated that the area liable to flooding could be changed by a higher rate of urbanization. The municipal law states as follows (PME, 1983):

> “....
> *Article 1* – The municipality is authorized to permit the construction of buildings for commercial, residential or mixed use above the urbanization rates permitted by law in the master plan, provided that:
>
> Paragraph 1: an area of land in the same zone and with an area equivalent to 4/10 of the built-up area exceeding that permitted in that place is set aside for public use as a green area or for institutional use.
>
> Paragraph 2: Where the area of land located in the permanent conservation or landscape conservation areas is set aside for public use, its value shall be equivalent to the built-up area exceeding that permitted in that place, and that area must be in the same zone or, if unavailable, in the nearest zone adjoining the place.”

The regulations state that areas liable to flooding are part of the permanent conservation areas, as specified in the master plan and below 24 m.

This type of policy enables an economic value to be maintained for the restricted areas and the risk areas to be managed. This type of planning has led to a reduction in losses from flooding over time. In the past 26 years there were seven floods above 24 m and three above 26 m.

6.1.2. River flooding and power generation in União da Vitória / Porto União - Brazil

The municipality of União da Vitória, a socioeconomic centre of the southern region of the State of Paraná (Brazil), has a population of 52 000 and borders on the municipality of Porto União - SC, population 36 000. They are delimited only by the Federal railway line, and are known as the “twin cities of the Iguaçu valley”.

In documents from 1842 (Figure 6.1), the expeditions exploring Campos de Guarapuava, from Campos Gerais, ended up discovering the Palmas fields. In order to shorten the route to Curitiba, a trail was opened up for use by herds of cattle to reach the Iguaçu valley. Over time settlements sprang up along this route as happened on the river banks. In 1882 the town received a major stimulus from the steamship. In 1909 a railway linked the city of Porto União da Vitória with the rest of the country, which stimulated growth, and the railway grew in importance.

Until 1917 there was one city, but as a consequence of the Contestado War it was divided into two: Porto União became a part of the State of Santa Catarina and União da Vitória remained in the State of Paraná.

In the early 1980s the Foz de Areia power plant was built 100 km downstream of the cities. The construction of the dam created a lake that influenced the river levels over a long section upstream.

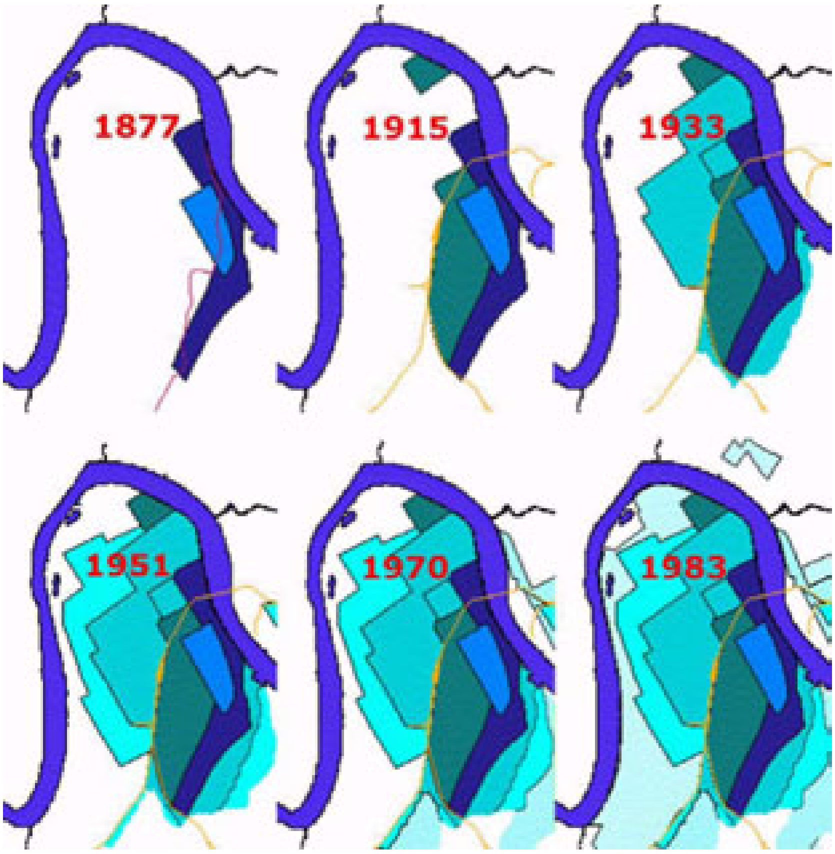


Figure 6.1. Evolution of the cities and settlement of the flood plain

Flooding

The cities of União da Vitória and Porto União grew up on the banks of the river Iguaçu, where for a reasonably long time (1953 to 1982) only small or medium-sized floods occurred. This low frequency, which also occurred in neighbouring watersheds such as the river Itajaí-Açu, prompted the population to settle in the risk area of the flood plain.

In 1983 the cities suffered flooding with a significant impact, with financial losses (figure 2.3) that meant major difficulties for the population and the industrial and commercial firms, some of which never recovered, and others still feel those losses even today, and are unable to make the investments essential for modernization. That flood has the highest water level in 107 years (risk estimated at 170 years and lasting 62 days), with an estimated loss of US$ 78.1 million. At that time, with only the continuously recorded data (1930-1983), it was estimated that the flood could have a return time of some 1 000 years. Nevertheless, these results took no account of the historical flood marks, and the return time was overestimated. In 1992 another flood occurred, less serious than in 1983, but with a similar magnitude and impacts (estimated risk of 50 years, lasting 65 days and losses of US$ 54.6 million). Note that the part of the cities affected by the flooding is an area that is generally well developed, close to the centre and with good infrastructure. This is particularly true of União da Vitoria, which additionally faces difficulties in expanding, limited by the river and Porto União.

Figure 6.2 and Figure 6.3 illustrate the extent of the flooding, the characteristics of the flooded areas; and hence the magnitude of the impact that they had on the population and the cities, quantified in Table 6..

Table 6.1. Estimated losses (in thousands of US$) in União da Vitória and Porto União (JICA, 1995)

	1982	**1993**	**1992**	**1983**
Level	746.06	746.86	748.51	750.03
Direct losses	6 910	17 289	36 388	52 081
Indirect losses (50%)	3 455	8 644	18 194	26 040
TOTAL LOSSES S$ 1 000	10 365	25 933	54 582	78 121

Figure 6.2. União da Vitória and Porto União in normal conditions

Figure 6.3. União da Vitória and Porto União during the 1983 flood

Conflict

In 1983 the population made a simple deduction: "before the dam there was no flooding, and since the dam was built we get flooded because of the dam", and began to regard the Foz de Areia dam and COPEL (the provincial company responsible for electricity generation) as the main culprits of the flooding. This led to a conflict, aggravated by communication problems between the parties. This conflict gradually faded over time until the 1992 flood. Since the population had understood that the risk was very small and a second flood had occurred in less than 10 years, the conflict intensified.

The long period (1935 to 1982) without major flooding had created a false sense of security among the population, who settled the riverside areas. This also led to the flood planning and prevention not being carried out. The 1983 flood sounded the alarm about the risk, but this was underestimated as a result of apparently reliable statistical studies (50 years of data) which nevertheless failed to take account of valuable existing information (the historical flooding marks). When renewed flooding occurred in 1992, of a lower level than in 1983, but of a similar magnitude and impact, a climate of revolt and distrust of the technical studies grew up in the population. In 1993 these conditions led to a non-governmental organization (NGO) being set up, SEC-CORPRERI (Contemporary Studies Company – Regional Standing Committee for the Prevention of Flooding in the River Iguaçu). This NGO has become the main agent of awareness and mobilization in society, and an effective spokesman with all the agencies (municipal, provincial and federal) with jurisdiction on the issue. SEC-CORPRERI’s activities include: (a) education campaigns and lectures; (b) commissioning of studies and technical advice to guide the city; (c) the SEC-CORPRERI action plan: a set of activities and proposals with the specific aim of minimizing the impact of flooding in the region; (d) support for the updating of the master plan.

Studies conducted by CEHPAR at the request of COPEL indicate that neither the Foz do Areia dam nor its operation during the floods influenced the levels attained in União da Vitoria and Porto União. However, the population did not believe in the results of the studies. Independent studies (Tucci and Villanueva, 1997) commissioned by CORPRERI confirmed that the Foz do Areia dam had had no influence on the recent flooding in the cities.

Control measures

Jica (1995) analysed the alternative of building the flood protection dyke for both cities and recommended a feasibility study. Independent studies (Tucci, 1993 and Tucci and Villanueva, 1997) and the discussion with the community eliminated the structural alternative on the following grounds: (a) funding of the works; (b) alteration of the city’s relationship with the river, which is a major factor for tourism. Accordingly, the following alternatives were recommended: (a) zoning of the areas of the cities liable to flooding and implementation of those areas in the master plan; (b) flood forecasting and warning.

The zoning proposal (Tucci and Villanueva, 1997) was to avoid building below the 10-year flood level and to regulate settlement up to the 1983 flood level. Figure 6.4 illustrates the risk areas on which the zoning of the cities was based. The city of Porto União incorporated the measures into law but in União da Vitoria there is still fierce resistance. The real-time forecasting system is operated by COPEL, which notifies the city’s civil defence when warning levels are reached.

Some related measures: (a) the recommendations were to mark the public streetlamps to identify the flood levels and to make the risks public, thereby avoiding real-estate speculation relying on ignorance; (b) construction of houses in lake style so as to live alongside flooding. It is now common to see houses 2 or 3 metres off the ground, as shown in Figure 6.5 (generally alongside others at ground level). Nevertheless, simply looking at many of these houses raises doubts as to the structural strength of the pillars in relation to the oncoming water. Other mechanisms for living alongside flooding that the cities are adopting is the occupation of areas liable to flooding with activities such as leisure areas and parks, to prevent the flood plains being settled (Figure 6.5).

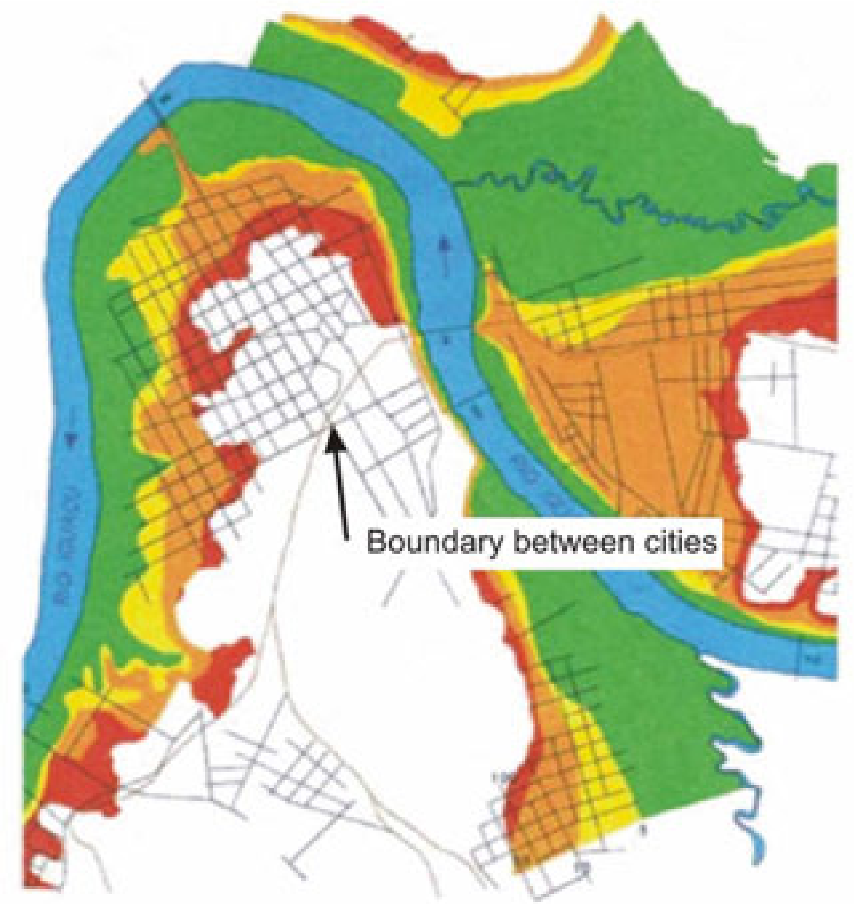


Figure 6.4. Risk areas in the cities of União da Vitória and Porto União

Figure 6.5. Lake-style houses for living alongside flooding. Using the flood plain as a park.

6.1.3. Flooding management in the Metropolitan Region of Curitiba – Brazil

The Metropolitan Region of Curitiba (RMC, State of Paraná, Brazil) has a population of 2.7 million, some 90% of which lives in the cities. It comprises 15 municipalities in an area of some 3 000 km^2, located mainly in the watershed of the upper reaches of the river Iguaçu (figure 6.6). The most populated municipalities are Curitiba, Pinhais and Sao José dos Pinhais. In 1992 an environmental sanitation programme was launched in the region funded by the World Bank, involving both flood-management and sanitation components.

Three stages were defined for flood control: (a) emergency measures tackling visible problems and immediate management; (b) flooding management on the banks of the river Iguaçu that are being reduced by the invasion of risk areas; (c) urban drainage master plan for the metropolitan area.

Flooding of the city of Curitiba and the surrounding area occurs due to a combination of river flooding and urban drainage of urbanized watersheds, flooding the main tract of the river Iguaçu. It is already quite well settled along with its tributaries the Belém, Atuba and Palmital, mainly owing to the urbanization of Curitiba and Pinhais.

Figure 6.6. Metropolitan Region of Curitiba in the watershed of the upper reaches of the river Iguaçu (the brown area represents the urban built-up area).

Control alternatives

Tucci (1996) studied the alternatives for controlling river flooding in the river Iguaçu:

a. *No action:* The alternative of taking no action is not acceptable since this option can lead to significant potential, present and future damage.
b. *Zoning of areas liable to flooding:* This alternative involves defining the flood risk levels for the area concerned, using that flood level map to define the rules for building and settlement of the high-risk areas and implementing them in the municipalities' master plan and building regulations.
c. *Reservoirs:* The reservoirs planned for supplying water in the headwaters of the rivers Irai and Piraquara should attenuate part of the flooding. Note that the watersheds influencing these reservoirs represent a small part of the drainage area, so their effect will be limited, mainly if we consider that the peak flows are influenced more by the more urbanized watersheds. The construction of reservoirs

on the rivers Palmital, Belém and Atuba would hardly be able to attenuate flooding from existing urbanization. The empty spaces will enable parks to be created for distributed attenuation along these watersheds. The use of reservoirs in parks and for water supplies could minimize flooding in watersheds that are still in the rural state, such as the rivers Piraquara, Irai and Pequeño. These measures are part of the long-term plans.

d. *Confining runoff with dykes:* This solution involves transferring the volume of water from the major bed to the minor bed or maintaining a predetermined width. This alternative also certainly means improving runoff in the minor bed and tends to create backwater in the upper reaches. This type of system should consider the following: (1) Drainage of urban runoff from contributing watersheds on each side;(2) Pumping system for forced drainage of lateral areas. In this case attenuation areas have to be provided to allow the use of lower capacity pumps. (3) Municipal maintenance and operation system. This type of system has safety limits for the dykes, and also requires a flood warning system.

e. *Increasing the runoff capacity:* This alternative consists of altering the natural bed of the river Iguaçu by increasing the section and/or gradient of the bed or of building a parallel canal to increase the total capacity of the system. This system can even combine the increased runoff capacity with the building of lateral dykes on some sections.

The solution off merely confining runoff within the minor bed, or even in two canals, implies that the population trusts it and will gradually settle the flood plain, since flooding will be less frequent. There will still be a risk of flooding with low-frequency events. With urban development the upstream watersheds will be settled and there will be densification of existing built-up areas, which will increase flood flow and frequency. When this occurs, there will not be any more space to extend the sections.

Devising control measures

The proposed solution involves extending the natural channel of the river Iguaçu within the RMC and in the downstream section that retains the runoff in the most settled section, building a parallel canal on the left bank beginning downstream of the confluence of the river Irai with the river

Paraquara, as far as the neighbourhood of the Contorno Sur bridge. This canal must create an area in the middle varying between 300 m and 1 km wide, where a public park has been created.

This situation increases the capacity of the minor bed to contain flooding from the tributaries on the right bank and uses a parallel open canal to discharge flow from the tributaries on the left bank and the upstream contribution of the river Irai. As the tributaries on the right bank are those that contribute to the peak flow, the present channel must also be widened to handle this contribution. The parallel channel has the dual function of increasing the runoff capacity and confining the conservation area within a natural barrier.

This reasoning must also be applied in the tributaries so that urbanization does not increase flooding downstream. Riverside areas must be conserved to maintain natural runoff conditions. In certain sections, it may be necessary to create small dykes and lateral drainage in view of the existing urban characteristics which for financial reasons do not allow expropriation and a hydraulic definition of the profile of the channel bottom. Figure 6.7 is a schematic representation of the system’s design features.

The internal park area was (and is being) expropriated at the same time as the building of the parallel canal, since after construction the areas increased in value and expropriation could become unviable, which would result in the settlement of the area between the channels, thereby depriving it of one of its main functions, acting as a barrier to clandestine urban settlement. Besides this, it is essential for the public authorities to create the park to prevent clandestine settlement.

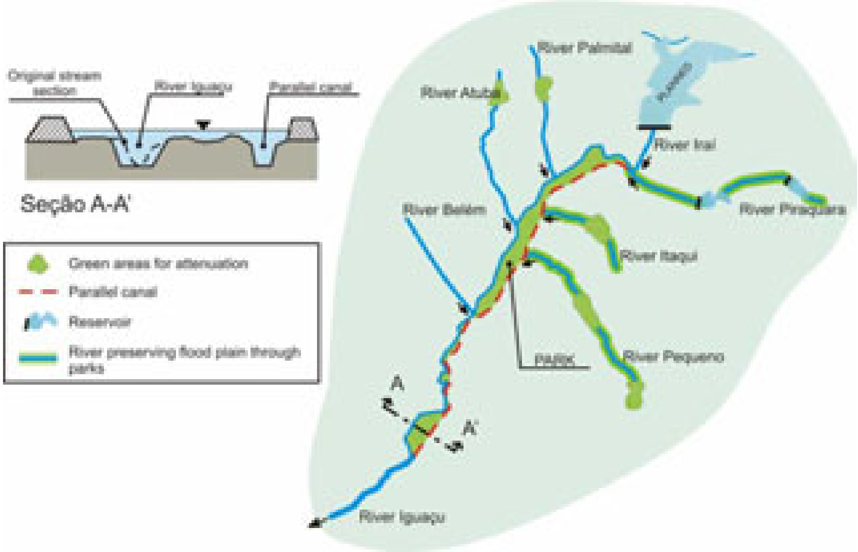


Figure 6.7. Flood control design

Accordingly, the RMC flood control design involves the following action:

- Flood control in the river Iguaçu/Irai by means of a parallel channel and supplementary runoff structures;
- Creation of the Iguaçu park along the section of parallel canal;
- Definition of attenuation areas to be implemented in linear urban parks along the tributaries to prevent urbanization increasing flooding.

The urban drainage master plan for the RMC provides for legislation on the construction of new housing developments, with the aim of preventing unsuitable areas from being settled and natural flooding from increasing.

Figure 6.8 shows the area liable to flooding, urban expansion and the two river beds. Figure 6.9 shows general views with the flooded area of the park that was created and an area already implemented.

Figure 6.8. Characteristics of the areas liable to flooding

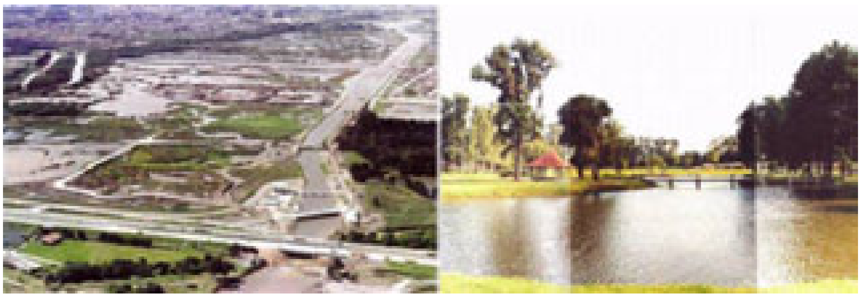


Figure 6.9. Flooded area, parallel canal and park (right)

6.1.4. Flood management in Porto Alegre

Description

The Metropolitan Region of Porto Alegre (State of Rio Grande do Sul, Brazil; population 3 million) is sited on the delta of the river Jacuí and lake Guaíba, with a watershed of some 80 000 km^2 and a confluence of four rivers at the delta that subsequently run into the lake. The city of Porto Alegre, sited on the edge of this system, has its centre next to the harbour, within the delta and on the lake. There are records of the maximum flood levels in Porto Alegre (Figure 2.5) since 1899, showing that there has been major river flooding such as in 1941 (Figure 6.10). In 1970 a dyke was built to protect the city against flooding. This system has a number of sub-watersheds that are drained by means of pumping stations. When the river water level is above street level drained runoff is pumped into the river. This system is operated and controlled by the Storm Drainage

Department of the Municipality of Porto Alegre.

The IPH (2001) presented phase one of the urban drainage master plan for Porto Alegre, aimed mainly at controlling flooding in the urban drainage. The following were produced: (a) Non-structural measures: legal and management aspects;(b) Master plan for three watersheds (a further three watersheds were recently developed);(c) Review of the dyke system with evaluation of the watersheds that drain into the dykes;(d) City urban drainage manual.

Figure 6.10. The 1941 flood in Porto Alegre

The non-structural measures established the maximum outlet flow for each structure and an estimate of the volume per housing development. A decree for the control of housing developments was also proposed. These are set out in annexes B and D. An analysis was also made of the recovery of costs for urban drainage, introducing a formulation for levying charges, set out in annex C.

The plan for each watershed followed the methodology described in chapter 5, i.e.(a) evaluation of the runoff capacity of the drainage system;(b) identification of areas liable to flooding;(c) combination of detention and increase in runoff capacity, endeavouring to keep the outflow equal to the current capacity for the future scenario;(d) check of scenarios exceeding the design values. The city had a detailed inventory of the drainage: level, diameter and length of each conduit on a 1:2000 scale plan, together with the topography of the city. This made it possible to detail the whole system in the sub-watersheds.

Figure 6.11 illustrates the watersheds (in green) that have their runoff pumped into the neighbouring rivers and the watersheds that run off by gravity (brown). The watersheds that converge on the pumping stations were simulated and a check was also made of the pumps' capacity to handle all the runoff during flooding. Below we present the results for the Areia watershed that was studied in the plan (IPH, 2001) and its recent update by Cruz (2004).

Figure 6.11. City of Porto Alegre bordering on the Jacuí delta and lake Guaíba. Runoff from the green areas is pumped into lake Guaíba when the dyke protects them from flooding. Runoff from the brown areas takes place by gravity and in conduits under pressure.

The Areia watershed – Porto Alegre – Brazil

The watershed is in two parts, the upper section (12 km^2) that drains in conduits under pressure above the 9 metre level directly into the river Gravatai, and a second part of a similar area that is drained by pumping (in the area of the airport). Figure 6.12 is an image of the two parts of the watershed and the same figure also shows the division of the watershed (11 sub-watersheds) and represents the drainage system. The simulation of the project scenarios identified the places liable to flooding at various risk levels. This alternative study was initially carried out by trial and error on the basis of the available places and the increase in the drainage capacity. Recently, Cruz (2004) revised the study and obtained a new specification on the basis of the optimization model.

Figure 6.13 shows the chosen detention basins, while figure 6.14 plots the hydrographs comparing the following solutions: (a) canalization of the system without considering the cost of enlarging the conduit passing through the airport; (b) combination of detention basins and enlargement to maintain the same downstream flow. Two alternatives were used in this case: optimization of the whole watershed and optimization by sub-watershed. Note that the best result was obtained by simulating the whole watershed.

Table 6.2 compares the two main alternatives, showing that the alternative with a detention basin costs less and does not increase the downstream flow. It was noted that in this watershed 77 m^3/ha were used and some 74% of the watershed's area with attenuation. In addition to detention basins, the conduits were extended to carry the runoff to the detention basins. The costs were broken down as follows: 79% to extend the conduits, 17.7% for the detention basins and 3.3% for expropriation.

Table 6.2. Comparative analysis of the alternatives

Variable	Canalization	Detention basins and extension
Peak flow (m^3/s)	99	48
Storage volume (m^3)	0	73 552
Cost of implementation (R$ million)	60.3	39.6
Cost per inhabitant (R$)	364.8	239.8

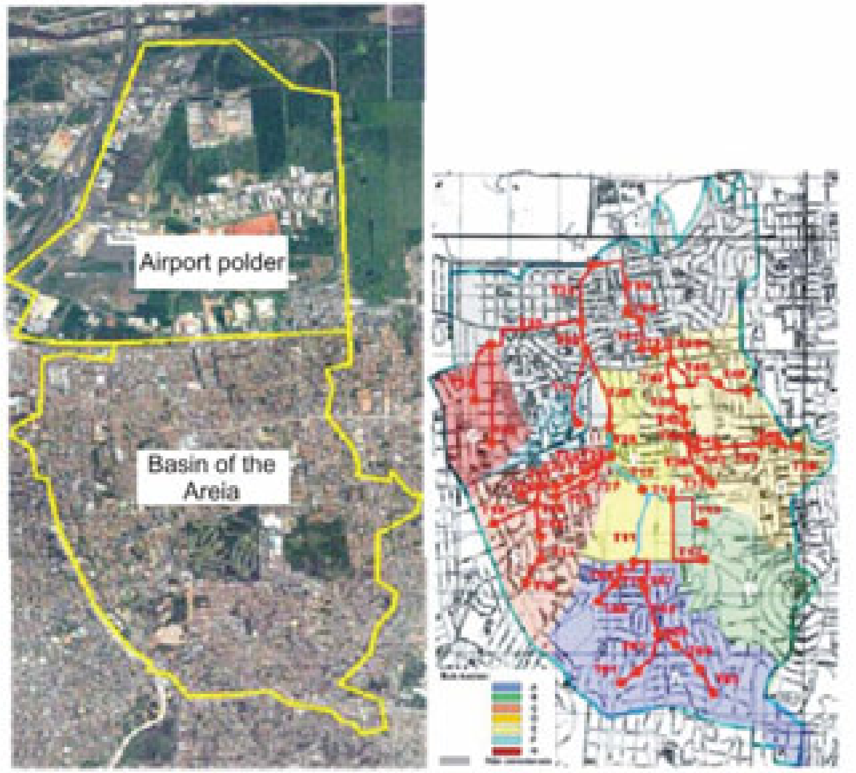


Figure 6.12. Image (left) of the Areia watershed together with the airport polder, and image (right) of the sub-watersheds with simulation of the drainage system (Cruz, 2004).

City drainage scenario

Cruz (2004) analysed the scenarios for the development of the urban drainage taking account of the following: (a) prior control: for an integrated planning scenario, i.e. implementation of an urbanized area together with the controlled drainage area; (b) post-hoc control: for a consolidated urbanization scenario.

Starting from the mean values obtained for the prior and post hoc scenarios an application was carried out in the municipality of Porto Alegre as a form of analysis of the planning carried out and to be carried out over the next 20 years, by comparing the costs involved. The city has 27 sub-watersheds and covers 430.27 km^2 and an expected population for the municipality of 1.8 million in 2025. Analysing the development that has taken place, we found that the post hoc control scenario costs 6.4 times more than prior control. Also considering the city's future urban development it was estimated that using canalization, the costs would be R$ 790 million (in real terms), while with control by attenuation the cost would be R$ 303 million at present-day values for a 20-year project.

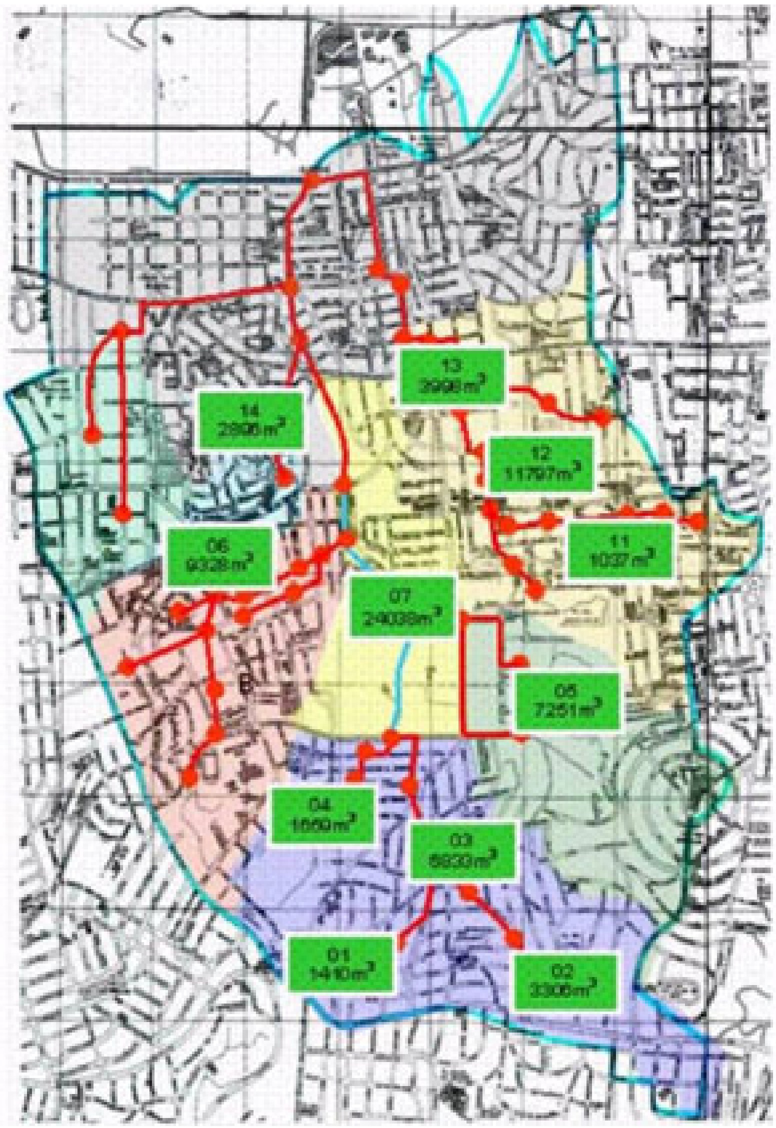


Figure 6.13. Detention basins planned for the Areia watershed (Cruz, 2004).

6.1.5. Brazil’s storm water plan

Brazil’s Ministry of Cities is devising a national storm water plan (Tucci, 2005), the main aspects of which are described below. This information is liable to change depending on future discussions within the Government. For more details, see the reference quoted above.

Objectives and principles

The proposed storm water programme aims to reduce the population’s vulnerability to river flooding and flooding from urban drainage, minimize environmental impacts by means of an institutional, economic and technical policy and introduce an action plan for the management of storm water in conjunction with the other elements of urban development in Brazilian cities. The principles are set out in Chapter 5.

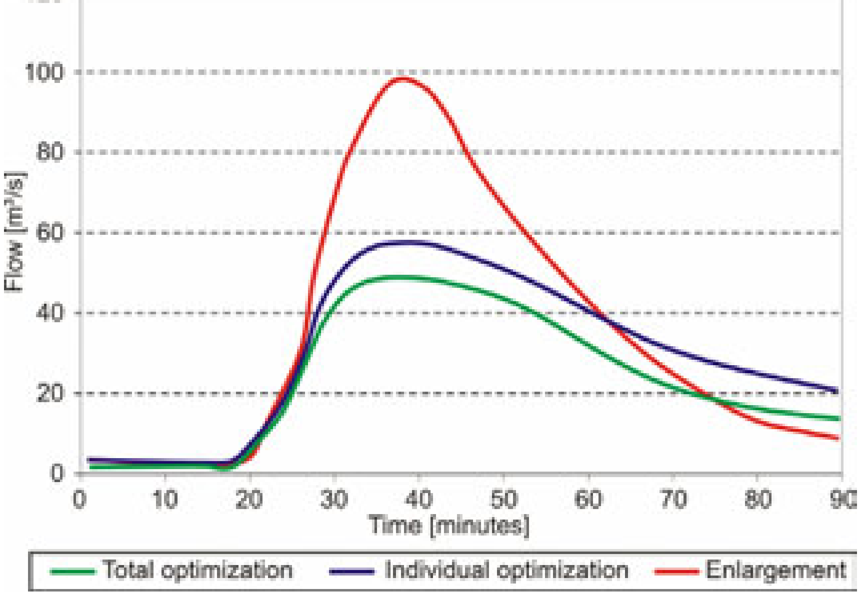


Figure 6.14. Comparison of hydrographs for the alternatives for the Areia watershed (Cruz, 2004).

The programme is based on the following elements:

- **Institutional:** covers the legal, management, training, science and technology and data aspects;
- **Technological:** emphasizing quantity and quality, this covers the technical aspects required for sustainable management;
- **Economic and financial:** covers the economic and financial viability aspects of storm water management;
- **Public participation:** covers the potential mechanisms for increasing public involvement in the implementation of the programme;
- **Action plan:** using the basis proposed in other plans, it sets out the action plan for the Ministry of Cities that is implementing the programme.

Structure

The proposed programme has the following basic levels for carrying out the measures under these elements, in accordance with current Brazilian legislation: (a) federal or provincial; (b) municipal.

At federal level (federal watersheds) controls outside the city are laid down by law. This legislation will encourage the provincial agencies to regulate provincial watersheds in the same way. Management can be divided in relation to:(a) inspection of approved uses; (b) running of the support programme for riverside areas based on prevention and warning; (c) funding;(d) technical support; (e) training and; (f) science and technology.

The legislation will prompt the municipalities to devise an environmental sanitation plan covering storm water, associated with the master plans of the cities and their implementation over time. At the municipal level the plan will have to incorporate land-use and urban-drainage components in the legislation, preparation of action plans by urban watershed for solving the current problems and short-, medium- and long-term programmes. Management will involve inspection and implementation of the plan with funding from the national programme.

Institutional

The institutional elements are the foundation on which the structure of the programme is built. These elements are broken down into: legal, management, training and science and technology. The legal elements draw up the proposal to pass legislation to underpin the programme; management establishes a basis for action by the agencies involved in implementing the programme; training and science and technology provide support for the staff and knowledge acquisition.

The urban drainage control policy involves two environments: outside and inside the city (see Chapter 4). There is a close interrelation between the elements of land use, environmental control and water resources, both within the city and in the watershed plan. The city management is controlled by the monitoring of what the city exports to the rest of the watershed, fostering its internal control using legal and financial means. The internal process within the cities is essentially a task of the municipality or of consortia of municipalities, depending on the characteristics of the urban watersheds and their development.

6.1.6. Regulation of control outside the city

Regulation mechanism: Law No 9433 on water resources, in Article 12, the section on approved uses, states that the following are subject to approval:

> *"III – discharge or sewage and other effluent into water courses..."*
>
> *and*
>
> *"V – other flows that impair the quantity and quality of the*

> *water in watercourses".*

It is the responsibility of National Water Resources Council to regulate the approval law in accordance with Article 13 of Law No 9433 of 8 January 1997 and Article 1 of Decree No 2612 of 3 June 1998. In Resolution No 16 of 8 May 2001 the Council defined the bases of approval. Article 12 states that approval must be in line with the water resource plans. Article 15 states that approval

> "for the discharge of effluents shall be granted for a quantity of water necessary to dilute the contaminant load, which may vary over the period of approval, on the basis of the water quality standards corresponding to the class of the recipient watercourse and/or specific criteria laid down in the corresponding water resource plan or by the competent agencies".

Article 12 V of Law 9 433 and Article 4 V of the Council resolution explain that approval is required for:

> *"other uses and/or interferences that impair the regime, quantity or quality of the water in a watercourse".*

In this way we observe that water resource legislation allows the introduction of regulation for controlling effluent in urban areas by means of approval, to the extent that runoff from those areas is shown to impair the quantity and the quality (see previous chapters). This regulation can thus be implemented by means of a resolution of the National Water Resource Council.

Justification for regulation by means of approval: Control outside the city has the following objectives:

- To maintain the water quality in downstream rivers for each class of river;
- To avoid impacts due to flooding of the urban drainage and riverside areas.

The first of these objectives is clearly defined under the approval conditions, in that urban areas impair water quality; therefore, a city that discharges into downstream rivers requires approval. Quantitative impacts caused by urbanization (changes in peak and volume) are also subject to approval in that urban areas "impair water quantity and quality". However, it would not be correct to use the approval mechanism as an incentive for the process of controlling urban river flooding. Since:

- the Constitution provides that the Federal Government must take action to prevent flooding and drought, which is also laid down in Article 3 X of Law No 9984 of 17 July 2000:

> *"plan and promote measures aimed at preventing and minimizing the effects of drought and flooding, under the National Water Resource Management System, in liaison with the National Civil Defence System, in support of the provinces and municipalities".*

- river flooding can also be caused by alterations in the major bed as a result of buildings throughout the city, the approval mechanism is also justified here.

Elements for regulation: It is possible to establish approval standards through the National Water Resource Council as a control mechanism outside the city to encourage the municipalities to devise measures within their own territory.

Some of the fundamental elements for drafting these regulations are:

- The proposal for a resolution must contain the basic parameters required for approval of urban effluent as a whole and not only urban drainage, since the impacts caused by sewage, urban drainage and solid refuse cannot be treated separately;
- It is not possible to require permits from all cities in the country in the short term, as not all the effective measures would be feasible and there would not be enough resources to fund the preparation of planning and control simultaneously;
- The approval rules must lay down procedures and goals in the planning of the measures according to the class of river being planned.

To resolve the first item mentioned, the resolution must request a municipal environmental sanitation plan: water supply, sewage, urban drainage and solid refuse (in accordance with the bill being prepared) and lay down standards that the municipalities must comply with in order to obtain approval. These standards must be laid down and will be the basis for the drafting of the environmental sanitation plans. To resolve the second item it is proposed to use deadlines depending on the size of the cities. The data are provisional and renewable in accordance with the deadlines and compliance with them. The third item is resolved by setting goals associated with the approval of the effluents in accordance with the programme goals.

The proposal was prepared taking account of the distribution of the cities in the country and the burden on the population. The Government's ability to fund the programme has not been assessed as this is a more political issue. This proposal should therefore be used as a basis for discussion. The important thing about a programme of this type is to draft it with goals that allow one to see the “light at the end of the tunnel” in terms of urban pollution.

Table 6.3 distinguishes four classes of municipalities according to the city’s population. As we said in the earlier chapters, the main problems are in the larger cities. There are 30 municipalities with at least 500 000 inhabitants, representing 27.25% of the Brazilian population. There are 190 municipalities with between 100 000 and 500 000 inhabitants, accounting for 23.68% of the population. There are therefore 212 municipalities with a population exceeding 100 000 inhabitants, accounting for a total of 51.13% of the population. Most problems with urban effluent occur in this segment of the country.

Accordingly, we propose that the municipalities’ measures be spread over time in accordance with the stages set out in Table 6.4. The stage of preparing non-structural measures involves the approval within the municipality of the regulations for controlling the impacts of new developments in terms of the various elements relating to environmental sanitation. The concluding phase of the plan is the finalization and approval by the municipal authorities. The conclusion is defined as the phase in which the municipality achieves the goals set out in the plan. Approval is to be granted for a given period, always subject to the results of the operation and maintenance of the treatment systems and the control of the environmental impacts. This later phase involves inspection of compliance of the operation and maintenance of the systems over time.

The programme would be implemented by granting approvals in accordance with the above-mentioned goals and renewing them providing they were complied with. The programme should introduce a tax break for municipalities attaining the goals before the deadline and penalties relating to the release of federal funds to municipalities that fail to attain approvals.

Regulation involves the following:

1. Preparation of the resolution to be proposed to the National Water Resources Council based on the same phases as described above;
2. Establishment of standards to be observed in the integrated plans of the municipalities that adopt the resolution. A manual should be drafted for preparing the plans, results of the implementation of the works and procedures for

monitoring the operation of the treatment and control systems outside the cities.

Table 6.3. Population distribution according to the 2000 census, based on IBGE data.

Cat.	Classification of municipality P = population	Number of municipalities	Proportion of total %	Population in millions	% of population
A	P > 500 thousand	30	0.54	45.257	27.25
B	100 < P < 500 thousand	192	3.49	39.337	23.68
C	20 < P >100	1224	22.23	48.155	28.99
D	20 < P thousand	3061	73.74	33.363	20.08
	Total	5507	100	166.112	100

Table 6.4. Phases and criteria of effluent approval

Phase	Category of municipality	Approval period (*) years	Cumulative period from start	Renewal constraint
I	A B C D	2 3 5 7	2 3 5 7	Environmental sanitation plan begun
II	A B C D	1 2 2 2	3 5 7 9	Non-structural measures implemented
III	A B C D	2 2 3 5	5 7 10 14	Environmental sanitation plan completed and works started
IV	A B C D	6 6 7 10	11 13 17 24	Works completed and goals attained
V	All	3	11 to 24	Approval reviewed every five years in accordance with city indicators

(*) the number of years of each activity must be conditional upon the Federal Government’s funding ability.

Investment

Cost estimates are based on the population and area of the urban watersheds. At this stage the areas of the urban watersheds for all the cities are not available for this analysis and the estimate was made using a unit value based on population. This value varies with the state of urbanization of the cities. For central urban watersheds with serious space problems and a large number of runoff transit structures, the value is of the order of R$ 235.00/inhabitant, while in medium-density watersheds with more space the costs are of the order of R$ 125.00/inhabitant. For smaller cities the value of R$ 80.00/inhabitant was adopted. In category A cities the cost of central areas was adopted for 35% of the population and the costs of medium-density areas for the remaining 65%. In category B cities the proportions adopted were 20 and 80% respectively. The medium-density value was adopted for cities in category C and the low-density value was adopted for category D. Table 6.5 shows the estimated totals for the works, the whole works programme costing some R$ 20.36 billion.

Table 6.5. Costs of plans and control structures for a 10-year risk.

Category	**Classification of municipality P = population in thousands**	**Population in millions**	**Estimated costs of works million R$**	**Cost of plans million R$**	**Total cost million R$**
A	P>500	45.257	7252.4	362.6	7 615.1
B	100 < P < 500	39.337	5 6215.2	281.25	5 906.5
C	20 < P >100	48.155	4 815.5	240.8	5 056.3
D	P <20	33.363	2 669.0	133.5	2 802.5
	Total	166.112	20 362.2	1018.1	21 380.3

6.2. Urban flooding in Argentina

Introduction

Argentina very often suffers flooding with serious consequences. The statistics indicate that on average one event in ten is serious. The World Bank (2000, *apud*, Bertoni, 2004) classified flooding in Argentina into four types, by geographical region: a) in the major river valleys, (b) in the foothills of the Andes, (c) in cities and rural areas subject to flash floods and (d) on the plains, linked to improper management of natural resources, especially the soil and vegetation. The first type of floods are important owing to their duration and the severity of their effects. They normally occur in the major rivers of the Plata watershed, the fifth largest in the world. This important region produces over 76% of the country’s GDP and houses 70% of Argentina’s population.

Approximately 90% of Argentina’s population is located in urban areas, which places it among the countries with the highest urban concentration in South America. We present below cases of urban flooding that occurred in the cities of Buenos Aires, Córdoba, Santa Fe and Trelew, along with particular floods that occurred in the mountain locations of San Carlos Minas and Villa Carlos Paz.

6.2.1. Flooding in the city of Buenos Aires, Argentina

Buenos Aires and its conurbation (17 districts forming the "Conurbano Bonaerense") has a population of some 12.5 million, ten times higher that Rosario or Córdoba (the nearest two cities in terms of urban concentration). The Buenos Aires metropolitan area covers approximately 700 km^2. The region with the highest density houses almost 15 000 inhabitants/km^2 (Maza *et al.*, 2004).

The Conurbano Bonaerense is home to 24.5% of the country's population and 63.3% of the province of Buenos Aires. Taken together with the city of Buenos Aires, it accounts for 41% of the country's total population, with an average population density of 2 165.6 inhabitants/km^2, so forming the third largest urban agglomeration in Latin America. It has a dominant effect on the whole country. The phenomenon even exceeds the concentration observed in other regions of the world (

Table).

Figure 6.15 illustrates the geographical expansion of Buenos Aires and its surroundings. The mean population density of the the Argentine capital is currently 150 inhabitants/ha and the green areas attain 0.6 m^2/inhabitant compared with 15 m^2/inhabitant recommended by the World Health Organization (C*larín, 23-09-00*).

Table 6.6. Large metropolises as a proportion of the urban population and total population of each country, 1990.

City	Percentage of the country's urban population	Percentage of the country's total population
Buenos Aires (Argentina)	41	36
Seoul (South Korea)	35	26
Mexico City (Mexico)	33	24
Cairo (Egypt)	39	17
Tokyo (Japan)	19	15
Paris (France)	21	15
Manila (Philippines)	29	14
London (United Kingdom)	14	13
Brussels (Belgium)	10	10
Lagos (Nigeria)	23	8

(Source: World Bank Indicators, 1995).

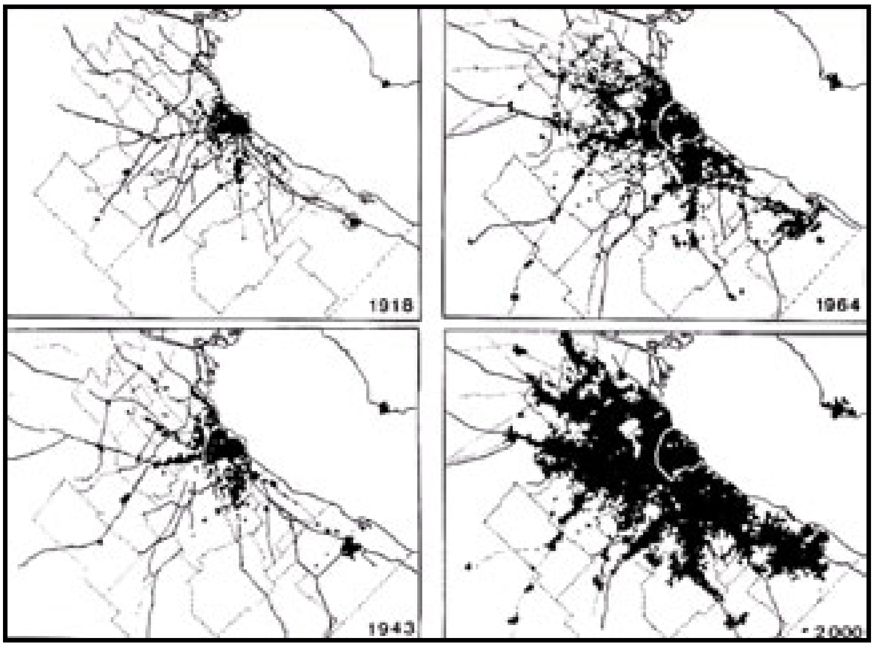


Figure 6.15. Growth of Buenos Aires and its conurbation. (Source: Guglielmo, 1996).

The constant, unplanned growth of the city of Buenos Aires, the lack of investment for over half a century and the change in the precipitation pattern, have rendered obsolete a drainage system that was exemplary in its day (Maza *et al.*, 2004).

In recent decades Buenos Aires has suffered frequent flooding, resulting in serious problems and considerable material damage. Falczuk (2001) points to the basic causes: (a) natural flooding of the watercourses that cross the city and the structural problems of the drainage system, the capacity of which has been exceeded by unplanned settlement of the flood plains and (b) strong south-easterly winds ("*sudestadas*") that cause higher water than the normal average in the River Plate, flooding the coastal areas. We should point out that with the prevailing weather conditions in the city of Buenos Aires it is rare for both effects to occur simultaneously, in other words short heavy rains rarely coincide with south-easterlies. From 1985 until March 1998 some 26 flood events occurred in the Buenos Aires metropolitan area due to rainfall and overflows from the drainage system. One of the most serious storms occurred on 24 January 2000 (Figure 6.16 and Figure 6.17), leading to loss of human life and serious financial losses.

Figure 6.16. Flooding in the city of Buenos Aires (January 2000). Intersection of Avenida Cabildo and Blanco Encalada. (Source: www.clarin.com.ar)

Figure 6.17. Flooding in the city of Buenos Aires (January 2000). (Source: www.clarin.com.ar)

Both subsystems were designed for a population and a population density much lower than the present values, assuming a city with open building, non-impervious areas and a low runoff coefficient. Nowadays, the high percentage of directly connected impervious surfaces, the low gradients and the large size of the watersheds makes drainage a complex issue when there is heavy rainfall.

The city currently has a complete drainage system that discharges into the River Plate. It comprises two subsystems covering two main areas: (i) *Radio Antiguo* and (ii) *Radio Nuevo*. The former is a mixed storm drain and sewage system covering about 3 000 ha; construction began in 1869. In the sector known as *Radio Nuevo*, the storm drain system was built after the sewage system, meaning that an extensive and populous region of the city was for years exposed to the effects of flooding as a result of overflows from the main streams crossing it (Maldonado, Vega and Medrano). These streams were subsequently enclosed, and a system of smaller conduits was added to the current drainage system.

Both subsystems were designed for a population and a population density much lower than the present values, assuming a city with open building, non-impervious areas and a low runoff coefficient. Nowadays, the high percentage of directly connected impervious surfaces, the low gradients and the large size of the watersheds makes drainage a complex issue when there is heavy rainfall. In summary, throughout its history, the city of Buenos Aires has handled flooding with a disaster mentality, i.e. as something that can be tackled and solved only after the event. Every catastrophic flood is the result of a continuous, daily process of social accumulation of risk. In this process urban management plays a fundamental role in terms of both flooding and of the policy on the use the land which, as in the lower watershed of the Maldonado, is at high risk of flooding.

Need for comprehensive urban flooding management

The city of Buenos Aires has always considered a single solution to urban management of flooding: the construction of engineering works which are necessary but not sufficient. Specific examples are the works carried out in the Maldonado stream: the closure of the main outlet and the removal of an old road bridge (at the intersection of Avenida Juan B. Justo and Santa Fe) were palliatives that helped to increase the flow capacity in the canal, but did not prevent flooding (Maza *et al.*, 2004).

Regarding the management of settlement in the city (town planning instruments), it is clear that at no time did the city of Buenos Aires consider flooding risk as a key factor in deciding land zoning and land-use intensities. Specific examples of this are the permissiveness of the relevant codes in relation to increases in settlement factors and the construction of basements beside a canalized former stream.

The two types of management were independent of one another: the first controlling the city hidden beneath the asphalt, the second controlling the visible city. A valid alternative that would aim to mitigate catastrophic flooding is the integration of both types of management, complementing the construction of engineering works with an urban policy able to redefine the guidelines for settling areas at risk of flooding. Such an integrated management system should also include mechanisms for communicating actual risks, as a means of linking together all the players involved.

In order to optimize the operation of the existing storm water system, and design structures that improve the city's ability to handle flooding, the municipality focused one of its lines of action on devising the flood protection programme (with funding from the World Bank), the core of which consisted of:

- The master water control plan, which covers the planning of the operation of the drainage system for the whole city using the latest technological tools, the design of new structures for a 50-year planning horizon, and the development of an additional set of standards and procedures to make the city less vulnerable to water-related disasters;
- The drafting of the executive project for the Arroyo Maldonado watershed, including the tender documentation for the execution of the works.

The master plan is the second scheme for planning the city's water system in more than 100 years. It includes mathematical modelling of all the city's watersheds and can simulate and forecast the operation of the urban storm water system in various circumstances.

The master plan must be an effective planning tool and the basis of the investments in public works and for adopting "soft measures" designed to optimize flood control for the next 50 years. Moreover, it must contain instruments for improving the technical management in the municipality's water department. Examples of soft measures are the management of green spaces and public woodland, use of porous and absorbent materials in certain types of building, management of emergencies, zoning of areas liable to flooding, and institutional improvements, among others.

Side effects of urbanization: rise in groundwater levels

A phenomenon of increasing concern is the gradual rise of groundwater levels in the Buenos Aires conurbation. Since the early 1980s problems began to appear in buildings below ground level (basements, underground car parks, vaults, etc.) owing to flooding caused by a rise in the water table.

The region's hydrogeological system is formed of a first aquifer (water table) and another underlying one that is semi-free (Pampean) behaving as a single entity. Beneath them and separated by a low-permeability stratum (aquitard) is a semiconfined aquifer (Puelche), the main source of water for the public water supply, industrial use and agricultural irrigation in the region. The remaining element of the hydrogeological profile is the Paraná aquifer, located at a deeper level (Figure 6.18). The water table is the transition element for meteoric recharge. The importance of the Pampean lies in the fact that it acts as a route for recharge and discharge of the underlying Puelche sub-aquifer, which is the area's most important hydrological unit. The top of the Puelche is located at a depth of between 25 and 50 m (depending on the geographical position) and it varies between 15 and 30 m in thickness.

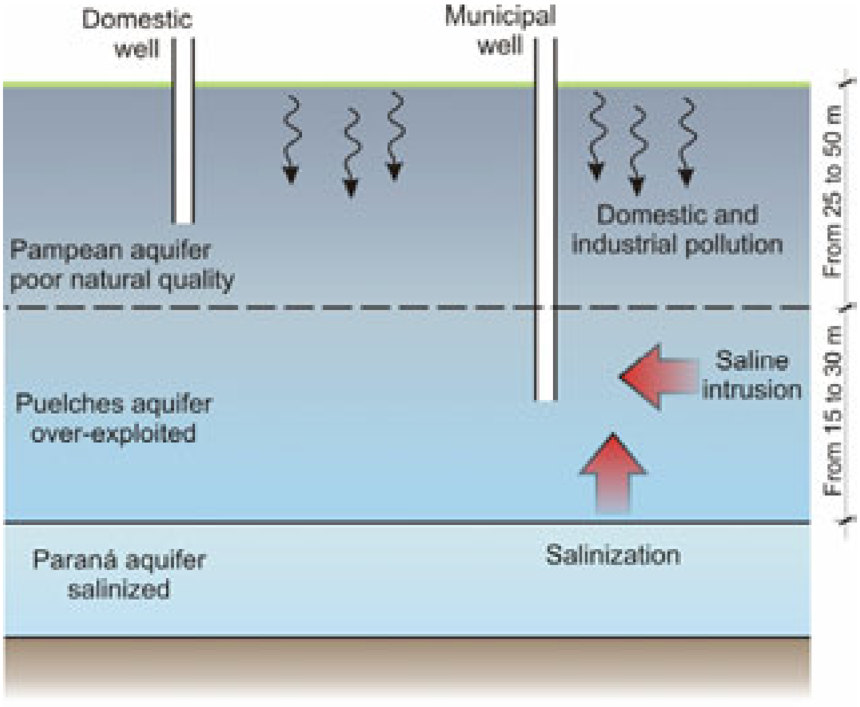


Figure 6.18. Aquifers and contamination issues in the Buenos Aires Metropolitan Area (Source: *Argentina, Water Resources Management*. Report No 20729- AR. World Bank, 2000).

The exploitation of the Puelche aquifer since the end of the last century led to over-exploitation, with a pronounced drop in water levels (piezometric levels) and in many cases with intrusion of saline water. These falling levels in turn brought down the water levels of the aquifer above (phreatic levels) through a process known as "vertical downward filtration" until the phreatic aquifer disappeared in critical positions.

It was in those conditions (depressed phreatic levels) that the greatest urban-industrial development took place in the conurbation. Already in the period 1970-1980, owing to the excessive depression of the Puelche, saline intrusion and/or the presence of nitrates in excess of potability standards (associated with the lack of basic sanitation or leaking sewage pipes), water supply wells began to be abandoned thereby enabling the piezometric levels to recover.

This recovery led in turn to a recovery of the phreatic levels, as the vertical downward filtration reduced substantially, returning almost to the original situation. As the water table rose it came up against a new sub-surface building infrastructure, leading to increasingly frequent flooding.

Furthermore, the deficit of water caused by drawing water from the wells was replaced by a contribution from three plants located in the conurbation (a project popularly known as “underground rivers”).

This additional incoming water, and the deficit in the sewage disposal systems, made a significant contribution to the raising of the water table. It was also influenced by leaks from the water mains and sewage and drainage systems.

There are currently serious contamination problems in both the water table and the semi-free Pampean aquifer owing to intensive use of domestic sewage effluent discharge systems. As stated previously, an example of this problem is in the municipality of Lomas de Zamora (a southern sector of the Buenos Aires conurbation).

The district of Lomas de Zamora has five localities: Lomas de Zamora, Banfield, Turdera, Llavallol and Temperley. It has an estimated population of 634 450 (year 2000) and a population density of 71.28 inhabitants/ha.

Ballester and Alvarez (2001) report that in the early 1990s the district supplied 67% of its population with running water, from borings into the Puelche sub-aquifer and surface water from the River Plate, after treatment for use as drinking water. The population served by the sewage system was 22.7% of all dwellings.

In 2001 some 30% of all dwellings in the district were connected to the sewage system, while 98% of the population had running water. The increase in this latter percentage was achieved by importing water into the system from the River Plate. From mid-1997 a gradual rise in the first water table was observed in the municipality of Lomas de Zamora, as in other parts of the autonomous city and conurbation of Buenos Aires, leading in some areas to a real water and sanitation emergency.

According to Ballester and Álvarez (2001), from 1998 to 2001 some 800 extraction pumps were installed in the municipality of Lomas de Zamora (as a palliative measure) which lowered the water table by controlled pumping.

6.2.2. Flooding in the city of Córdoba, Argentina

Development of the city and problems with storm water drainage

Set on the flood plains of the river Suquía, the city of Córdoba (population 1.4 million; 398 m asl) has developed throughout its history in line with a typical urbanization process: uncontrolled increase in impervious areas, settlement of areas liable to flooding and use of structural measures only.

Other factors that have helped to aggravate the problem of urban flooding are the region's undulating relief and the trend towards the gradual urbanization of the highest districts. As a result, the lower central districts, which used not to flood, have for some years been suffering serious flooding problems (Figure 6.19 and Figure 6.20).

Figure 6.19. Flooding in Córdoba's central district (calle La Pampa)

Figure 6.20. Flooding in Avenida Vélez Sarsfield (central district) of the city of Córdoba (Source: newspaper La Voz del Interior).

Another characteristic of note is the natural tendency of the adjoining rural watersheds to drain into the currently urbanized area of the city. Since 1987 there has been a growing trend in the increase of areas for farming and urban use. In the neighbouring rural area the native woodland has increasingly been cleared, while the remaining woodland has been seriously damaged by fire, indiscriminate felling, etc. The damage to and/or elimination of the natural vegetation and the continued working of the soil using techniques that are inappropriate for conservation has given rise to a continuous rise in the volume of runoff (and the associated peak flows) generated by heavy rainfall. The water problem has become more acute with the development of a road and urban infrastructure that has not taken account of all the characteristics of the natural water system.

The worst situations occurred in the early 1990s when there was a very wet period. Various outlying districts of the city, generally located in areas with a high probability of flooding, were hit by surface water from the neighbouring rural areas.

Since 1982 the municipality has taken action under the city's storm water master plan, which is regarded as a fundamental milestone in the understanding of its storm drainage problem (Esteve, 2001). The plan divided the city into 34 watersheds and a complete preliminary design of the drainage system for each watershed, specifying the main and secondary conduit dimensions. As reported by Esteve (2001), the city's development altered the original plan, changing priorities and increasing requirements, as building, commercial and industrial projects formed new centres of development within the city. In 1995 the main drainage plan was readjusted to take account of the requirements for that year, with forecasts up to 2004.

In summary, all the types of flooding affecting the city (river, urban, rural origin, etc.) made up a complex picture of the situation that forced the municipality to build storm-water control structures during the 1990s.

Experience of urban storm water runoff in the city

As part of its urban storm water management, in the early 1990s the city of Córdoba built in the principle of attenuating peaks in storms so as to delay the incoming flow and optimize the existing drainage system. Toya *et al.* (2003) presented a preliminary diagnosis relating to the first 10 years of managing retardation basins in the city. We set out below the main aspects of that diagnosis.

The authors report that during the early years of the study, adaptation and awareness-raising for decision-making, in both the private and public domains, in 1995 construction began of the first urban retardation basins.

The design and construction parameters were gradually adapted as specific cases arose with new constraints. This led the municipality to require the drainage studies to include a feasibility analysis and to specify the retardation basins for each type of structure. The measure was used to compensate for the rapid advance of urbanization in relation to a slowdown in public investment for the building of main storm-water trunk lines.

From a basic analysis of the existing documents the authors summed up the situation in the city of Córdoba in 2003 as follows:

- There are four retardation basins totalling 26 ha. constructed and operated by the municipal administration.
- A number of retardation basins associated with new urban developments, totalling 74 ha., are at the design stage. They will gradually be handed over to the public domain.
- These are 22 retardation basins built and maintained by private enterprise, mainly associated with industrial plants, amounting to another 2 ha set aside for this purpose.

In making the diagnosis the authors analysed 13 retardation basins built during the first 10 years of experience with these structures. Figure 6.21 shows the location of most of the structures built and planned.

The following characteristics were analysed:

- surface area,
- connected system,
- design specification,
- concurrent uses,
- maintenance,
- presence of stagnant water, refuse, sediment,
- presence of flies, mosquitoes, rodents or other animals,
- records of related accidents or other hazardous events (rupture of walls, overflows, contamination with other kinds of effluents, etc.),
- appropriation of space regarding landscaping and maintenance undertakings (public or private).

Figure 6.22, Figure 6.23 and Figure 6.24 illustrate the characteristics of some of the structures built in the city.

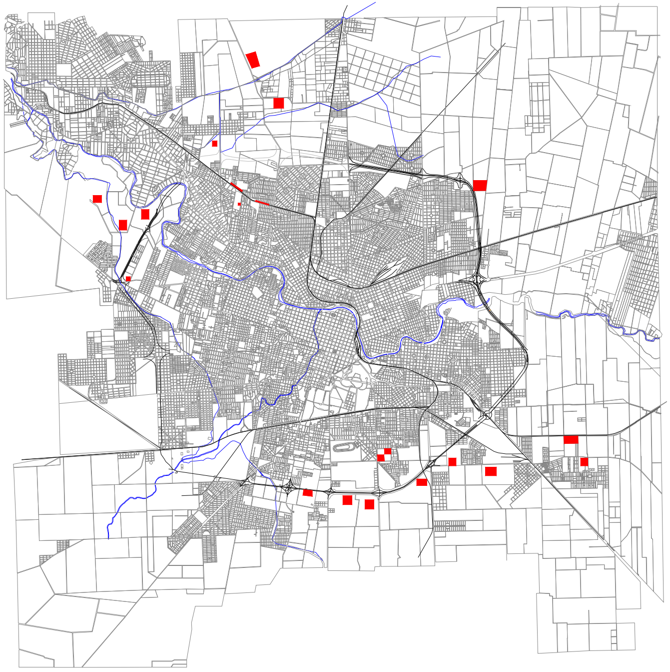


Figure 6.21. Location of retardation basins for urban storm water runoff in the city of Córdoba, Argentina (Source: Toya *et al.*, 2003).

Figure 6.22. Detention basin built for a private project. Córdoba, Argentina (Source: Toya *et al.*, 2003).

Figure 6.23. Detention basin built for a private commercial project. Córdoba, Argentina (Source: Toya *et al.*, 2003).

Figure 6.24. Large detention basin built by the public sector.

From their analysis of all the information compiled and their own experience in the city, Toya *et al.* (2003) concluded their diagnosis as follows:

- The drainage system of the city of Córdoba currently has 28 ha of retardation basins to attenuate surface flows. This area rises to 102 ha if we include the retardation structures associated with new urban developments (at the design stage).
- On-site observation during rainfall events and an analysis of reports indicate that so far there have been no problems with the hydraulic operation of these structures.
- The basins constructed are linked to existing storm drains, which act as a collector system. A small number of the planned structures discharge by overflowing into ditches.
- Most basins have so far been built by private enterprise, generally linked to large industrial plants, supermarkets, etc. These are generally small structures, each with its own maintenance. In some cases, as a result of a good maintenance plan, there is very good integration with the surrounding urban environment.
- The larger basins have so far been built and maintained by the municipality. They typically present a worrying environmental problem: contamination by liquid and solid residues that cause odours and may carry disease (grey water, accumulation of refuse, etc.), deterioration of the infrastructure (erosion of banks, sedimentation, etc.) and presence of weeds and mosquitoes. In short, they are poorly integrated into the urban and suburban

environment.

- On the other hand, the smaller public basins are better integrated with their surroundings, thereby minimizing the above-mentioned problems.

When diagnosing the prevailing situation, the authors recommend the following:

- In the case of the public basins located in the outlying areas of the city (generally close to districts in critical socio-economic situations) there is a serious need for awareness-raising and education measures with a view to informing the inhabitants of the purpose of and protection afforded by retardation basins. The authors have suggested that such measures be taken in line with a comprehensive approach to the watershed, through participative measures that include action by the municipal authority and NGOs.

The current municipal regulations need to be adapted, not only as regards the hydrological specification and hydraulic design of these structures, but also in terms of their relationship to environmental management, urban planning and maintenance. Therefore, they suggest broadening participation and commitment to include various competent areas within the community management.

6.2.3. Management of storm water drainage in the Córdoba Access Network (RAC)

Owing to its geographical position the city has historically been the hub connecting the country's Central, Cuyo, Noroeste, Litoral and Sur regions. Intercity traffic to and from the city is organized through the Córdoba Access Network (RAC) which embraces all the accesses within a radius of some 35 km. The RAC comprises six conventional roads, two motorways and the city's ring road (Figure 6.25). It is approximately 400 km in length. The RAC handles a total traffic of 240 000 vehicles a day. In 1996 the provisional government granted a 25-year concession for the RAC to a single company.

The contract obliged the concession-holder to carry out a major set of hydraulic and road works. The relevant studies were carried out during the second half of the 1990s. The first stage of the plan of works was completed early in 2001 at an investment cost of S$ 240 million. The drainage works accounted for 20% of that investment (Bertoni *et al,* 2004). The economic crisis that hit the country late in 2001 brought new works to a standstill and imposed serious restrictions on the maintenance plan for others. We describe below the problems observed in one sector of the RAC that receives direct contributions from the city of Córdoba.

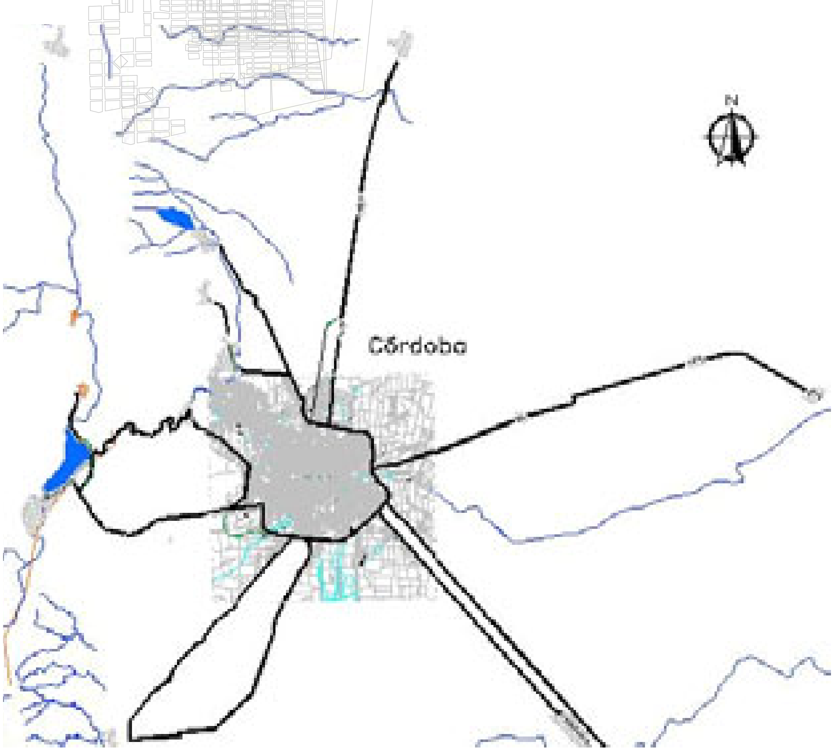


Figure 6.25. Córdoba Access Network (RAC), Argentina

Flooding on the north-east section of the Córdoba ring road

Since it was built, the north-east section of the city of Córdoba's ring road has suffered serious problems with storm water runoff during heavy storms. Repeated material damage to the existing infrastructure works and even loss of human life during heavy rains are an illustration of the scale of this recurring problem.

The north-east section of the ring road is in the outlying area of the city, where the natural gradient of the ground is predominantly in the north-east–south-west direction. The road's storm water drainage system basically consists of two main canals: "inner" and "outer", both running parallel to the carriageways (Figure 6.26).

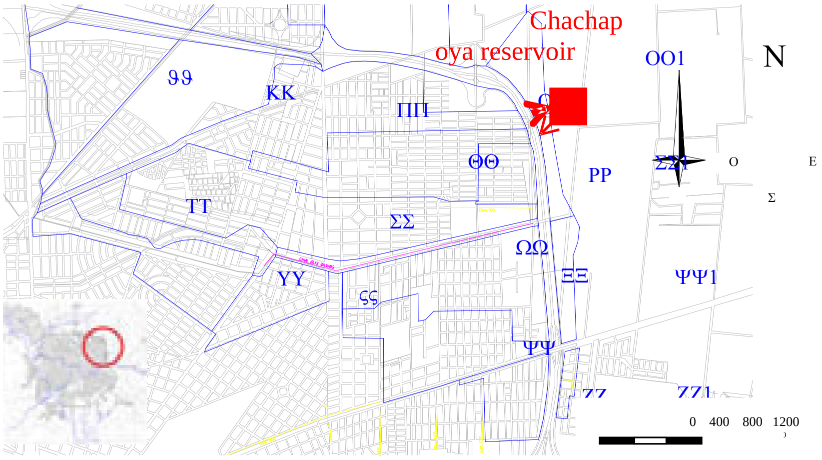


Figure 6.26. Watersheds directly contributing and indirectly linked to the north-east section of the Córdoba city ring road.

The inner canal runs between the city and the ring road and is fed by the urban watersheds. The outer canal, as its name suggests, runs along the outside of the road and is fed by a number of watersheds, where most land use is still rural. In the sector adjoining the outside of the road there are also extensive commercial and industrial sites, on large plots of land.

Since they were originally built in the 1980s, the area’s storm drainage has experienced a number of problems. Among other things (Bertoni, *et al, 2005*), they derive from:

1. The constant advance of urbanization and agricultural expansion in the contributing watersheds;
2. The lack of joint planning and monitoring between the municipal and provincial levels with a view to achieving sustainable urban development over time, interpreting and controlling the necessary interaction between the city and its ring road;
3. Errors in design and/or construction of the drainage system itself (sections of canal with a critical hydraulic gradient; lack of attention to the complex and delicate interaction between the loessic soil and the rigid hydraulic structures, etc.);
4. Inadequate transit structures (canals and piping).

In 1997-98 the Empresa Caminos de las Sierras S.A., the concession-holder for the RAC, upgraded the system, increasing its overall transit capacity. This increase was basically achieved by:

a. Widening the existing piping sections;

b. Building a major accumulation and flow regulation structure (known as the Chachapoya reservoir).

Although the northern and north-eastern sections of the ring road are linked both by road and hydraulically, the flow control structure (Chachapoya) practically divides these sections into two. This detention reservoir or basin, the largest ever built in the city of Córdoba (600 000 m^3), is fed by the inner and outer canals of the northern section.

The structure was built on land adjoining the outer canal and receives all the runoff from the northern section via that canal. Furthermore, the inner canal has been altered to divert all the flow from storms with a 25-year return time. In view of the canal's upstream freeboard it is estimated that the diversion structure could handle substantial proportions of the flow generated by storms of up to 100 years return time.

The Chachapoya reservoir has two conduits of 2.0 m in diameter for the free evacuation of the flow to the outer canal. The output flows are kept practically constant over a wide range of situations, the total output to the outer canal from the north-east section being of the order of 15 m^3/s.

Another main characteristic of the system is that practically from the Chachapoya reservoir the inner and outer canals are excavated in cuttings, i.e. with gradients lower than that of the adjoining land. Therefore, with the exception of some urban watersheds that feed the outer canal over a canal bridge, all the others feed the inner one, with mantiform surface runoff from the streets or concentrated in underground conduits.

Even after the Chachapoya reservoir was built, a number of isolated problems have been recorded from 1998 to the present day. A particular critical situation, although there were no victims in the sector under analysis, occurred during the evening of 26 December 2003, when a serious storm broke over the city of Córdoba.

Over the south-west of the city the storm was accompanied by a devastating tornado. The rainfall, amounting to 113 mm in 1.45 h (65 mm of which fell in 20 minutes), caused material damage to the road and hydraulic structures in the north-east section. Besides serious flooding in the districts adjoining the ring road, the rain also caused both canals to overflow. These overflows in turn led to erosion and undermining of various sections of the earthworks of the embankments and verges (Figure 6.27 to Figure 6.30).

Figure 6.27. Damage to the outer canal during the storm of December 2003. Situation before and after the peak of the flood.

Figure 6.28. The inner canal overflowing during the storm of December 2003.

Figure 6.29. The inner canal during the storm of December 2003. Note the effect of the poor hydraulic design of the transition.

Figure 6.30. State of the central canal of the north-east section during the storm of December 2003.

The severity of the problems with the road and water systems led to a study being conducted with the aim of recommending possible action to be taken on the drainage basins in order to achieve greater control of the flows discharged, and recommending any changes to the existing drainage structures to improve their hydraulic operation.

The study involved hydrological analyses and a check of the behaviour of the hydraulic system for the 2003 storm and storms with a return time of 25 and 100 years (Bertoni *et al.*, 2005). Since there were no flow or level data that could be used for reliable calibration of the models used, the analysis of the runoff coefficient (ratio of precipitation vs. runoff) was used as an additional check of the information obtained from the inhabitants. From the studies conducted it was inferred that in critical situations this coefficient varied between 0.70 and 0.78. In turn, it was deduced that the urban watersheds studied produce average specific peak flows (peak flow per unit of area) of the order of 55, 85 and 115 l/s-ha associated with return times of 25, 100 and 150 years respectively.

The study proposed adopting measures jointly at provincial and municipal levels so as to bring the production and transfer capacity (volume and flows) of the contributing watersheds into line with the physical limitations of the area's drainage canals. It was also recommended that improvement works gradually be carried out on both canals.

6.2.4. River flooding of the city of Santa Fe, Argentina

Introduction

The city of Santa Fe (Province of Santa Fe, Argentina; population 400 000) is located in the central region of the Argentinean river system, next to two important waterways, the Paraná and Salado rivers (Figure 6.31). In 2003 a flood occurred of the river Salado which was far more serious than any previous one. It had dramatic consequences for the city of Santa Fe and the adjoining areas, with deaths and much material damage. The phenomenon also affected various of the province's rural areas, seriously affecting the activities that habitually take place in the Santa Fe watershed of the river Salado. The area directly influenced by the city of Sante Fe has a population of 500 000, many of whom are living in poverty. At the time of the 2003 flood, unemployment in the region stood at 23.5% and 53% of households were living in poverty.

Historically the problem of flooding of the riverside areas of the city of Santa Fe has been perceived as being linked to the behaviour of the river Paraná. During the 1990s, using international loans of US$ 25 million, the government of the State of Santa Fe built a protection system consisting of a number of dykes and embankments surrounding the city and neighbouring areas. This system gave the city a certain level of protection from flooding of the river Paraná. However, it proved inadequate for flooding of the river Salado.

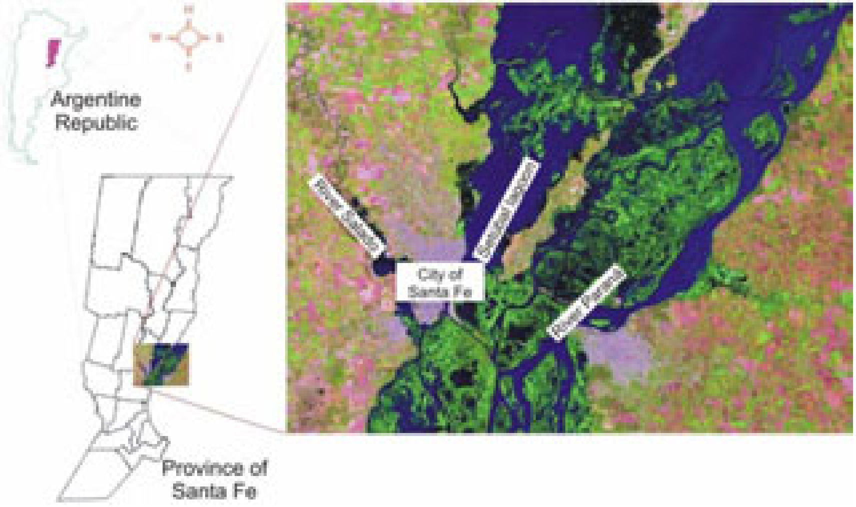


Figure 6.31. Location of the city of Santa Fe in the Argentine Republic.

Aspects of the lower watershed of the river Salado

The river Salado watershed covers a total area of some 247 000 km^2 and is some 1 500 km in length. While there is no definite boundary, the river Salado's lower catchment area is conventionally considered to be the area within the province of Santa Fe, measuring 55 950 km^2 (about 42% of the province's territory).

The region is a plain, with a large section that acts as a huge storage area (known as *Bajos Submeridionales*). In various places the boundaries of the contributing sub-watersheds are imprecise and are constantly altered by human activity, mainly road systems and waterways (Ferreira, 2005). The climate of the region is at the transition between the eastern sub-humid and the western semi-arid types, with an annual precipitation coefficient of 1 100 to 800 mm (period 1941-1970). Over the past three decades (1971-2000) the area has seen a general increase in mean precipitation, from 900 mm to 1 200 mm (Paoli, 2004). Activity in the river Salado basin is typically rural, associated with farming (soya/wheat), the milk industry and livestock rearing in general.

There are a number of urban centres within the watershed. The largest is the city of Santa Fe, at the outlet of the river Salado into the Paraná river system (Figure 6.32).

The main feature of the final section of the river Salado, immediately before it runs into the Paraná river system, is that the level of the river depends on the flows of both the river Salado itself and the levels in the river Paraná.

Figure 6.32. Tributaries and areas feeding the lower watershed of the river Salado. Province of Santa Fe (Paoli, 2004).

Flooding of the river Salado in 2003

During the months of October 2002 to March 2003 there was heavy rainfall in the Santa Fe watershed of the River Salado. This precipitation was far higher than the average of the records and significantly increased the soil humidity. As a consequence, much of the rainfall was transformed into surface runoff.

In the early months of 2003 floods were recorded with peaks in excess of 1 000 m^3/s, caused by precipitation falling in various parts of the watershed. The heavy rains continued throughout April 2003. The positive precipitation anomaly throughout April 2003 was 200 mm (Figure 6.33).

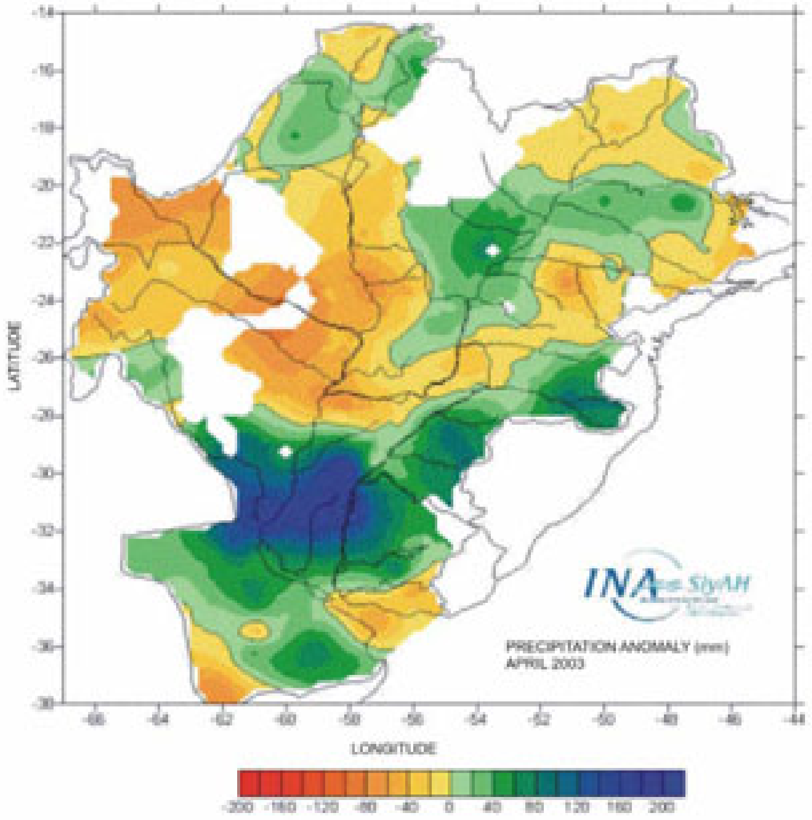


Figure 6.33. Precipitation anomaly for April 2003 (Source: Paoli, 2004).

During 23-25, 28 and 29 April the storms took place that gave rise to the flooding, with a maximum of 3954 m^3/s being recorded on 30 April 2003. The factors contributing to the formation of the peak included the following: (i) the saturated state of the ground in much of the watershed; (ii) the low evapotranspiration in that period; (iii) the occurrence of successive earlier floods, keeping the river level high, with flows exceeding 500 m^3/s.

Figure 6.34 shows hydrographs for three floods of the river Salado. It can be seen that in the case of the 2003 flood the rising and falling plots have much steeper gradients.

A study based on a statistical analysis combining historical flood marks and the available systematic records (Bertoni *et al.*, unpublished) indicated that the return time for that flood was 800 years. The recurrence differed from the estimated based on shorter statistical series. These were apparently representative but did not take account of the occurrence of significant events recorded in the late 19th and early 20th centuries.

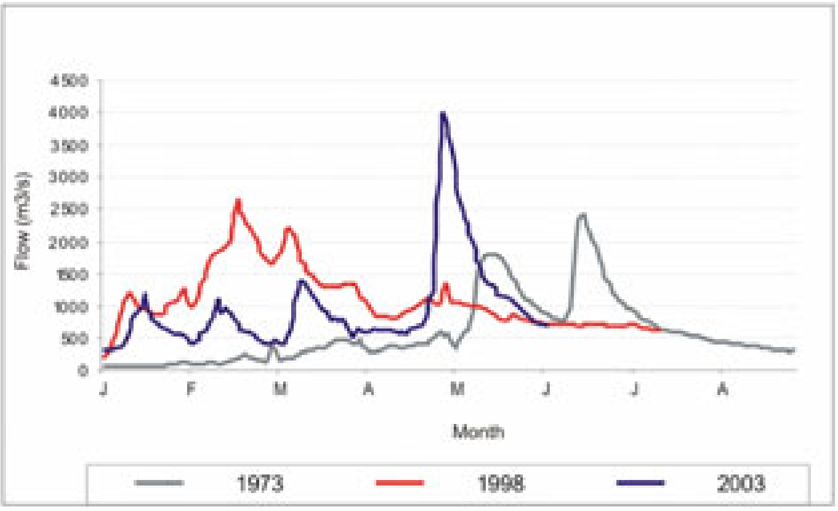


Figure 6.34. Hydrographs for three floods of the river Salado (Source: Paoli, 2004).

Santa Fe city defence system

During the 1990s the city of Santa Fe developed a flood defence system. The goal of the work programme was to protect the city mainly against flooding from the river Paraná. To the west of the city a series of lateral dykes was implemented as part of the construction of the western ring road. These dykes were designed to protect the city from flooding of the river Salado.

For the eastern bank of the river Salado the system of protection with embankments had some particular features, resulting from the combination of road and hydraulic structures. The protection was designed in three parts, linked to the city's western ring road, built from 1995 to 1997. By 2003 only the first two parts of this road and hydraulic system had been implemented (sections I and II, close to the mouth of the river Salado (Figure 6.35b). As a result, during the 2003 flood one section of the city was unprotected, from the extreme north of the defence system.

(a) (b)

Figure 6.35. (a) City of Santa Fe at the mouth of the river Salado on the Paraná system; (b) Area flooded in April 2003 (Source: El Litoral, www.litoral.com.ar).

Flooding of the city of Santa Fe

The magnitude of the peak flow led to the formation of runoff in the lower tract of the river Salado with high levels that exceeded the minimum overflow level into the city centre, in the area near the racecourse, when the river levels exceeded 15 m (level based on the system of the Military Geographical Institute – IGM).

The rise in river levels plus the lack of proper protection at the final end of tract II gradually undermined the structure and formed a breach over 100 m long. It was through this breach that most of the volume of water entered the city, when the water level rose to almost 17 m IGM.

The water entered over a period of several days, flooding one third of the city. In many districts the water was over 2.50 m deep. The incoming water was gradually stored in the urban area, contained within the barriers formed by the lateral defence structures, which were not equipped with fuse-plug spillways to be activated in emergencies. The demolition and opening of breaches in these defences began when the water level within the urban area, in the most critical areas, was some 2.40 m above the river level.

Causes of flooding of the city of Santa Fe

The flooding of the city of Santa Fe occurred for a number of reasons, which can be grouped into structural and non-structural (or emergency).

The former include the expansion of the city of Santa Fe on the flood plain of the river Salado, which was a permanent phenomenon. The following paragraph briefly summarizes this aspect.

The city's gradual development towards the west in turn gave rise to the building of a number of urban and road infrastructure works, which are currently located in the alluvial valley of the river Salado. The Santa Fe-Rosario motorway bridge (which has an opening of 155 m in a flood plain more than 3 000 m wide) reduces the river's natural flow capacity, leading to serious restrictions of normal runoff in times of flood. According to studies, at the time of the 2003 flood, this bridge raised the upstream water level by some 0.70 to 0.80 m.

As already stated, two sections (I and II) of the defence structures in the Salado alluvial plan had been completed at the time of the flood. The design of section II provided for a temporary closure by means of a provisional wall, across the axis of the embankment, formed of reinforced masonry. The need was also foreseen to supplement this closure as an emergency measure in the event of flooding. It is reasonable to suppose that this project design was based on the assumption of continuing relatively quickly with section III of the defence. However, it is obvious that there was a high risk in relation to potential flooding of the river prior to the construction of this final section.

Regarding structural measures in the contributing watershed, we would point out that in the lower watershed of the river artificial canals are used to drain areas that are relatively low-lying or adversely affected by the road and/or rail infrastructure routes. Hydrological studies estimated that these measures could have a hydrological impact on one of the system's main sub-watersheds by increasing the magnitude of the flows by some 30% and reducing the arrival time at the outlet of the sub-watershed by about 12 hours. As we can logically assume that there could be equivalent impacts in the other sub-watersheds of the river Salado where similar measures have been taken, we deduce that human intervention in the watershed has certainly had an effect in relation to the situation prior to the 1970s, and led to substantial changes in both the peak and the arrival time of 2003 flood wave.

Prominent among the non-structural causes was the lack of an emergency plan or associated contingency plan. If these important organizational and working tools had existed, the following non-structural and structural measures could have been taken during the emergency:

- Orderly evacuation of potentially affected people;
- Determination of the place and time for making breaches in the defensive embankment;
- Early closure of the defence with sandbags, which would have allowed it to be done while dry and created a higher and longer defence, thereby mitigating the timing of the events;
- Hydrological forecast of the flood, with sufficient minimum warning to carry out the above-mentioned works.

Figure 6.36. Flooding of the western districts of the city of Santa Fe, Argentina (Source: Paoli, 2004).

Urban settlement of the river Salado flood plain

A review of a city's historical cartography is very important for the purposes of analysing and understanding the evolution of its inadequate growth on the flood plain on the bank of the Salado river.

Until the late 19th century the city of Santa Fe expanded in harmony with the river Salado. As a result, there was practically no public perception of flooding on the river Salado.

The most significant trends towards expanding the city to the west, especially onto the river Salado's natural flood plain, took place during the first half of the 20th century, beginning with the railway embankments that offered a sense of security by isolating various districts from the river's natural flood plain. In 1937 the western defence, known as the Irigoyen embankment, was built which helped to extend the city of Santa Fe's urban radius onto the river Salado flood plain.

Since 1940 until the present there has been a sustained process of urbanization of the river Salado's natural flood plain. In 1914 there was a major flood of the river Salado with an estimated peak flow of some 2 750 m^3/s. In 1973 there was another flood of the river Salado with an observed peak flow of 2 430 m^3/s. Between the two floods there was a relatively dry cycle lasting 59 years. During that period no flooding of the river Salado exceeded 800 m^3/s (except in 1946 when that threshold was barely exceeded). This was a decisive element that prompted all the decision makers of those years to ignore the need to plan the city's urban development in a manner that was compatible with the characteristics of the river Salado's flood plain. With hindsight, this was a clear failure of the decision-makers' training and/or policy, which led to planning errors.

Another important fact, of significant importance for understanding the evolution of the urbanization of areas liable to flooding in the city of Santa Fe, was the gradual establishment of the idea of solving flooding problems solely by building engineering works.

The combination of failings described led to inappropriate decisions, such as the construction of the new children's hospital and the electricity substation in areas identified as at high risk of flooding.

The design and construction in 1996 of the western defence embankment for the ring road, without actually implementing a number of non-structural measures, such as warning and contingency measures, are an example of a approach based solely on the construction of engineering works.

To complete this summary of the evolution of urbanization of the western sector of the city of Santa Fe, Figure 6.37 illustrates a comparison of the various levels of the city's urban development over time. The illustrations show the presence of infrastructure works (roads, railway lines, etc.) as they were implemented over the years. These structures are shown in the colour corresponding to the year in which urbanization was assessed. They also show the contour lines, which record the city's advance into the lower-lying areas.

Figure 6.38 shows a comparison of the view of the western sector (photo No 1) with the same place today. Figure 6.39 depicts the same comparison for photo No 2.

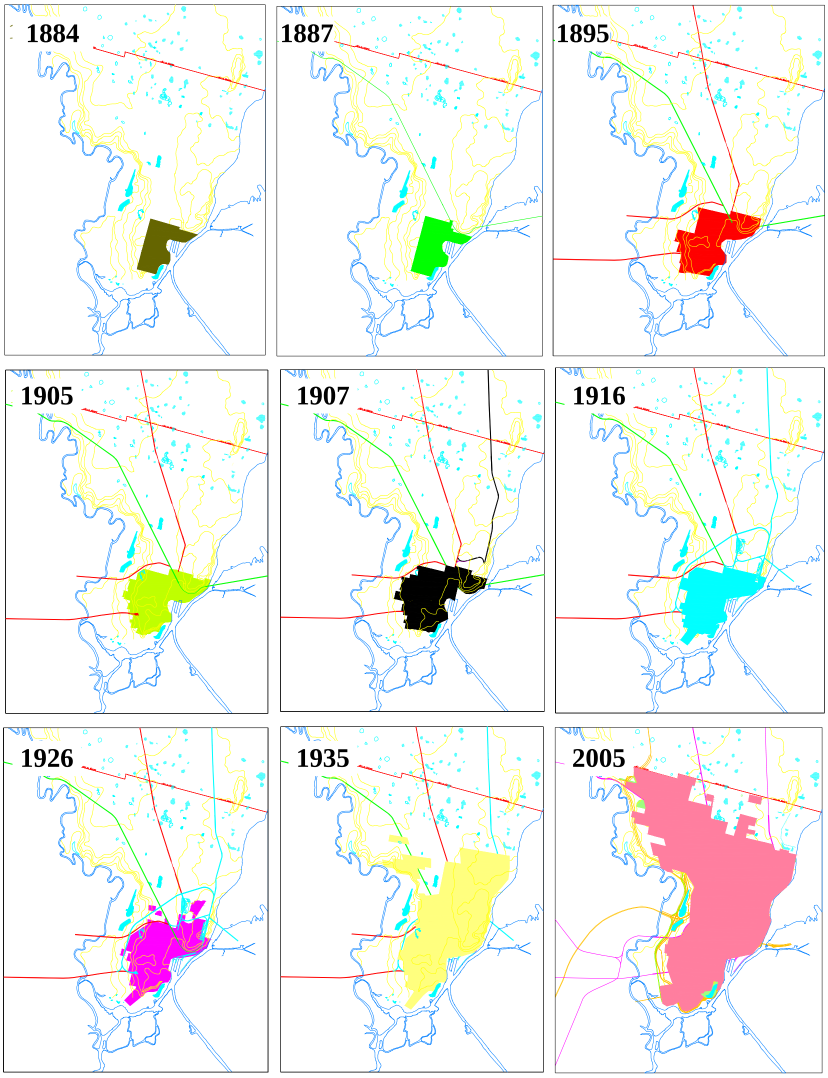


Figure 6.37. Urban development of the city of Santa Fe from 1884 to the present day.

Figure 6.38. Urban transformation: comparison of two images of the same area

during the 1930s (riverside marshlands) and in 2005.

Figure 6.39. Urban transformation: comparison of two images of the same area during the 1930s and in 2005.

6.2.5. Flooding of the city of Trelew, Argentina

We describe below a particular case of flooding in the city of Trelew (in the Patagonian region of Argentina), where the lack of planning of urban expansion, defective maintenance of hydraulic structures and even vandalism contributed to creating major flooding, during extraordinary rainfall, in a large part of the city. The material presented was taken from Serra (2004).

The city of Trelew, located in the lower valley of the river Chubut, currently occupies an area of about 15 km^2. The city has grown in an area of lagoon and riverside depressions subject to natural flooding. The building of housing developments in these areas, along with roads on embankments without proper hydraulic structures, the real-estate taxation policy, and scant regard for hydro-environmental planning criteria in decisions on new urban developments, all contributed to aggravate the problem of urban flooding. These are therefore the main government practices to be changed.

An example of unplanned urban expansion is the siting of districts restricting the outlet of a major alluvial system, known as the Cañadón del Parque Industrial. This water system is active only during rains of a certain magnitude and drains into the Chiquichano lagoon, located in the city centre (Figure 6.40).

To alleviate the problem of flooding caused by high-water events in this watershed, construction began in 1984 of three large embankments on a low-lying area in the industrial area of the city of Trelew. The aim was to put a stop to river flooding and control the drainage, with lower flows and a longer runoff time. During major rains in May 1992, these structures were altered and rebuilt with contributions from the Interior Ministry’s Emergency programme.

The alterations included:

- The removal of the first embankment;
- An increase in the mass and height of the second embankment (Dam II) and third embankment (Dam III);

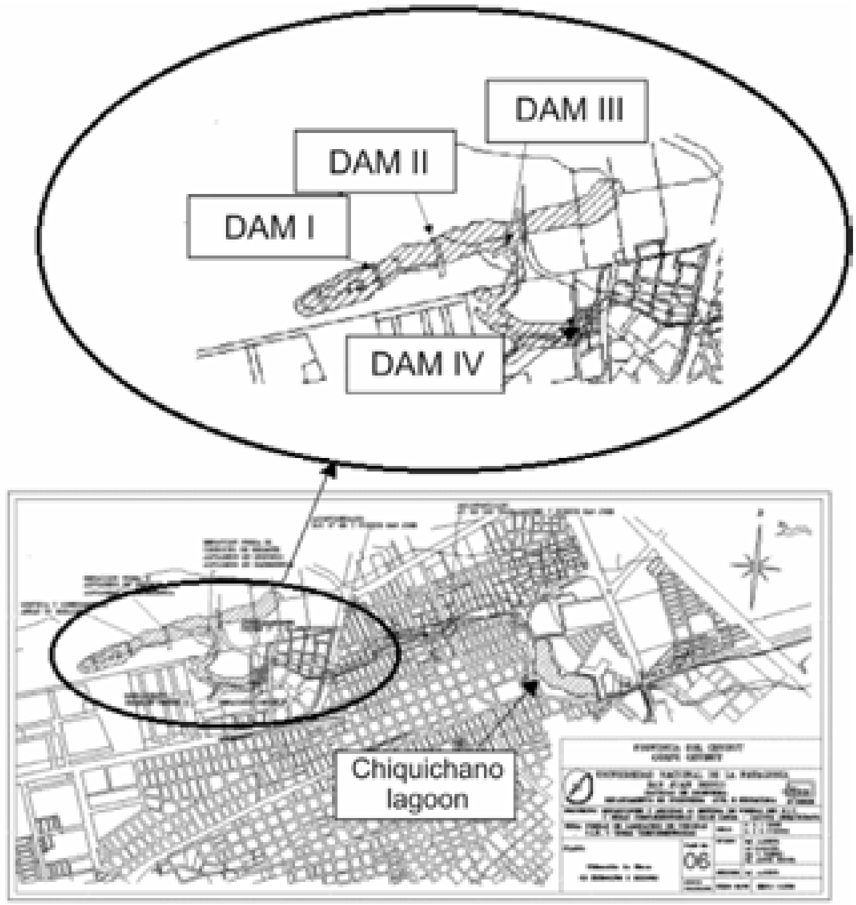


Figure 6.40. City of Trelew and area affected by the April 1998 flood. (Source: Serra *et al.*, 2002).

- Incorporation of an impervious clay core into the dams;
- Proper compacting of ground, incorporation of filters or drains and stone covering on the walls to protect them against wave action;
- Incorporation of piped conduits in each embankment to regulate and drain the water;
- Incorporation of a lateral diversion spillway to handle large floods exceeding the storage capacity of the small dam or dyke;
- Covering with gabions to protect against erosion, in line with standard building practice.

A fourth, very low embankment (Dam IV) was also built a few metres from the Constitución district, with the simple task of collecting and diverting the regulated water from the low-lying area to the Chiquichano lagoon.

The works carried out included an intake and an underground conduit to carry the regulated water from Dam IV to the Chiquichano lagoon, under the streets of the Constitución district and street canal (storm drain).

The whole system was designed to store temporarily in the small reservoirs the water from the natural watershed, spread over the adjoining plateau. The need for regulation arose because some districts of the city restrict the natural outlet of the system into the Chiquichano lagoon. All the water was to be collected by Dam IV, opposite the Constitutción district and carried in the underground conduit already mentioned.

The heights of the dams were designed to prevent flooding of neighbouring industrial areas. For this reason the dams also incorporated lateral spillways. Storm water that exceeded the storage capacity was to be diverted to the street canal. As an additional safety measure in the event of extreme flow levels was the slow and controlled erosion of the spillways in Dams III and IV (fuse-plug spillways).

Between 1992 and 1998, all the runoff from rainfall was retained, with controlled drainage through the underground conduit. However, in April 1998 there was a freak storm linked to the El Niño phenomenon. Total precipitation measured 251 mm in 54 hours, 150 mm of which fell in one day. This quantity was double the peak daily rainfall in Trelew over the 50 years observed by the National Meteorological Service. Although no similar historical rainfall references were detected in the area of the lower valley of the river Chubut, the geomorphology of the low-lying fields is an indicator of the past occurrence of freak events, of even greater magnitude than the one recorded.

The runoff generated during that freak event silted up Dam II which started it draining through the emergency spillway into Dam III. Vandals had removed the galvanized iron erosion-protection mesh from the spillway of the first dam. The opening of a breach in the spillway and wall of the dam reduced its storage capacity. When the volume accumulated in Dam III forced the lateral emergency spillway into operation, it proved to be obstructed by truckloads of debris that had been tipped into it, and even a chassis abandoned in the basin. For several minutes this raised the reservoir water level above the crest of the embankment, seriously eroding its walls and weakening the dam wall. At the same time, the water pressure at the spillway inlet suddenly blew out the tipped debris, generating a first and surprising “flood wave”. The same thing immediately happened at Dam IV, suddenly flooding the Constitución district and continuing through the street canal towards the lagoon.

Owing to the incessant runoff, one of the buttresses of Dam III gave way, causing the second flood wave. A few hours later the roadway embankment over that dam was breached, causing the third flood wave. 48 hours later the reservoirs were empty, after carrying an estimated volume of 1 000 000 m^3 of water. This volume of water filled the Chiquichano lagoon to unusual levels which, along with the water that had accumulated in the city centre, flooded a huge urban area (Figure 6.41). The situation was aggravated by route 25 acting as a dyke.

If the dams had not existed during the flood, the peak flows in the Constitución district would have been somewhat lower. However, the volume of water entering the lagoon would have been the same over a day and a half instead of the four days that it took owing to the delaying effect of the dams, even though they failed. This situation would have produced more serious flooding in heavily populated districts around the lagoon.

Figure 6.41. Image of the Mil Viviendas sector, within the Cañadón del Parque Industrial system, Trelew, during the freak storm of 24-25 April 1998.

Various alternatives were proposed to solve the problem, ranging from the removal of all the dams (returning to the original natural state of the area), to various alternatives for rebuilding and improving the reservoir system. The solution finally adopted involved the redesign of the whole regulation system. In the context described, the dams to not solve the whole problem, but they do offer substantial control over the flooding of the low-lying field, allowing greater storage in an area that makes up for the storage lost by urban development, among other things.

The events of 1992 and 1998 marked a need for change in the urban planning guidelines in Trelew and a raising of public awareness, taking account of the limits on the use of land liable to flooding, the handling of the mass of storm water in major rainfall events and water safety, and the debate is still going on. The case also highlights the need to consider the geomorphological features of a region as fundamental factors for mitigating probable disasters due to freak or episodic water events. Finally, the lack of maintenance and vandalism are two collateral aspects of the problem that cannot be ignored in the present circumstances in Latin America.

6.2.6. Flash flood in San Carlos Minas, Argentina

The small village of San Carlos Minas (population 1 000) is located in the State of Córdoba, in central Argentina. It lies on the banks of the Noguinet stream. Its watershed (260.4 km^2) covers an area featuring hills and steep slopes. In January 1992 the village was devastated by a flash flood (Barbeito *et al.*, 2004).

The convective storm that caused the flood precipitated 240 mm in 6 hours in the upper watershed, 140 mm in 7 hours in the middle and 204 mm in 6 hours in the lower watershed. The average intensity of the rainfall was calculated at 180 mm/h. In San Carlos Minas the flooding activated a system of ancient palaeobasins (Figure 6.42). The capacity of the watercourse was suddenly exceeded and the village was flooded in a few minutes. At the same time large trees uprooted by the current accumulated at a bridge located at the entrance to the village. The bridge's design capacity was 800 m^3/s but this figure was drastically reduced by the obstruction of the uprooted trees. This created a dyke effect that a few minutes later caused a frontal wave, similar to the wave from a rupturing dam. This huge wave devastated the village with a peak flow of some 1.900 m^3/s. As a consequence, 30 people died, 40 disappeared and there was substantial material damage. Figure 6.43 illustrates the peak water level in the section upstream of the bridge. Figure 6.44 shows some of the damage caused by the flood passing over the bridge.

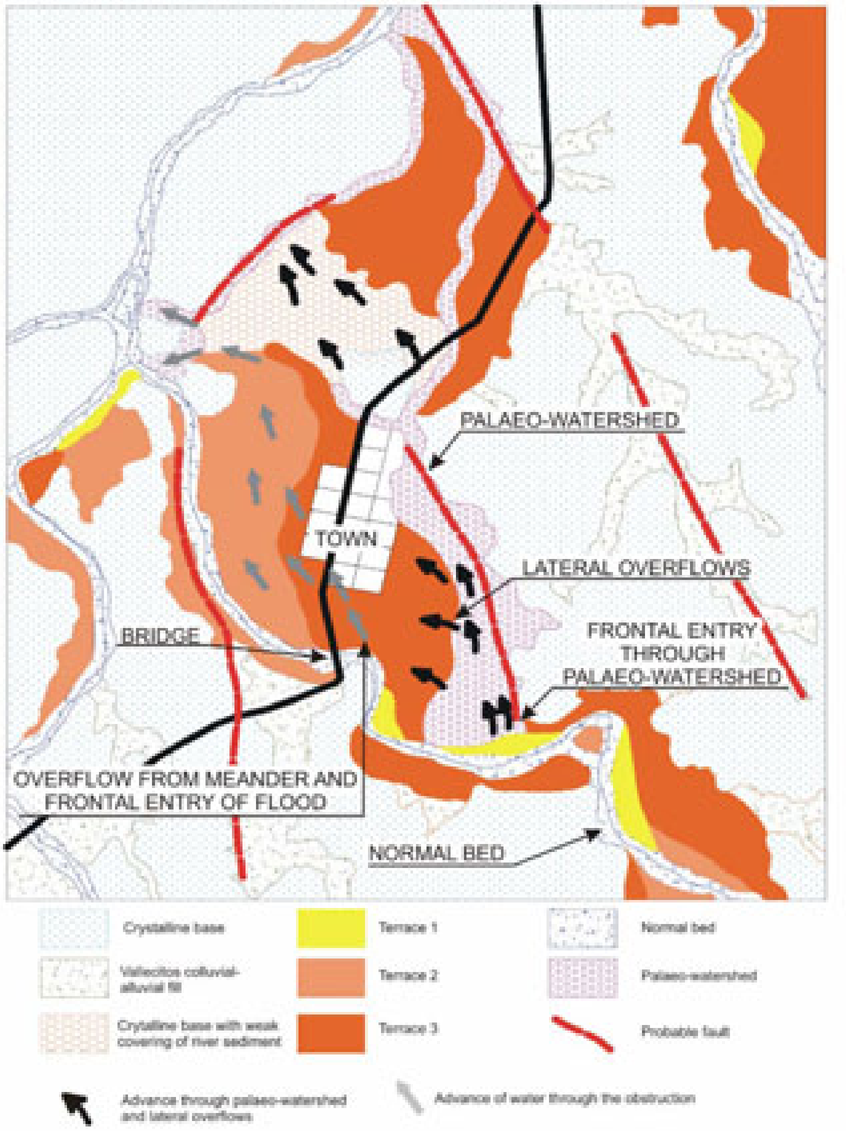


Figure 6.42. Path of the flash flood at San Carlos Minas in January 1992. (Source: Barbeito *et al.*, 2004).

Figure 6.43. Area immediately upstream of the bridge. Event of January 1992 at San Carlos Minas, Argentina (Source: Barbeito *et al.*, 2004).

Figure 6.44. Damage to dwellings in a district of San Carlos Minas, Argentina. Flooding, January 1992.

6.2.7. Possible solutions

The Study and Design Department of the Provincial Directorate of Hydraulics (DPH, 1992) considered a number of solutions, all structural. To determine the flows passing through San Carlos Minas the precipitation in the watershed was studied. As mentioned above, it was characterized as heavy and of short duration, with quantities varying between 60 and 250 mm and lasting close to 2 hours, mainly falling in the Gaspar peaks.

After a hydrological study based on the little available data the flows were adjusted for various return times (Table 6.7). As a control for these studies data were processed from the Pichanas dyke (the final collector of the contribution from the watershed) where the input to the flood had been recorded over time. This confirmed the calculated flows and return times.

Table 6.7. Peak flows associated with various return times. Noguinet stream in San Carlos Minas, Argentina

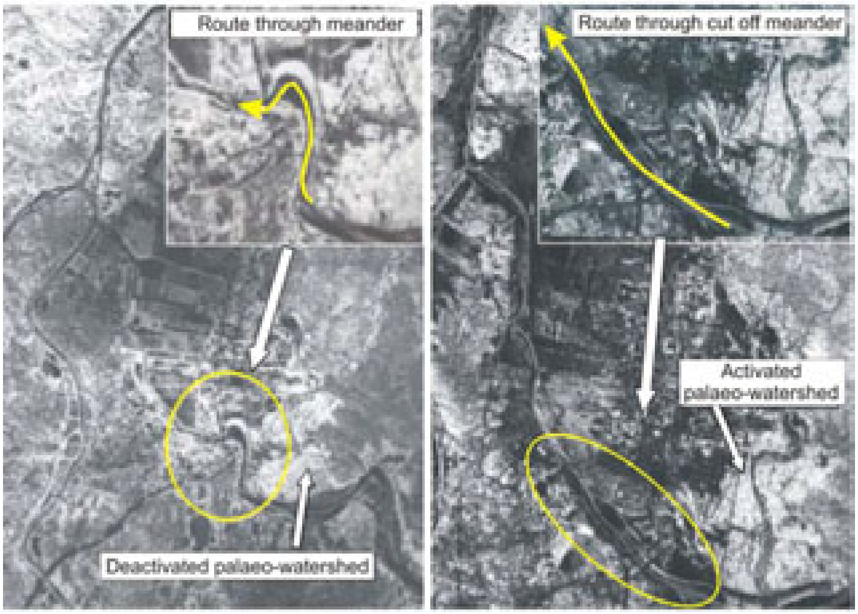
Return time [years]	**Peak flow [m^3/s]**
50	750
100	980
500	1 200
1 500	1 500

The DPH proposed alternative structures for various flows and, hence, for various levels of security for the population. These alternatives included:

- Defence with bridge and ford,
- Defence with bridge,
- Canal system.

The first two alternatives described structures in the same area as the bridge, with design flows of the order of 1 250 m^3/s and a return time of 500 years. In the event of higher flows it was planned that the structures would overflow, with controlled flooding of some parts of the built-up area.

The third solution was finally adopted as a solution, as it was considered to offer the highest safety factors for the population. The structures designed for a flow of 1 950 m^3/s, with a return time of 5 000 years, rerouted the river bed away from the village towards the south (Figure 6.45b).



(a) (b)

Figure 6.45. Aerial photo (a): 1970 and (b) 1998, when the canal was built to straighten the natural meander (Source: Barbeito *et al.*, 2004).

This structure cut out the bend in the river from which the water made its uncontrolled entrance on the day of the catastrophe.

The following works were proposed as part of the project:

- An 815 m canal, varying between 40 and 80 m in width and up to 10 m deep. It was excavated partly out of the rock and the remainder out of the soil, giving a total volume of earth to be moved of 180 000 m^3.
- A dam across the river 180 m in length and 6.40 m high above water level, made of loose material taken from the canal excavation. The dam has a system of injections into the alluvium and a mixed core of fine and coarse material in the main wall.
- A longitudinal wall in the flood branch, 550 m in length and 1.50 m high on average, made of loose material.
- A road bridge over the canal 48 m in length. The infrastructure, piling and reinforced concrete buttresses were founded directly on the bedrock.
- Reconstruction in the affected areas of Provincial Route No 15.
- Improvement of the river bed downstream from the outlet of the canal to the confluence with the river Salsacate.
- Renovation of the drainage gully on the old flood branch.

- Renovation of the irrigation ditches in affected areas in line with the new urbanization.
- Construction of a new supply, feed and connection to the existing drinking water mains.
- Water supply system for future health resort.

A study of all the factors involved showed that natural factors, such as weather, hydrology, geology and geomorphology, played a major part in the flood. But it was the human element that turned this flood into a disaster.

The magnitude and intensity of the precipitation that occurred, and also the geological characteristics of the watershed surface (with high percentages of exposed crystalline rock alternating with very superficial rapidly saturated discontinuous soils) and the torrent tract watershed (deduced from the calculated morphometric parameters) were undoubtedly the natural factors that most influenced the freak nature of the flood.

The intermediate level of degradation to which the watershed is exposed, through degradation of the natural vegetation, certainly did play a role, though it was a secondary one.

The resulting river dynamic affected geomorphological units and elements that were clearly defined and recognizable both in the analysis of the photograms and in field checks.

The studies carried out indicated that all of the village and its surroundings was located in an area that was unstable from the hydrological point of view, to varying degrees depending on the geomorphological position. This is why the human element, basically the badly sited building infrastructure, was what carried most weight when the disaster occurred.

For the location of the village and in particular the new districts, and the road bridge that produced the dam effect, no account was taken of the obvious hydrological risk inherent in those areas.

The seriousness of the catastrophe, and the level of subsequent investment in seeking solutions, is a clear example of a failure to plan measures both before and after a critical event. Indeed, during the urbanization of the town neither the provincial nor the national authorities made any effort to have it sited elsewhere. However, the investments after the event demonstrated a high level of aversion on the part of the authorities to water risks.

The adoption of a structural measure on the scale of the one that was built (designed for a 5000 year return time) is compatible neither with the public coffers nor with the many other mountain settlements subject to similar threats, for which little or nothing has been done since.

6.2.8. Lake flooding in Villa Carlos Paz, Argentina

The San Roque dam (**Error! Reference source not found.**) is located in the geographical centre of mainland Argentina, in the province of Córdoba. It has a watershed of 1 650 km², with rugged relief. The climate is typical of a temperate Mediterranean zone, with rains and high temperatures concentrated in the summer. Mean annual precipitation, calculated over the period 1945-1979, was 720 mm.

Towards the end of the 19th century the main concern of the governors of the province of Córdoba was to take advantage of the water source offered by the river Suquía. Thus in 1881 negotiations began for the construction of a dam to protect the city of Córdoba from major flooding.

On 12 April 1890 the San Roque dam (**Error! Reference source not found.**) was inaugurated, which at the time was the largest in the world. The engineer Gustave Eiffel, professor at the Ecole Polytechnique of Paris of two of the engineers responsible for the project (Dumesnil and Casaffoust), said at the time: *“Two structures are attracting the world’s attention at the moment: my tower and the Córdoba dam; the difference is that the latter is productive whereas my tower is not”*.

A new dam was built in 1944, replacing the original structure 150 metres upstream of the present one, which has a storage capacity up to the level of the spillway of 200 hm³. The original dam could also store 200 hm³, as both spillways were a similar height above sea level. The present dam is designed to contain and control up to 150 hm³ in the event of flooding whereas the original dam was able to control only about 30 hm³.

The San Roque dam provides most of the water supply needs of the city of Córdoba (population 1 400 000), as well as irrigation water and hydroelectric power. It has regulating valves and a “morning glory” type spillway, designed in such as way that its peak flow quickly attains 240 m³/s. This makes it a measure to protect the city of Córdoba (the provincial capital) against flooding, as it is downstream of the dam.

At the top of the spillway (35.3 m) the water surface covers 16.83 km² and contains 184.9 hm³. Up to the altitude of the original expropriation of the perilake (38.0 m) it covers an area of 18.82 km², with a volume of 238.40 hm³. If the level were to attain the crest of the dam (43.0 m), it would cover 22.50 km², with 344.23 hm^3.

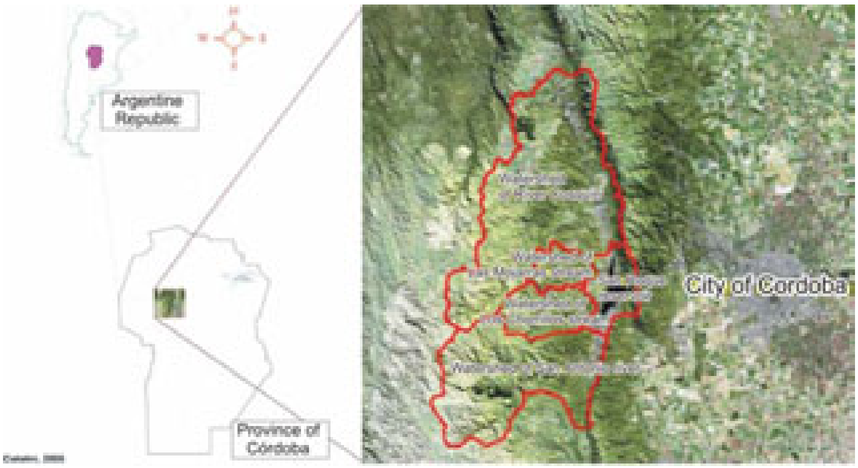


Figure 6.46. Watershed feeding the San Roque reservoir. Geographical location and hydrological units.

Figure 6.47. Photograph of the original San Roque dam, with a 33 metre reservoir. (Source: Zuleika Gore-Edwards Bialet Laprida).

The system's vulnerabilities, which make the San Roque reservoir a prototype for studying lake flooding, notably include the following:

- A number of tourist resorts are located by the lakeside, the largest being the city of Villa Carlos Paz, with a resident population of 45 000. During the summer tourist season the city population triples. Flooding from the rivers feeding the reservoir occurs in summer, when the tourists are there.
- Much of the visitors' activities take place on or around the reservoir and its tributaries.

- The municipality of Villa Carlos Paz set the effective expropriation level around the perilake at a lower level (36 m) than the 38 m originally considered in the reservoir design. Even this 36 m level is often contravened, demonstrating the lack of control by the municipality and the provincial water authority.
- As mentioned, to protect the city of Córdoba, the reservoir has a limited discharge capacity.
- The reservoir is currently seriously eutrophicated, mainly owing to the settlements around the lake discharging untreated domestic organic loads, and phosphorus from the bush fires that occur during the dry season.

In recent decades rainfall in the feed area has increased substantially, and since the privatization of the city of Córdoba's water supply service, the reservoir tends to be kept at a high level as a means of controlling eutrophication. Both causes have given rise to a rising trend in the water level of almost 8 cm/year (Caamaño and Catalini, 2002). Consequently, the threat and risk of lakeside flooding have increased, and have become a serious problem in recent years. Late 1999 saw the most serious flood to occur around the lake, affecting large areas of the city of Villa Carlos Paz (**Error! Reference source not found.**). This gave rise to the study of likely critical scenarios and the demarcation of areas at risk of flooding. This work was carried out by Caamaño and Catalini (2002) and Catalini (2003).

Figure 6.48. Flooding of the city of Villa Carlos Paz, Argentina, in 1999, in the perilake of the San Roque dam.

Forecast of critical scenarios at the San Roque reservoir

The water level at the surface depends on the volume entering the reservoir, its initial state, the operating and discharge conditions and the distribution of feedwater over time.

Caamaño and Catalini (2002) and Catalini (2003) estimated the mean peak flow entering the reservoir for a given return time and for a given number of days duration of the event. Various working hypotheses were accepted for the other factors in drawing up the water risk map. These are presented below.

Theoretical duration of the event to be analysed

By observing the historical series of the reservoir levels (1944-2005) it was concluded that the system's reaction time to rainfall in the watershed is up to four days, depending on the initial state and the location of the heaviest rainfall in the watershed.

Determination of the initial level of the reservoir

The results obtained show that the reservoir level is tending to rise, which made it impossible to determine an average level from the daily series. Figure 6.49 shows an analysis of the annual maximum, average and minimum values. We observe that the rising trend in the daily series is also present in the annual maximum, average and minimum. There is a greater increase in the minimum levels (amounting to 9.9 cm/year). The maximum levels reflect the trend observed in the daily values. If this behaviour persists, it will reduce the range between the maximum and minimum levels (of the order of 6.75 m). Taking account of all these aspects, the initial level of the reservoir adopted for the simulations was the lip of the spillway ($h_0 = 35.30$ m).

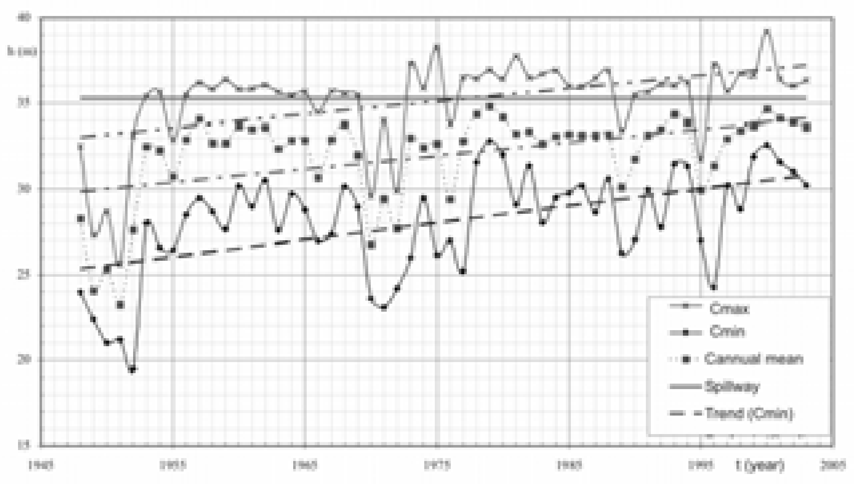


Figure 6.49. Series of annual maximum, average and minimum levels (period 1947-2003)

Determination of the operating conditions for discharges

For any simulation of the behaviour of a reservoir it is necessary to know the discharge conditions and the operating policy of the hydraulic structure adopted by the authorities. In this particular case the authors concluded that there was no consistent policy over time (in fact it was discovered that there was no policy), so they established two arbitrary alternatives during the analysis: discharge of 100% (24 m^3/s) through outlets and 90% (mean 72 m^3/s) through valves. The *risk map* was drawn up on the basis of these assumptions.

Determination of levels with associated return times

The maximum levels associated with various return times were obtained from a water balance between inputs to and outputs from the reservoir. For the former three, possible time distributions during the day were analysed: (i) *average* *contributions at the start of the day,* (ii) *uniform during the course of the day and* (iii) *assumption of the occurrence of a hydrograph deduced from a hydrological model determined by the authors.* This last alternative was actually used to draw up the risk map, as not all the necessary hydrological information was available for the watershed. For the study 10 return times were selected associated with inputs to the reservoir, varying from 10 to 10 0000 years.

Based on the modelling, the following associated risk levels were selected: *high, medium, low and minimum.* The first three have a return time (Y) and an associated maximum level (h), while the last was adopted following the guidelines of the original design of the dam which state that the reservoir can store volumes even exceeding the level of the crest (43.00 m). Table 6.8 gives information on these four levels, where the risk is defined as the probability of flooding at least once in n successive years, which can be expressed as:

$$R = 1 – [1 – (1 / T)]^n = 1 - P (\ddagger)^n \qquad (6.1)$$

Table 6.8. Selected risk levels

Risk level	Tr [years]	Level [m]	Δh	Risk %. N
High	10	37.01		10.00 %
Medium	500	38.23	1.22	0.20 %
Low	1000	39.19	0.96	0.10 %
Minimum	---	43.00	3.81	

Areas liable to flooding

On the basis of bathymetric data and level curves, the surface areas of the water and perilake were estimated for the various assigned risk levels to draw up the water risk map for the perilake of the San Roque reservoir (Figure 6.50). Updated satellite images were used to obtain the value corresponding to the urbanized area of the city of Villa Carlos Paz (850 ha), which was adopted as a reference value for the percentages of urban area at risk of critical hydrological events. In turn other parameters of interest were determined relating to the areas liable to flooding (Table 6.9).

The San Roque reservoir risk map indicates that the minimum building level adopted in recent years (36 m) is too low for a large part of the city of Villa Carlos Paz. This indicates the need to actually adopt the level originally considered in the reservoir studies (38 m). The adoption of this level would not reduce the risk in already built-up areas of Villa Carlos Paz, but it would prevent the problem getting worse and would also serve as a basis for all new townships being built in other municipalities adjoining the reservoir.

The space liable to flooding in the perilake between levels 36 and 38 m is 200 ha, approximately 94 ha of which is currently part of the Villa Carlos Paz urban area. It represents 47% of the potential flooding area, meaning that by setting the level of 38 m as the lower limit for urbanization, approximately 106 ha would be kept risk free.

Table 6.9. Areas liable to flooding for the city of Villa Carlos Paz and percentage of urban areas at risk of flooding

Level [m]	**35.30**	**37.01**	**38.23**	**39.19**	**43.00**
ΔA (km²)	---	0.618	0.365	0.277	1.452
Area liable to flooding (ha)	---	***61.83***	***98.33***	***126.07***	***271.23***
% of urbanized areas at risk of flooding for Villa Carlos Paz					
In relation to the surface area corresponding to the crest height	---	10.90%	17.34%	22.23%	47.83%
In relation to the whole city	---	7.27%	11.57%	14.83%	31.91%

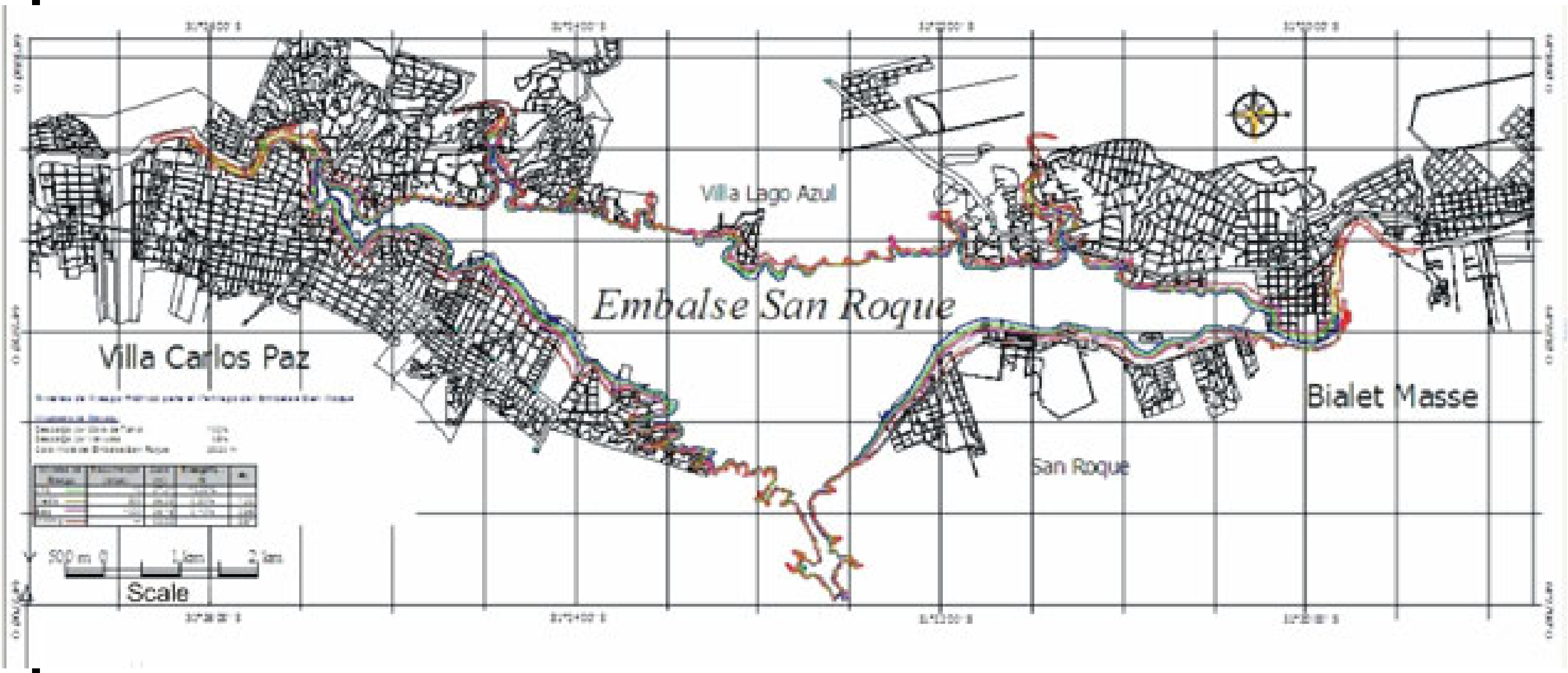

Villa Lago Azul
Embalse San Roque
Villa Carlos Paz
Bialet Masse
San Roque
500 m 0
1 km
2 km
Scale

Figure 6.50. Water risk map with associated return time for the city of Villa Carlos Paz (Source: Catalini, 2004)

6.3. Urban flooding in Central America

Central America has 54% of its population concentrated in urban areas, most of which has serious problems associated with urban drainage. The occurrence of severe storms, uncontrolled development of urban areas, with a strong tendency to apply only the sanitation engineer approach of discharging water as quickly as possible downstream, shortcomings in urban infrastructure and a marked presence of solid refuse on public thoroughfares, all contribute to recurring urban flooding.

Below we present some relevant issues regarding the metropolitan area of San Salvador (AMSS) and the city of Managua (Nicaragua).

6.3.1. Urban flooding in the Metropolitan Area of San Salvador

El Salvador has 55.4% of its population concentrated in urban areas. The Metropolitan Area of San Salvador (AMSS) has a population of 2 million. Ten per cent of them live in extreme poverty, mostly in high-risk areas (areas subject to storms, hillsides at high risk of landslip, etc.). Seventy-five per cent of dwellings are served by the sewage system though less than 10% of sewage collected is treated.

The Metropolitan Area of San Salvador has complex urban drainage issues. Most of the problems currently observed in the area are related to the quantity and quality of runoff water. The occurrence of urban flooding and ongoing problems of contaminated runoff are the result of traditional unplanned urban growth, the systematic application of the sanitation engineer's approach to storm water drainage and the lack of a government policy on the matter.

Population pressure, demand for land and services, the state of urban infrastructure and lack of planning have led to an exponential increase in the risks of flooding. It occurs not only in areas adjoining the rivers but also at higher altitudes.

The AMSS spreads over the upper section of two watersheds: the Acelhuate and the Ilopango. The main part of the AMSS is sited on the former. This watercourse receives sewage effluent discharges of 5 m^3/s. In the AMSS the water supply system is insufficient to meet the demand from new urbanization, and there is a constant need for new water sources of adequate quality and quantity. For many years the problems of the storm drainage system were tackled by building hydraulic structures such as conduits, drains, etc. In other words, they typically focused on structural measures designed to accelerate and concentrate surface flow. Owing to its continuing growth (Figure 6.51) the region has also experienced an uncontrolled increase in impervious surfaces

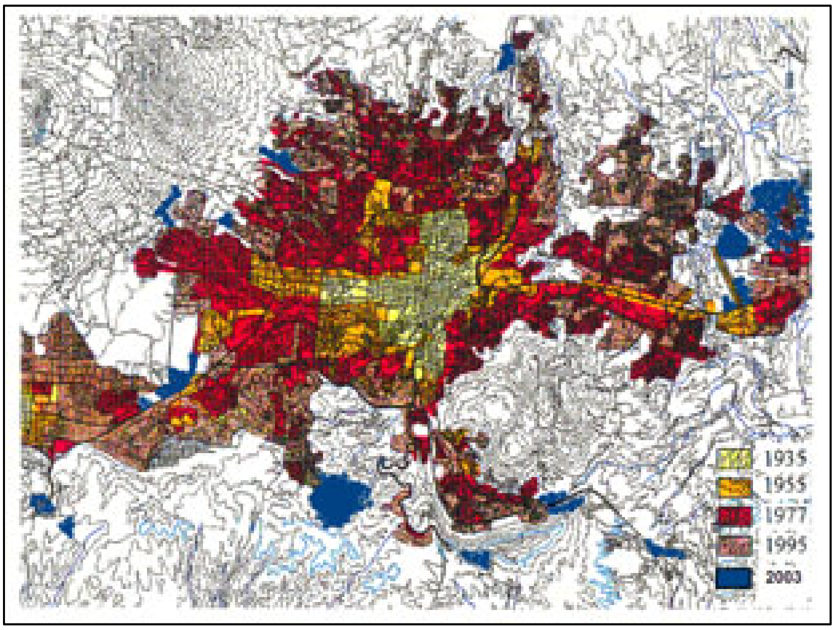


Figure 6.51. Growth of the Metropolitan Area of San Salvador (AMSS), 1935-2003 (Source: OPAMSS, 2005).

6.3.2. Urban flooding associated with tropical storm Stan (2005)

Over the first few days of October 2005 tropical storm Stan affected several countries in Central America. We list below some aspects of the situation in the AMSS.

From 28 September 2005 rainfall over El Salvador had begun to saturate the ground. On 1 October 2005 the atmospheric system caused a depression zone (1008 millibars) on El Salvador’s Pacific coastal region, encouraging the humidity to move over the country. From that morning, the Intertropical Convergence Zone caused rainfall and heavy cloudbursts throughout El Salvador, mainly in the central belt of the coastal areas.

Over a period of one week storm Stan produced heavy rainfall; for the AMSS total rainfall in six days exceeded 500 mm (Figure 6.52). According to SNET (2005) mean rainfall for October is 205 mm. The succession of floods and landslips that occurred in the 14 municipalities of the AMSS led to 65 deaths and a large number of homeless. Figure 6.53 illustrates the phenomenon in the urban sector.

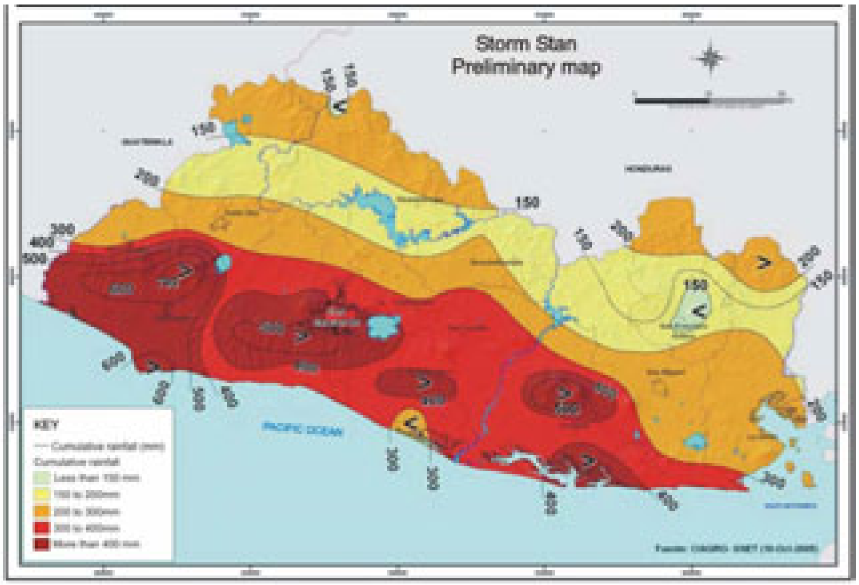


Figure 6.52. Total rainfall distribution during storm *Stan* in El Salvador (Source: SNET, www.snet.gob.sv).

Figure 6.53. Flooding in San Salvador during storm *Stan*. (Source: OPAMSS, 2005).

Figure 6.54. River flooding associated with tropical storm “Stan”. San Salvador. (Source: OPAMSS, 2005)

Some sources of information have claimed that this situation was caused almost exclusively by global climate change. Although the harsh climate in the Central American region has received much attention, the real causes of the problems observed are linked to social, technical and management factors.

As pointed out by Cruz and Molina (2004), the AMSS storm drainage system suffers from a number of problems. These include the absence of an institution legally responsible for planning, cleaning and general maintenance, resulting in the system currently being badly deteriorated and in poor working order. The Public Works Ministry has been responsible for maintaining the part of the system belonging to the public network. However, from 2000 a process began in which the Ministry gradually washed its hands of the problem.

The AMSS system of underground conduits consists almost entirely of circular-section concrete pipes. The problems identified in the drainage system include serious structural defects, inadequate hydraulic capacity, wrongly connected sewage and industrial effluent (Figure 6.55), poor design, decreasing downstream diameters and inspection covers sealed under the road surface.

Figure 6.55. Pipes discharging directly into the storm drains. (Source: Cruz and Molina, 2004).

Another important factor is that the climate has two clearly defined seasons: rainy and dry. The latter lasts five to six months on average, during which refuse and assorted waste accumulates. Heavy rain produces the conditions necessary to move all this solid waste and it goes into the storm drains.

All of the above results firstly from the lack of planning in the system and the lack of regulation of projects and, secondly serious shortcomings in the planning of the growth of the metropolitan area.

6.3.3. Test of regulating systems: case of the Paso Fresco urban housing development

The Paso Fresco urban housing development is located on the slopes of the San Salvador volcano. It has an area of some 2 ha, with 38 lots averaging 400 m² in area and an impervious area of 70%. Development began in 2004. The Environment Unit (UA) of the AMSS Planning Office (OPAMSS) proposed a flow regulation system that was one of the first of its kind in the AMSS area.

The storm water drainage and control system consisted of a conventional collection system (inlets and pipes) along with an underground storage and attenuation basin at the outlet of the housing development. The latter consists of three access chambers, a conduit 1.8 m in diameter and a restricted outlet (0.50 m in diameter) which acts as a regulator of the outflow into the municipal system (Figure 6.56). The connection between the large-bore conduit and the outlet to the public system is made in a chamber with two compartments connected by bottom feeds (0.30 m in diameter) and a spillway, as illustrated in Figure 6.57.

a. View of one of the access chambers to the regulator.

(b) Internal view of the regulation conduit, with marks of maximum levels during storm Stan (October 2005).

Figure 6.56. Conduit regulation system (Paso Fresco housing development).

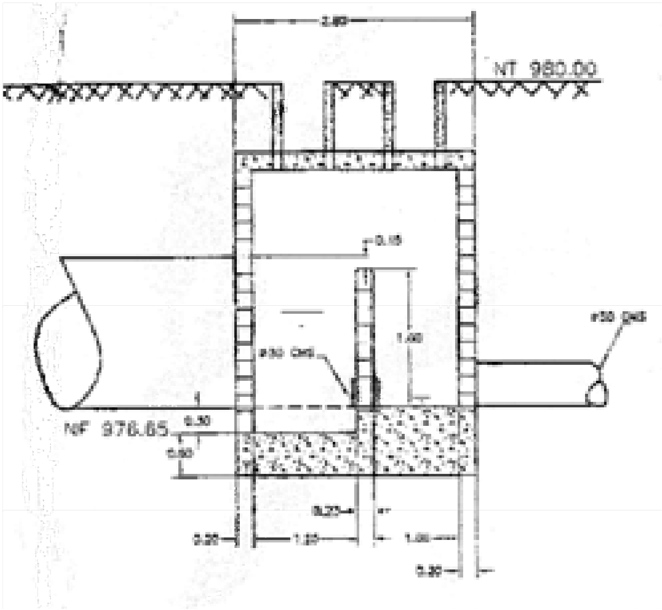


Figure 6.57. Detail of the construction of the storage and regulation chamber (Paso Fresco housing development, AMSS)

The system was simulated mathematically, including the dwellings, green spaces and streets (Figure 6.58; Bertoni and Catalini, 2005). To test the behaviour of the drainage system in various scenarios, design storms were used based on the I-D-F curves for the region. These events were analysed for a duration of two hours, with return times of 2, 5, 10, 25 and 50 years.

The simulations carried out reflected the behaviour of the drainage system in three basic alternative scenarios:

(i) rural pre-urbanized state,
(ii) traditional urban “sanitation engineer” approach, and
(iii)urban development with runoff control.

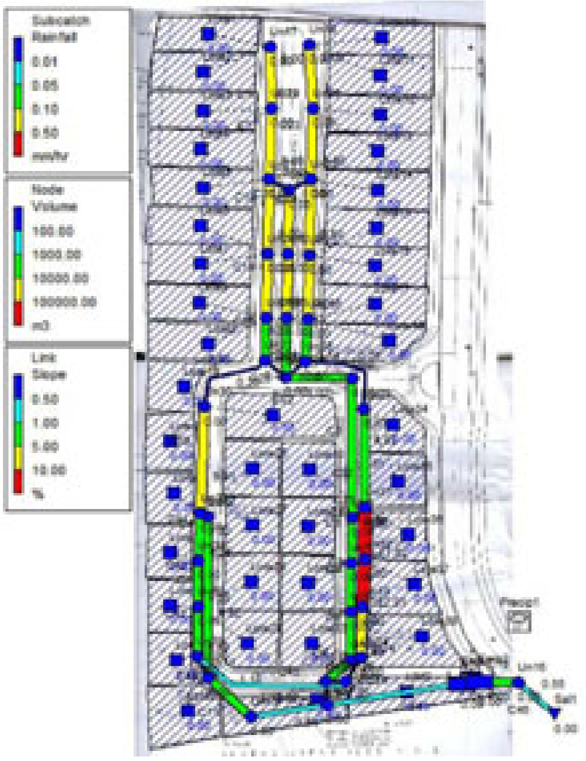


Figure 6.58. Simulation scheme of the Paso Fresco urban housing development

The first scenario reflects the conditions that should be maintained during urbanization. The second allows observation of the impact of traditional urban development based solely on collection and conduit structures that accelerate runoff. The simulations in the third scenario included:

(a) an analysis of the existing regulation system;
(b) optimization of the existing system, involving a reduction in the diameter of the runoff control conduit, and
(c) the adaptation of the control system adding an infiltration/exfiltration system in the form of a trench of porous material and perforations in the walls of the conduit used as an underground regulation system.

Simulation of rural pre-urbanized state

In this case the whole urbanization was assumed to be in the rural state. Table 6.10 shows the results obtained based on that assumption.

Table 6.10. Outlet flows and volumes for the pre-urbanized rural scenario

Tr [years]	**2**	**5**	**10**	**20**	**50**

Outflow	**[l/s]**	410	560	650	780	950
Volume	**[m³]**	762	1005	1338	1416	1707

Simulation of sanitation engineer scenario

Table 6.11 shows the values modelled for the various return times under analysis. Logically, we observe that urbanization has a greater impact in the more frequent storms, i.e. for low return times. This impact is an increase in runoff flows and volumes and a reduction in watershed response times.

Table 6.11. Outlet flows and volumes for the “sanitation engineer” scenario

Tr	**[years]**	**2**	**5**	**10**	**20**	**50**
Outflow	**[l/s]**	554.0	771.5	837.1	962.1	1092.4
Volume	**[m³]**	1227	1500	1852	1939	2227

Simulation of existing system (scenario of current regulation)

The results are shown in Table 6.12.

Table 6.12. Outlet flows and volumes for the existing regulation system

Tr	**[years]**	**2**	**5**	**10**	**20**	**50**
Outflow	**[l/s]**	457.1	769.9	838.0	960.5	1091.6
Volume	**[m³]**	1224	1483	1859	1963	2234
Depth	**[m]**	1,66	1,81	1,84	1,87	1,91

The information shown led to the conclusion that the system for attenuating and retaining excess runoff that is currently in operation has the capacity to regulate storms with return times exceeding those tested in this study. In other words, for storms with return times of between 2 and 50 years, the 0.50 m outlet pipe and the insufficient storage volume (formed by the 1.80 m conduit) are not able to attenuate the outflows.

To sum up, the characteristics of the output hydrographs indicate that the diameter of the outlet pipe to the municipal system is too large, preventing the system from retaining the excess runoff for sufficient time to make a significant reduction in the impact of urbanization on the storm drain system. The mathematical modelling of the whole housing development showed that the current storm drain system is generally oversized (street system, collector conduits, etc.).

Optimization of the existing system

In this scenario the selected alternative was to reduce the diameter of the system’s outlet pipe from 0.50 m to 0.30 m, i.e. a 40% reduction in the diameter of the regulation pipe. The results achieved with this alteration are shown in Table 6.13. Note the significant reduction in peak flows in relation to the current system. As expected, the effect of flow attenuation increases for the longer return times of heavy storms.

Table 6.13. Outlet flows and volumes for the existing system, with a 40% reduction in the outlet pipe.

Tr	**[years]**	**2**	**5**	**10**	**20**	**50**
Outflow	**[l/s]**	410.0	444.8	445.2	445.9	446.3
Volume	**[m³]**	1227.00	1506.84	1852.08	1946.40	2215.89
H above roadway	**[m]**	0.0	0.20	0.22	0.23	0.23
Duration	**[min]**	0	20	30	30	50

Logically, reducing the diameter of the outlet pipe increases the maximum levels in the 1.80 m diameter feed conduit. For long return times (10 to 50 years) it causes minor flooding (about 0.20 m) in the lowest areas (streets) of the housing development, for periods of time that never exceed 1 hour.

This type of controlled flooding (in terms of duration and maximum depth) is regarded as acceptable within the street’s design parameters, as it allows it to fulfil its basic function even in heavy storms.

Redesign of the existing system

A new alternative modelling carried out on the housing development was established starting from the assumption of installation an infiltration/exfiltration system in addition to the existing system. The redesign of the control system included the existence of a partial regulator trench around the feed conduit. The flow passes from the conduit into the trench through eight lines of holes bored in the conduit. Where the natural ground conditions allow, the flow from the trench infiltrates down to lower strata. As a conservative estimate of the operation of the trench, it was simulated using mathematical model parameters corresponding to a trench tested at the IPH-UFGRS in Brazil. We would point out that that trench was dug in ground that was much less pervious than that of the AMSS, so it is highly likely that most parts of the AMSS will allow higher infiltration volumes than those obtained in simulation.

The results shows substantial reductions in the peak outlet flow to the municipal system for all the return times analysed (Table 6.14).

Table 6.14. Outlet flows and volumes for the system with infiltration/exfiltration

Tr	**[years]**	**2**	**5**	**10**	**20**	**50**
Outflow	**[l/s]**	339.5	395.1	434.9	435.5	444.8
Volume	**[m³]**	1209.57	1476.99	1830.60	1920.63	2145.00
h above roadway	**[m]**	0.00	0.00	0.00	0.01	0.20
Duration	**[min]**	0	0	0	5	35

Comparing the results with those for the alternative of optimizing the existing system, we observe that only at long return times do the levels rise above street level, with a substantially shorter duration. The reductions in input volumes were insignificant owing to the conservative estimate of the effect of the trench. In practice, this type of system would be able to reduce runoff volumes.

Comparison of results obtained from all scenarios

Figure 6.59 shows the hydrographs for the outlet from the Paso Fresco housing development for each of the scenarios tested, for a return time of 10 years.

The most significant aspects are as follows:

- The urbanization of the Paso Fresco housing development according to the conventional process of building hydraulic structures of the “sanitation engineer” type would have a severe hydrological impact in relation to the rural pre-urbanized state of the area. This impact would be a significant increase in peak flow, a shorter peaking time and a substantial increase in total runoff volume;
- The existing runoff control system at the housing development succeeds in maintaining the peak of the hydrograph generated by the housing development to within 10% above the pre-urbanized situation. However, the runoff volume is similar to that of the sanitation engineer scenario;
- Optimizing the existing system (reducing the outlet pipe diameter) produces a “zero hydrological impact” in terms of flow and peaking time in relation to the rural situation. The runoff volume is similar to that of the sanitation engineer scenario;

- The adoption of a control system using infiltration can achieve a “positive hydrological impact” for the urbanization, since there is a significant reduction in the peak flow and an increase in the peaking time in relation to the pre-urbanized state. The runoff volume is lower than the other urban situations tested. The magnitude of the reduction depends on the prior permeability and humidity of the surrounding soil.

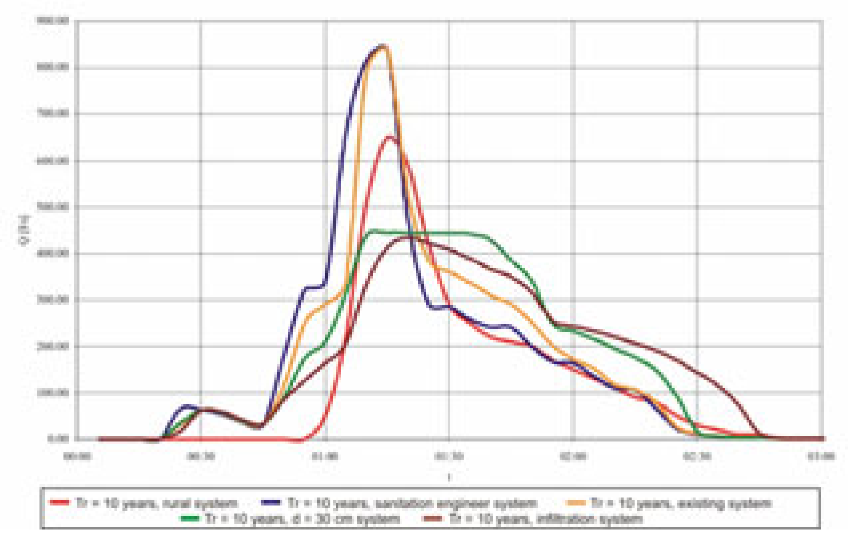


Figure 6.59. Output hydrographs for all the scenarios tested (Tr = 10 years)

In other words, the function of the proposed runoff control systems means that increasing the storm return time increases the duration of the peak flows without increasing peak flows, as is usually observed in urban areas (Figure 6.60).

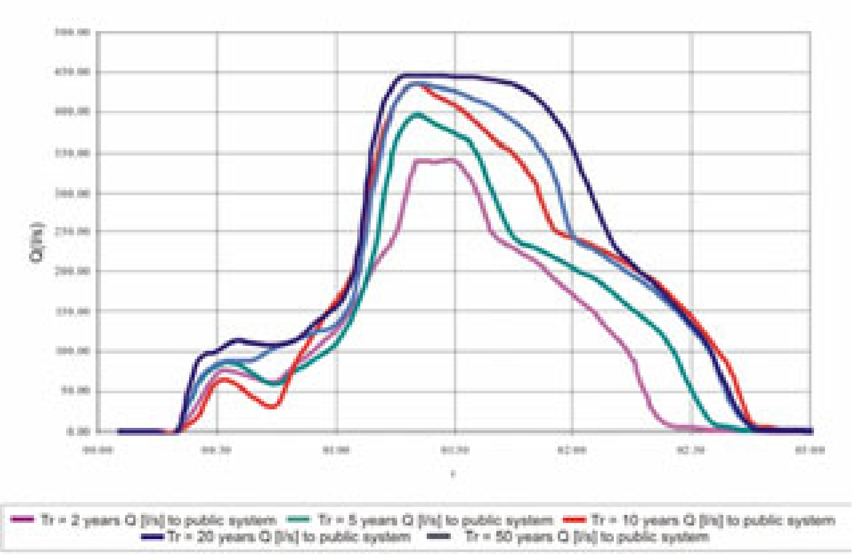


Figure 6.60. Effect of increasing duration of peak flows generated by the proposed control systems

6.3.4. Network of micro-dams in Managua, Nicaragua

The city of Managua, the capital of Nicaragua, has a total area of 544 km^2 of which 173.7 km^2 is urban area. The city has a population of approximately one million and an annual growth rate of 2.5%. The city is sited on an area of foothills above Lake Xolotlán (or Lake Managua). The relief of the region is rugged, which explains why the city is crossed by a huge system of watersheds, mostly with steep gradients, flowing into Lake Managua (Figure 6.61).

Throughout its history the city has been badly hit by a number of earthquakes (1844, 1855, 1931 and 1972). As a result of that, the city is currently formed of dispersed urban centres, interspersed by areas of lower population density. From the 1990s the city began a phase of strong renewed growth, in line with the country’s economic development. The accelerated growth of the city of Managua, with expansion towards the periphery, led to a deficit in basic facilities and services.

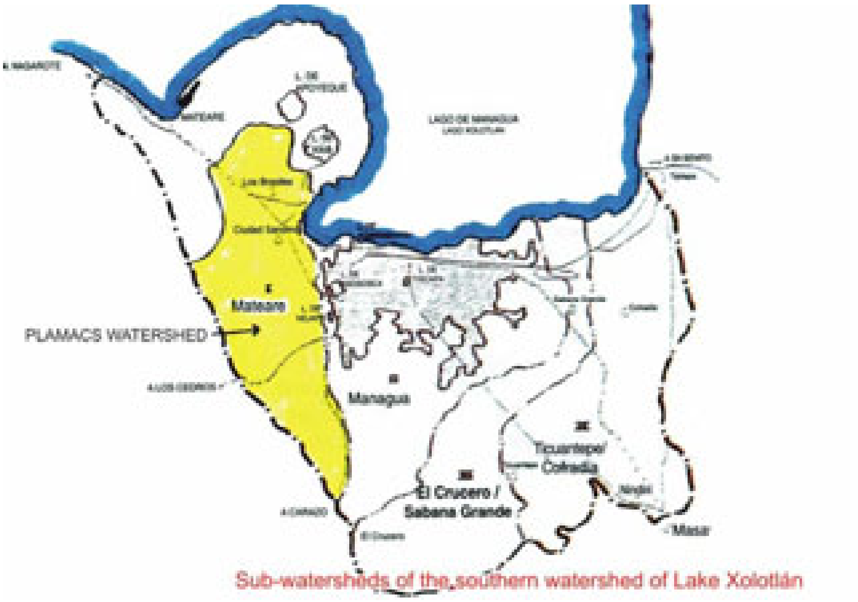


Figure 6.61. City of Managua and main contributing watersheds (Source: ALMA, 2005).

The city’s most sensitive urban problems include the following (Managua municipality, 2005):

- Its geographical location, which makes it more vulnerable to natural disasters, since it is crossed by active geographical fault lines, a huge system of natural watersheds and a fairly accentuated south-north inclination, towards the coast;
- Weak urban control owing to the lack of enforcement of and compliance with town planning laws and regulations, and a failure to update them, leading to anarchical growth of the city;
- A housing deficit;
- Limited coverage of basic services in the impromptu residential areas;
- Shortcomings in the refuse collection service.

The region has a tropical type climate, with frequent convective storms producing heavy cloudbursts. Floods originating in the watersheds that cross the city bring with them a considerable amount of solid material. In the upstream areas most of the refuse is agricultural waste produced by crop harvests. In the middle and lower areas of the watersheds, settled by the urban population, most of the waste is PET type plastic containers.

Since the 1980s the city has established a system of micro-dams in the middle and lower sections of each watershed, with the dual aim of collecting refuse and attenuating flood peaks (Figure 6.62). Some 15 micro-dams have so far been built. Although there is no systematic monitoring of the solid refuse collected and extracted, Sarria Duarte (*personal communication*, 2005) analysed the volume of sediments extracted from each micro-dam, with the results set out in Figure 6.. A new 95 000 m^3 reservoir was built in 2005 to collect refuse from one urban area (Figure 6.64).

Figure 6.62. Villa Fontana micro-dam in the city of Managua (Source: ALMA, 2005)

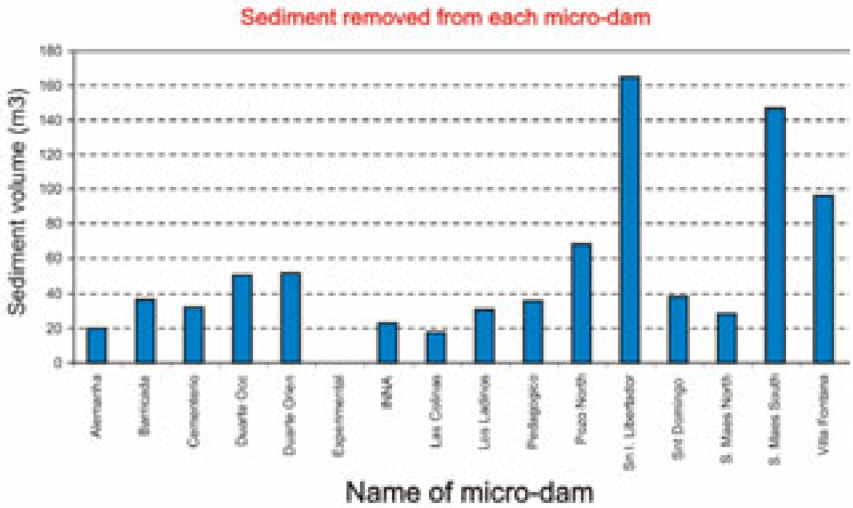


Figure 6.63. Volume of sediment collected by the network of micro-dams in the city of Managua (Source: Sarria Duarte, *personal communication*, 2005).

Figure 6.64. Concentration of urban refuse in the Los Gauchos Tiscapa micro-dam, opened in 2005. City of Managua.

References

BALLESTER, R. AND ÁLVAREZ, G. 2001. Problemática provocada por el ascenso de la napa freática en el municipio de Lomas de Zamora. Conurbano de la provincia de Buenos Aires. IIIº Jornadas de Saneamiento Pluvial Urbano. Conference proceedings. Municipality of Rosario. Available on CD.

BARBEITO, O., AMBROSINO, S., BERTONI, J.C. AND PAOLI, C.U. (2004). Inundaciones Severas por Crecidas Extremas. Chapter 9 in: Bertoni, J.C., Inundaciones Urbanas en Argentina, 2004, 270 p.

BERTONI, J.C. (ORG.) (2004), Inundaciones Urbanas en Argentina. Ed. GWP-SAMTAC. ISBN 987-9406-76-1. 270 p.

BERTONI, J.C., VATER, G. AND REDOLFI, E. (2004), Storm water Management in the Highway around network to access to Cordoba city, Argentina, Proceeding of Novatech, Lyon, France, 895-902.

BERTONI, J.C., PEUSER, G. AND SIMES, E. (2005). Estudio Hidrológico-Hidráulico correspondiente a las Cuencas de Aporte y a los Canales de Drenaje. Avenida de Circunvalación de la Ciudad de Córdoba Arco Noreste. Report to Caminos de las Sierras S.A. 96 p.

BERTONI, J.C. CATALINI, C.G. (2005). Dispositivos de Regulación y Control del Drenaje Pluvial Urbano. Service Contract No FORGAES 054-2005-SER. Report to OPAMSS. 320 p.

CAAMAÑO NELLI, G.; CATALINI, C.G (2002); Adaptación de técnicas para estimar lluvias de diseño a la predicción de crecientes en lagos y embalses, XIX Congreso Nacional del Agua. Full article: ISBN 987-20378-1-7, CD. Summary: ISBN 987-20378-0-9, pp. 43-44. Comité Permanente de los Congresos del Agua. Villa Carlos Paz. Argentine Republic.

CATALINI, C.G; Predicción de Ingresos de Agua al Embalse San Roque, Informe de Pasantia, Instituto Nacional del Agua, Centro de la Región Semiárida. Villa Carlos Paz, Argentina.

CATALINI, C.G (2004) Predicción de Crecientes en Embalses de Córdoba, Informe de Beca Especial convocatoria 2002 Agencia Córdoba Ciencia, S.E.

CRUZ, C. Y MOLINA L. (2004). Criterios para el drenaje de Aguas Lluvias. Segundo Curso Riesgos Urbanos: Drenajes de Aguas Lluvias

CRUZ, M., 2004; *Optimizaçào do controle da drenagem urbana*. Doctoral thesis, Instituto de Pesquisas Hidráulicas. UFRGS.

ESTEVE, J. R. (2001). Planes generales de desagües pluviales de la ciudad de Córdoba. IIIº Jornadas de Saneamiento Pluvial Urbano. Conference proceedings. Municipality of Rosario. Available on CD.

FALCZUK, B. (2001). Plan Director de Ordenamiento Hidráulico de la ciudad de Buenos Aires. IIIº Jornadas de Saneamiento Pluvial Urbano. Conference proceedings. Municipality of Rosario. Available on CD.

FERREIRA, G. (2005), Descripción de la Crecida del Río Salado e Inundación de Santa Fe en 2003. XX Congreso Nacional del Agua, Mendoza, Argentina. Proceedings on CD.

GUGLIELMO, R. (1996). Les grandes métropoles du monde et leur crise, Ed. A.Colin, Paris, 268 p.

IPH, 2001. *Plano Director de Drenagem Urbana de Porto Alegre*. Instituto de Pesquisas Hidráulicas. DEP Departamento de Esgostos Pluviales

Municipal authority of Porto Alegre. 5 volumes.

JICA, 1995. *The master study on utilisation of water resources in Parana State in the Federative Republic of Brazil.* Pectoral Report vol. 11. Flood Control.

MAZA, J. (2004). Inundaciones en los grandes centros urbanos, Chapter 5 in: Bertoni, J.C., Inundaciones Urbanas en Argentina, 2004, 270 p.

OPAMSS, (2005); Compendio de Informaciones sobre el AMSS, para ejecución del Contrato 054.2005-SER

PDDURM, 2002. *Plano Director de Drenagem urbana da Regiâo Metropolitana de Curitiba Volume: medidas não-estructurais*. SUDHERSA and CH2MHILL do Brasil Serviços de Engenharia Ltda..

PAOLI, C.U. (2004). Inundaciones ribereñas en el tramo del Parana Medio. Cap. 4 in: Bertoni, J.C., Inundaciones Urbanas en Argentina, 2004, 270 p.

PME, 1983. *Law No 1790. Municipal authority of Estrela 3p.*

PME, 1981. *Law No 1707. Municipal authority of Estrela 10p.*

REZENDE, B and TUCCI, C.E.M, 1979. *Análise hidráulica e hidrológica dos problemas de inundação urbana na cidade de Estrela.* RS. Technical report, p. 29

SERRA, J.J., MALNERO, H., SAINZ TRÁPAGA, J. AND CHACHERO, M. (2002). Aspectos más relevantes de la problemática hídrica en el valle inferior del río chubut (UNPSJB, Trelew, Chubut). XVIII Congreso Argentino de la Ciencia del Suelo; Puerto Madryn.

SERRA, J.J. (2004). Urbanización e Inundaciones en Sistemas Hídricos del Centro de la Región Patagónica, Chapter 6 in: Bertoni, J.C., Inundaciones Urbanas en Argentina, 2004, 270 p.

SNET (2005). Informaciones colectadas para el desarrollo del contrato 054/2005-SER. Servicio Nacional de Estudios Territoriales (unpublished).

SUDERSHA, 2002. *Medidas nâo-estructurais.* Plano Director de Drenagem Urbana da Regiâo Metropolitana de Curitiba. CH2MHILL. Engenharia do Brasil Ltda..

TOYA, M.; RAHMANNE, I. OLIVERA, S. AND BERTONI, J.C. (2003). Gestión de cuencos de retardo en el sistema de drenaje pluvial urbano de Córdoba. Poster. XIII Congreso Argentino de Saneamiento y Medio Ambiente. AIDIS. Buenos Aires. Argentina.

TUCCI, C.E.M 1996. *Estudios Hidrológicos e Hidrodinâmicos no rio Iguaçu na*. RMC. COMEC/PROSAM, 2 vols

TUCCI, C.E.M; VILLANUEVA, A, 1997. *Controle de enchentes das cidades de união da Victória e Porto União.* CORPRERI, 117 p.

TUCCI, C.E.M. Y BERTONI, J.C. (ORG.) (2004), Inundações Urbanas na América do Sul. Ed. GWP-SAMTAC, OMM, ABRH. ISBN:85-88686-07-4. 471 p.

TUCCI, 2005. *Proposta do Plano Nacional de Águas Pluviais*. Ministerio das Cidades Brasilia 120p.

Inundaciones. San Salvador.

WORLD BANK (1995). 1995 World Development Indicators, N.Y. USA.

WORLD BANK 2000. Argentina – Water Resources Management – Policy Elements for Sustainable Development in the 21st Century. Volume I – Sector report. Report No 20729-AR.

Annex A

Definitions and glossary

A.1 Drainage system: Drainage systems are classified as *at source, microdrainage and macrodrainage.* Drainage *at source* is defined as runoff that occurs in a housing development, condominium or individual project, car parks, parks and public thoroughfares.

Microdrainage is defined as the system of rainwater conduits or canals of a housing development or of the primary urban system. This type of drainage system is designed to handle drainage of rainfall with a moderate risk.

Macrodrainage denotes a collector system for a number of microdrainage systems. Macrodrainage covers an area of at least 2 km^2 (or 200 hectares). These must not be taken as absolute values as urban networks can have a wide variety of configurations. This type of system should be designed to handle precipitation higher than the microdrainage with risks depending on the potential human and material losses.

One of the points that has characterized this kind of definition has been the estimating method, since the Rational Method is used to estimate flows in microdrainage, and the hydrological models that determine the runoff hydrograph are used in macrodrainage. The simplifications accepted for specifying using the Rational Method can be used for watersheds of around 2 km^2, which corresponds to the limit laid down above.

A.2 Runoff and design conditions: Runoff in a river depends on a number of factors that can be divided into two classes:

Downstream control. Downstream control that alters upstream runoff is a constraint in the drainage system. Downstream control may consist of bottlenecks in the river owing to bridges, backfills, changes in section, reservoirs, sea, etc. These controls reduce the flow in a river regardless of the local runoff capacity.

Local control. This defines the capacity of each section of the river to carry a quantity of water. The local runoff capacity depends on the cross-sectional area, width, perimeter and roughness of the walls. The greater the runoff capacity, the lower the water level.

As an example of the process, it can be compared with the traffic in a street. The vehicle traffic capacity of a street, at a given speed, depends on its width and number of lanes. When the number of vehicles exceeds that capacity, the traffic moves slowly and there is congestion. In a river, as a volume of water arrives that exceeds the normal flow, the level rises and floods the riverside areas. Therefore, the system is limited in this case to the local capacity to carry water (or vehicles).

Consider, for example, the case of a wide road with two lanes in each direction, but where there is a section where the two lanes merge into only one. There is a transitional section, before the lane change, that slows down all the vehicles, creating congestion, not because of the road’s capacity at the point, but because of the situation in the next section. In this case, the capacity is limited by the change of lanes (taking place downstream), not by the local capacity of the road. Similarly in a river, if there is a bridge, backfill or other obstruction, the upstream flow is reduced by the downstream restriction rather than by the local capacity. As the flow reduces, levels rise. This is often known as the *backwater* effect.

The transition section, which is affected by the downstream conditions, depends on factors that vary with the level, gradient and flow capacity over the whole section.

Runoff can be regarded as a steady or non-steady state. Steady-state runoff is used in design work, generally with the peak design flows for a particular hydraulic system. The non-steady state can be used to determine levels and flows along the river and over time, and represents the real situation. Generally, a hydraulic structure that depends only on the peak flow is specified for steady-state conditions and tested in the non-steady state.

A.3 Risk and uncertainty: In this text the risk of a flow or precipitation means the probability (p) of the occurrence of an equal or higher value in any year. The return time (T) is the inverse of probability (p) and represents the *average* time at which this event is likely to recur.

$$T = \frac{1}{p} \qquad \text{(a.1)}$$

For example, consider a *die* with six faces (numbered 1 to 6). At any time the probability of throwing a number 4 is p = 1/6 (1 chance in six). The return time is the *average* number of throws for the desired number to come up again. In that case, using equation a.1 gives T = 1 (1/6) = 6. Therefore, **on average**, the number 4 comes up every six throws. We know that this number does not come up exactly every six throws, but the average will certainly hold true after thousands of throws. Therefore, the number 4 can come up twice in a row or it may not come up for a long time, but on average it will come up every six throws. By analogy, each throw of the *die* is a year for flooding. A return time of 10 years means that, on average, the flood may repeat every 10 years or that every year there is a 10% chance of this flood occurring.

The risk or probability of occurrence of greater or equal rainfall or flow in a particular period of *n* years is:

$$P_n = 1 - (1 - p)^n \tag{a.2}$$

For instance, what is the chance of a 10-year flood occurring over the next five years? In other words, we wish to know the probability of occurrence over a period of time and not just one particular year. In this case:

$$P_n = 1 - \left(1 - \frac{1}{10}\right)^5 = 0.41 \text{ or } 41\% \tag{a.3}$$

The probability or return time is calculated on the basis of the historical series observed at the place. To calculate the probability the series must be representative and homogeneous over time. When the series is representative, the existing data allow the probability to be calculated correctly. For example, the period of flooding between 1970 and 1998 in the river Guaíba in Porto Alegre, Brazil, is not very representative, as only minor floods occurred and several major ones occurred outside that period.

The series is *homogeneous* when changes in the watershed do not produce significant changes in its behaviour and, as a result, in the river's flow statistics.

When planning urban areas, as there are alterations to the watershed, *the risk used relates to the occurrence of a particular precipitation, and it is accepted that it is not influenced by* *urbanization*. The combination of the occurrence of the precipitation, its distribution over time, prior conditions, etc. mean that the risk of precipitation is not the same as the risk of the resulting flow.

The risk adopted for a project defines the relationship between the investments involved to reduce the frequency of flooding and the losses accepted. By adopting an annual risk of 10%, or a return time of 10 years, it is accepted that on average events may occur causing damage once every 10 years. A proper analysis involves an economic and social assessment study of the impacts of flooding when defining risks. However, this is not a feasible practice for small areas owing to the cost of the study itself. Accordingly, the risks usually adopted are presented in table a.1.

The designer must also try and analyse the following:

- Choose the upper limit of the interval from the table when there are serious risks of interrupting the traffic, material damage, potential interference in infrastructure works such as electricity substations, water supplies, storage of hazardous products when mixed with water, and hospitals;
- When there is a risk to human life, one should endeavour to set up a civil defence and warning programme and use a design limit of 100 years.
- Evaluate the impact for events exceeding the design values and plan a warning and damage control system.

Uncertainty is the difference between the statistics of the sample and the population of a set of data. Uncertainties are present in errors of data collection, parameter definitions, characterization of a system, simplifications in models and in the processing of this information to design the drainage project.

A.4 Glossary: ***Natural system:*** A natural system is formed by the set of physical, chemical and biological elements that characterize the natural system of the watershed and water resources formed by the rivers, lakes and seas.

Ecosystems can be viewed as dynamic production factors for social and economic development (Folke, 1997). Ecosystems produce renewable resources and related mechanisms on which human society is based. At global level the ecosystem is energized by solar radiation and sustained by the water cycle, and at local level by the biota that support life and the integrated environment (Falkenmarker, 2003).

Table A. 1. Return time for urban systems

System	Type	Interval	Frequent value
Microdrainage	Residential	2 – 5	2
	Commercial	2 – 5	5
	Areas of public buildings	2 – 5	5
	Airport	5 – 10	5
	Commercial areas and streets	5 – 10	10
Macrodrainage Zoning of riverside areas		10 - 25 5 - 100	10 100*

* limit of regulation area

Conservation: the act of minimizing human action on the ecosystem;

Preservation: the act of avoiding any human action on the ecosystem;

Sustainable development: economic and social development that conserves and preserves the ecosystems over time.

Integrated water resource management: the process that fosters coordinated development and management of water, land and related resources to maximize the economic and social outcome in an equitable way without compromising the ecosystem’s vital sustainability (GWP, 2000).

Load: the product of concentration of a water quality parameter and flow; it is more representative than the concentration of a water quality parameter. A concentration may be high with a small flow or very low with a high flow.

Water availability: the availability of water in a particular place over time. It may refer to the availability of surface or ground water.

Flow regulation: The availability of water can be natural, without the effect of regulation, and with regulation from a reservoir. Regulation can be measured on the basis of a proportion of the average flow, as the peak flow, that can be regulated, is the average flow representing the peak available flow. Depending on the climate and the topographical conditions the regulated flow may vary between 0.25 and 0.8 of average flow. For humid climates in Brazil values of 0.6 to 0.7 of the average flow have been used and for semi-arid climates 0.20 to 0.40 (Silva and Tucci, 2002);

Water-borne diseases: There are many diseases that are transmitted in water. In Brazil 65% of hospitalizations are due to water-borne diseases. Diseases transmitted through water can be classified according to the scheme of White *et al.* (1972) and presented by Prost (1993):

- Water-borne diseases: these depend on water for transmission, such as cholera, salmonella, leptospirosis (developing during flooding by mixing with mouse urine), diarrhoea, etc. In this case the water becomes the passive vehicle for the infection agent;
- Water-washed diseases: these depend on the education of the population and the availability of safe water. These diseases are linked to ear, skin and eye infections;
- Water-related diseases: in which the agent uses the water, such as malaria, schistosomiasis (the agent uses the water to develop) and haemorrhagic fever.

Contaminating sources: diffuse and point sources. The origin of diffuse sources is generally urban (rainwater runoff), agricultural (rainwater runoff carrying organic material, sediments, agrichemicals, etc.), diffuse livestock production (poultry and pig farms), dispersed mining (use of mercury, coal mining producing acid water, etc.); sewage effluent in trenches; traditional point sources are urban and rural domestic effluents and industrial effluents.

Water quality indicators: the indicators may be indices combining concentration of certain constituents of the water. The indices aim to reflect the condition of the water for various uses depending on the river class (definitions for use). The indicators can also be the concentration of certain water quality parameters that reflect the conditions depending on the contaminating sources. For instance, the concentration of coliforms (in parts per million) is generally used to characterize water contamination for use in water supplies where the source is human organic. Dissolved oxygen (DO) and biochemical oxygen demand (BOD) are quality parameters that indicate the state of the river in terms of organic pollution in general and aquatic life. Nitrogen and phosphorus concentration are used to determine whether a water system can eutrophicate. COD is chemical oxygen demand, used as an indicator of pollution by certain industries.

Flood control measures:

Structural measures: when humans alter the natural system to control flooding, using dykes, dams, reforestation, etc.;

Non-structural measures: where humans live with flooding using: flood insurance, flood forecasting and warning, zoning of areas liable to flooding, local protection and associated legal measures.

Millennium goals: The United Nations has set the goal of halving world poverty by the year 2015. In the context of water and sanitation, these goals are also to halve the proportion of people without access to safe water and the same proportion for sanitation of domestic effluents.

Climate change: changes in climate variability due to human activity.

Consumptive uses of water: these are uses that reduce the volume between taking water from the system and returning it. The following are generally regarded as consumptive uses: human and animal water supplies, industry and irrigation.

Climate variability: variations in the climate depending on the natural constraints of the earth and interactions between them. *Climate change* is change to the climate as a result of human action. However, the IPCC (2001) defines *climate change* as change in climate over time whether due to natural variability or as a result of human activity.

Vulnerability to extreme events: the population’s inability to return to the conditions prior to the occurrence of the event in terms of housing and socio-economic conditions.

Annex

B

Regulations for Porto Alegre, Brazil

Federal and provincial (or departmental) legislation: Legislation on urban drainage and river flooding is related to: water resources, land use and environmental licences.

Water resources: Brazil’s Federal Constitution defines responsibilities for rivers, and federal legislation defines water resources at federal level and lays down the basic principles of management by watersheds. The watershed of the river Guaíba, in which the city of Porto Alegre is located, is in a water system that is the State’s responsibility.

Article 171 of the State Constitution establishes the Provincial (Departmental) System of Water Resources and, in paragraph 1, states that the system shall take action to *“control surface and ground water”:* Provincial Law No 10.350 of 30 December 1994 governs the Provincial System of Water Resources. Article 2 states that one of the policy’s objectives is to *“combat the adverse effects of flooding, drought and soil erosion”* and to *“prevent the degradation and promote the improvement of the quality and increase the capacity of supply from surface and ground water sources...”*

Article 3 emphasizes that “*all uses of water resources affecting its availability in terms of quality and quantity, except those to satisfy basic individual living needs, are subject to prior approval by the State”*.

The legislation states that decentralized management by the Watershed Committee is the first stage for resolving conflicts over the use of water resources.

Article 29 states that “*any project or activity adversely affecting the quantity and/or quality of surface or ground water shall be subject to approval of the use of water, in accordance with the*

Provincial Plan and Watershed Plans”. In this context, storm water runoff from cities must be approved or controlled by provisions of those plans. As these procedures are not yet being enforced by the State, for the time being there is no direct pressure to reduce the impacts of urbanization.

The tendency will be for the State Committees, in their areas of responsibility, such as the lake of the river Guaíba near to Porto Alegre, to lay down water quantity and quality standards to be observed by the municipalities.

Land use: Article 30 of the Federal Constitution states that land use is a municipal responsibility. However, the States and the Union may lay down rules governing land use on grounds of environmental protection, control of pollution, public health and security. This means that urban drainage, involving environment and pollution control, is a joint municipal, provincial and national responsibility. The municipalities tend to introduce urban macro-zoning guidelines in urban development master plans, encouraged by the provinces.

However, in many of the country’s cities land use zoning has not taken account of drainage or flooding.

On the other hand, there has been restrictive legislation to protect water sources and settlement of nature reserves, without the municipality acquiring ownership or levying taxes on them. Highly restrictive legislation merely leads to negative reactions and disobedience. It does not therefore foster the aims of urban drainage control. This takes the form of the invasion of protected areas, unlawful housing developments, etc.

Environmental licence: This licence sets limits on building and operating drainage canals, pursuant to Law 6938/81 and CONAMA resolution No 237/97. Likewise, Article 2, VII of CONAMA resolution 1/86 requires an environmental licence for “water drainage works”.

Recently, on the subject of environmental licensing procedures in the city of Porto Alegre, it was agreed that this would be the responsibility of the municipality, taking account of existing legislation, higher authorities or similar.

Regarding the boundary with other cities, Porto Alegre has a small area of watershed in common with other municipalities. The main ones are: (a) the upstream section in the watershed of the Diluvio stream, which is in the municipality of Viamão, where that city’s activities can affect the downstream Diluvio watershed, in Porto Alegre; (b) a contributing area of the left bank of the Feijó stream, forming the boundary of Porto Alegre with the cities of Alvorada and Viamão. In this case, the urban regulations and control on both sides of the stream must be consistent with the drainage control policy.

Institutional drainage control involving more than one municipality can be achieved by: (a) municipal legislation appropriate to each municipality; (b) provincial legislation setting standards to be maintained in the municipalities so that no impacts are transferred; (c) both of the above procedures. The last case will probably have to occur in the long term, but in the short term the first option is more viable, until such time as the Watershed Committees and Provincial Plans enact sectoral regulations. Therefore, when watershed plans are devised that involve more than one municipality, attempts should be made to agree on joint action between the municipalities in order to achieve planning of the whole watershed.

Urban and Environmental Development Master Plan

We set out below the main elements of the municipal legislation, the Urban and Environmental Development Master Plan (PDDUA), Law No 434 of 1999, on urban drainage.

Environmental enhancement, principles and strategies: Article 1 paragraph II of the PDDUA of the city of Porto Alegre states that its basic principles are *to promote quality of life and of the environment, reducing inequality and social exclusion*. The Plan embodies the principle of environmental sustainability in its title, principles and directives (Article 2).

Article 13 sets out the Plan’s environmental enhancement objectives, while Article 15 defines the natural elements of the environment and Article 16 describes a watercourse as a liquid mass covering a surface, following a course or forming a pool, with a perennial, intermittent or periodic current.

The environmental strategy (Article 17) is to be implemented, *inter alia*, by *promoting sanitation measures, monitoring contamination and optimizing energy consumption*. Urban drainage falls within the context of environmental sanitation. Still within the strategy of environmental qualification, examples of the programmes provided for in Article 18, which are in some way interrelated with the plan, are the Programme for Establishing and Maintaining Urban Green Areas (III), the Environmental Management Programme (V), and the Pollution Prevention and Control Programme (VI). Article 25 sets out the city planning strategies, notably the Information Systems Programme and in (IV) the Environmental Communication and Education Programme, which includes similar programmes provided for in this plan.

Formulation of policy, plans and programmes: Article 39 sets out the functions of the *Municipal Environmental Development Council* which has the task of formulating urban development policy, plans, programmes and projects, one of which is the Urban Drainage Master Plan (PDDRU). This council has representatives of the municipal, provincial and national levels, government agencies, non-governmental organizations and the city planning regions.

Article 42 states that planning shall be carried out under the PPDUA (Urban and Environmental Development Plan) and Article 43 provides for sectoral and inter-sectoral plans.

Regulation instruments: The regulation instruments lay down the project types, studies needed depending on the characteristics of the projects, emphasizing environmental adaptation and contamination control, drainage being an important part of this.

In this context, the Urban Planning Feasibility Study is required for urban projects, with the aim of analysing the impact of the urban infrastructure, including drainage (Article 63, paragraph 1).

The PDDUA provides, in the legislation, for some instruments of importance to urban drainage depending on the types of areas:

- *Sparsely inhabited areas* (Article 65) where there is provision for measures that monitor water contamination, do not change in soil absorption and do not create risks of flooding.
- *Urban growth containment areas* (Article 80) are areas that may be demarcated on the basis of the current densification and its future aggravation of restrictions through the increase in flooding or drainage constraints. The city of Porto Alegre has an extensive riverside area where drainage costs are very high. With excessive impermeabilization of these areas significant drainage problems may arise, with frequent flooding. The plan for each watershed may allow these areas to be identified;
- *Renewal areas* (Article 81): these represent areas of environmental heritage or which are relevant to the city

requiring special treatment. Article 83 defines the following areas: the historic centre, the islands of the Jacuí delta, the Guaíba coastal strip, Belas beach. Only the historic centre is not in the riverside flooding risk area owing to the protection afforded by the Mauá wall.

- *Areas of special environmental interest:* these are outstanding areas requiring special treatment (Article 85, paragraph I).
- *Environmental protection areas* (Article 87) may be permanent preservation and conservation areas; they have special features and require specific zoning.

Regulating plan: Article 97 lays down one of the basic principles for regulating urban drainage; in recognized problem areas rainwater detention basins must be built. Its sole paragraph states that it is to be the Executive's responsibility to lay down the criteria by decree.

Article 134 restricts the division into plots of land liable to flooding until action has been taken to ensure that water can run off and to protect against flooding, and of land where the geological and hydrological conditions are unsuitable for building (Annex 8.1). Paragraph 3 lays down space restrictions for urban drainage as "non-building" land and paragraph 6 states that new projects must preserve the watershed's original conditions by attenuating rainwater flows.

Article 137 sets aside areas for urban amenities, including urban drainage.

Article 160 of the transitory provisions highlights the need for a decree of the legislature defining and specifying rainwater reservoirs.

One aspect related to environmental protection and urban drainage is the belt alongside urban streams. The Forestry Code provides for a distance of 30 m from the banks of streams, determined by the section of the minor bed. This limit has not been complied with in the development of the city, which makes it difficult to control the urban drainage infrastructure. In this connection, there is a need for measures applicable to the developed city, with approval of subdivisions and payment for future subdivisions in the city.

Proposed regulations

The regulations proposed are based on the principles of control of rainwater runoff at source by using systems to attenuate runoff from impermeabilized areas and/or recover the infiltration capacity by means of pervious materials or drainage in infiltration areas.

In view of the municipal legislation setting up the PDDUA, discussed in the previous section, the decree proposed here implements Article 97 as provided for in the sole paragraph and Article 160 of the transitional provisions. In addition, it should be pointed out that in Article 134 paragraph 6 on the division of land, the law also lays down the same conditions for new projects.

We present below a proposal for a municipal decree for assessment by the Executive, intended to implement Articles 97 and 134 of the Environmental and Urban Development Plan.

This proposal is based on standardizing basic elements to be regulated, namely:

- Peak outflow to be maintained in all urban developments such as new buildings or housing developments;
- Detention volume required to maintain the peak flow referred to in the previous section;
- Space for the use of pervious paving and other measures for entrepreneurs to control urban drainage at source;
- Rights of way and constraints for new plot divisions.

Proposal for a decree

DECREE No

Regulating the control of urban drainage.

The Mayor of the Municipality of Porto Alegre, pursuant to his powers under the law and taking account of Articles 97 and 135 paragraph 6 of Supplementary Law 434/99 and whereas:

- It is for the public authority to prevent the increase of flooding caused by impermeabilization of the ground and canalization of natural streams;
- Impermeabilization causes more frequent flooding and increases the charge of solid material, thereby degrading the urban environment and impairing water quality;
- It should be the responsibility of each entrepreneur to preserve the prior flooding conditions in the city’s streams, and to avoid transferring to the rest of the

population the burden of making urban drainage compatible;
- Preserving the infiltration capacity of urban watersheds is a priority for the environmental conservation of streams and rivers comprising the macrodrainage and of rivers receiving runoff from the city of Porto Alegre,

Hereby declares as follows:

Article 1. The specific peak outflow to the public system from any settlement resulting in an impervious surface shall not exceed 20.8 l/(s.ha).

§ 1. The peak outflow is calculated by multiplying the specific flow by the total land area.

§ 2. Impervious area denotes all surfaces that prevent water infiltrating into the subsoil.

§ 3. Water precipitated onto the ground may not be drained directly into streets, gutters or drainage systems except as provided for in paragraph 4 of this Article.

§ 4. Areas set back from the public thoroughfare and maintained as green spaces, may be drained directly into the drainage system.

§ 5. For land of an area less than 600 m^2 for private houses the flow limit laid down at the beginning of this Article may be waived at the discretion of the Department of Rainwater Drainage.

Article 2. Where land is divided into plots, any development shall be subject to the specific peak flow provided for in Article 1.

Article 3. Proof of the maintenance of the prior settlement conditions on the plot of land or housing development shall be furnished to the Department of Rainwater Drainage (DEP) of Porto Alegre.

§ 1. For land of an area of less than 100 (one hundred) hectares where the entrepreneur opts for control by means of a reservoir, the reservoir volume shall be determined by the following equation:

$$v = 4.25 \cdot AI$$

where v is the volume per unit area of land, in m^3/ha, and AI is the impervious area of the land, expressed as a percentage.

§ 2. The volume that needs to be reserved for areas exceeding 100 (one hundred) hectares shall be determined by means of a specific hydrological study, with a design precipitation having a 10% probability of occurring in any year (return time = 10 (ten) years).

§ 3. The area to be used for the calculation referred to in paragraph 1 may be reduced if the following measures are taken:

- Laying of pervious paving (perforated blocks filled with sand or grass, porous asphalt, porous concrete) to halve the area used by such paving;
- Disconnection of roof gutters for drained pervious surfaces: reduce area of drained roof to 40%;
- Disconnection of roof gutters for undrained pervious surfaces: reduce area of drained roof to 80%;
- Implementation of infiltration trenches: reduce areas drained by trenches to 80%.

§ 4. The application of the structures listed in § 3 shall be subject to authorization from the DEP, after due assessment of the minimum infiltration conditions of the ground at the site of the project, to be declared and checked by the interested party.

§ 5. The rules for specifying and constructing the structures listed in § 3 and reservoirs shall be taken from the Urban Drainage Manual of the Porto Alegre Urban Drainage Master Plan.

Article 4. Once the DEP has approved the rainwater drainage design for a building or housing development, no additional surface shall be impermeabilized.

Single paragraph: A surface may be impermeabilized where provision is made for retention of the additional volume generated in accordance with the equation in Article 3 § 1.

Article 5. Any cases not covered by this Decree shall be subject to a technical analysis by the DEP.

Article 6. This Decree shall enter force on the date it is published, and any provisions that contradict it shall be repealed.

MUNICIPALITY OF PORTO ALEGRE

Annex C

Sharing urban drainage costs for uncontrolled areas

C. Maintenance cost

The uniform unit cost would be

$$Cu = \frac{Ct}{A_b}\left(\$/m^2\right) \qquad (c.1)$$

where A_b is the area of the watershed in km^2 and CT the total cost in millions of \$. A_b the area of the watershed may be subdivided into:

$$100 = A_p + A_i \qquad (c.2)$$

where Ap is the proportion of pervious areas (%) and Ai the proportion of impervious areas (%).

In an urban area the impervious areas may be broken down using the expression:

$$A_i = \alpha i_m + \beta i_l \qquad (c.3)$$

where α is the proportion of area with streets and public amenities, such as parks and squares; i_m, is the impervious proportion of that area (%), β is the proportion of the area occupied by urban housing developments and i_l is the impermeabilized proportion of the housing development. In this case it is assumed that $\beta = l - \alpha$.

The previous equation gives:

$$A_i = \alpha i_m + (1-\alpha) i_l \qquad (c.4)$$

The value of α usually varies from 0.25 to 0.35 of the housing development area. Taking a value of α = 0.25 and with a distribution of 15% for streets and 10% for squares and, assuming the streets have 100% impervious area and the squares close to zero, we get

$$i_m = (0.15x100 + 0x0.10)/0.25 = 60\% \qquad (c.5)$$

Equation 4 gives:

$$A_i = 15 + 0.75 \cdot i_l \qquad (c.6)$$

The charge levied for the operation and maintenance of urban drainage works on the principle of proportionality in relation to the volume of surface runoff generated. Since impervious areas have a runoff coefficient of 0.95 and pervious areas 0.15 (Cp = 0.15 and Ci = 0.95), the volume generated by the impervious areas is 6.33 higher than that of the pervious areas. Accordingly, the unit cost of a pervious area is:

$$\mathrm{Cu_p} = \frac{0.15}{0.95}\mathrm{Cu_i} = 0.158 \cdot \mathrm{Cu_i} \qquad (c.7)$$

where $\mathrm{Cu_i}$ is the unit cost of the impervious areas. The total cost of operation and maintenance is equal to:

$$\mathrm{Ct} = \frac{A_b}{100}\left(\mathrm{Cu_p} \cdot A_p + \mathrm{Cu_i} \cdot A_i\right) \qquad (c.8)$$

Using equations 2 and 7 in equation 9, this gives:

$$\mathrm{Ct} = \frac{A_b \cdot \mathrm{Cu_i}}{100}\left(15.8 + \ 0.842 \cdot A_i\right) \qquad (c.9)$$

The unit cost of the impervious areas is:

$$\mathrm{Cu_i} = \frac{100 \cdot \mathrm{Ct}}{A_b \cdot \left(15.8 + \ 0.842 \cdot A_i\right)} \qquad (c.10)$$

where Cu is expressed in $\$/m^2$, Ct in millions and A_b in km^2.

Knowing the values of Ct, A_b and A_i for the whole watershed, the value of Cu_i is established for the watershed or for the total area concerned.

The calculation of the cost to paid by a property of area A, in m^2, is:

$$Tx = \frac{A}{100}\left(Cu_i \cdot A_i + Cu_p \cdot A_p\right) \qquad \text{(c.11)}$$

and

$$Tx = \frac{A}{100}\left[Cu_i A_i + 0.158 \cdot Cu_i \cdot (100 - A_i)\right] \qquad \text{(c.12)}$$

$$Tx = \frac{A \cdot Cu_i}{100}\left(15.8 + 0.842 \cdot A_i\right) \qquad \text{(c.13)}$$

where Ai is the impervious area of the property, as a %. The expression of A_i can be obtained from equation 5 which, substituting in equation 12, gives:

$$Tx = \frac{A \cdot Cu_i}{100}\left(28.43 + 0.632 \cdot i_l\right) \qquad \text{(c.13)}$$

To check the consistency of this equation, consider a watershed with a total impervious area of 40%. For the total area of the watershed to have 40% of impervious areas, the impervious area of the housing developments (according to equation 5) will be i_l = 33.33%, and assuming A = Ab, using equations 11 and 12, we should obtain Tx = Ct.

As an example, consider the cost of $ 1 400.00/ha, in a watershed with 40% impervious area, the maintenance cost of a 300 m^2 housing development is obtained initially using equation 9:

$$Cu_i = \frac{100 \text{ x } 0.14}{1 \text{ x } \left(15.8 + 0.842 \text{ x } 40\right)} = \$0.283/m^2 \qquad \text{(c.14)}$$

$$Cu_p = 0.283/6.33 = \$0.045/m^2 \qquad \text{(c.15)}$$

and equation 12, giving

$$\mathrm{Tx} = \frac{300 \cdot 0.283}{100}\left(28.43 + 0.632 \cdot i_l\right) = 24.137 + 0.545 \cdot i_l \qquad \text{(c.16)}$$

Table C. 1. Example of cost-sharing based on the impervious area of the housing development

Impervious area %	**Annual charge for land of 300 m^2 ($)**
5	26.86
10	29.59
20	35.04
30	40.49
40	45.94
50	51.39
60	56.84
70	62.29
80	67.74

Sharing of costs for implementing structures in the Drainage Plan.

In this case, the costs are divided up only for impermeabilized areas that have increased the flow above the natural values. In this case equation 1 is:

$$\mathrm{Cup}_i = \frac{\mathrm{Ctp} \cdot 100}{A_b \cdot A_i} \qquad \text{(c.17)}$$

where Ctp is the total cost of implementing the Plan and A_i is the distribution of the impervious areas in each area, given by equation 5.

The charge to be levied for each area of the urbanized housing development of i_l % is obtained using the expression:

$$\mathrm{Txp} = \frac{A_i \cdot \mathrm{Cup}_i \cdot A}{100} \qquad \text{(c.18)}$$

which, according to equation 5, gives:

$$\mathrm{Txp} = \left(15 + 0.75 \cdot i_l\right)\frac{\mathrm{Cup}_i \cdot A}{100} \qquad \text{(c.19)}$$

Substituting equation 14 gives:

$$\mathrm{Txp} = \frac{A \cdot \mathrm{Ctp} \cdot \left(15 + 0.75 \cdot i_l\right)}{A_b \cdot A_i} \qquad \text{(c.20)}$$

where, as before, A_i is the impervious area of the whole watershed as a %; A is the area of the land in m^2; A_b is the area of the watershed in km^2; Ctp is the total cost in $ million, and i_l is the impervious area of the housing development as a %.

For a housing development with no impervious area, the owner's contribution relates to the common part of the streets, giving:

$$\mathrm{Txp} = \frac{15 \cdot \mathrm{A} \cdot \mathrm{Ctp} \cdot}{\mathrm{A_b} \cdot \mathrm{A_i}} \qquad \text{(c.21)}$$

Consider a watershed requiring a $ 3 million investment to comply with the Master Plan. The impervious area is 40% and the watershed area 5 km^2. The charge payable for a 300 m^2 plot of land for the implementation of the measures in the watershed is obtained from:

$$\mathrm{Txp} = \frac{300 \cdot 3 \cdot (15 + 0.75 \cdot i_l)}{5 \cdot 40} = 67.5 + 3.375 \cdot i_l \qquad \text{(c.22)}$$

Table C.2 shows the values according to the impervious area of the housing development.

Table C. 2. Charge for implementing the watershed Master Plan for a 300 m^2 plot of land.

Impervious area %	**Tx [$]**
0	67.50
10	101.25
20	135.00
30	168.75
40	202.50
50	236.25
60	270.00
70	303.75
80	337.50

Annex D

Background to regulations for Porto Alegre

In the regulations on urban development it is necessary to establish basic calculation criteria, so as to simplify the definition of legal measures and the specification of control due to impermeabilization. Some of the basic parameters to be regulated are:

- Specific flow before development;
- Specific volume necessary to control a particular area.

Flow before development

The flow before development corresponds to the conditions closest to the natural situation. In principle, this flow must be maintained after development. To regulate this flow simple criteria have to be established that are generally applicable in the city, without detriment to control. The flow can be obtained using the Rational Method by the expression:

$$Q = 0.278 \cdot C \cdot I \cdot A \qquad (d.1)$$

where Q is the peak flow in m^3/s, I is the precipitation intensity in mm and A is the area of the watershed in km^2. This equation can be expressed for the natural specific flow as:

$$q_n = \frac{Q}{A} = 2.78 \cdot C \cdot I \qquad (d.2)$$

where q_n is obtained in l/(s.ha).

This equation depends on C, the runoff coefficient and I, the intensity of precipitation in mm/h.

Runoff coefficient: The runoff coefficient of a watershed with variable surfaces can be estimated by weighting the coefficient of various surfaces. Considering an urban watershed where two types of surface can exist: pervious and impervious, we can therefore establish that:

$$C = \frac{C_p A_p + C_i A_i}{A_t} \qquad \text{(d.3)}$$

where C_p is the runoff coefficient of the watershed's pervious area; A_p is the area of the watershed with a pervious surface; C_i is the runoff coefficient of an impervious area; A is the proportion of the watershed with impervious area. This equation can be transformed in accordance with the following:

$$C = \frac{C_p A_p}{A_t} + \frac{C_i A_i}{A_t} = C_p + \left(C_i - C_p\right) \cdot AI \qquad \text{(d.4)}$$

where AI = A_i/A_t, represents the proportion of impervious areas.

Average coefficient: The runoff coefficient can be expressed using a linear relationship to the rate of impervious area, where the subindices represent the values of the pervious and impervious areas. The influence of AI depends on the difference between the coefficients, as can be seen in the second term of equation (4).

Based on 44 small American urban watersheds, Schueler (1987) obtained the following ratio:

$$C = 0.05 + 0.9 \cdot AI \qquad \text{(d.5)}$$

This equation was obtained using $R^2 = 0.71$. Urbonas *et al.* (1990) used data from 60 urban watersheds in the United States and obtained:

$$C = 0.858 \cdot AI^3 - 0.78 \cdot AI^2 + 0.774 \cdot AI + 0.04 \qquad \text{(d.6)}$$

As the data used correspond to two years of data for the previous two equations, the coefficient probably refers to precipitation with a risk of the same order (Urbonas and Roesner, 1992).

In this case, for equation (5): $C_i - C_p = 0.9$, $C_p = 0.05$ and $C_i = 0.95$. The result of the adjustment shows that the coefficient of impervious areas is 0.95, owing to a 5% loss, that may be due to inaccurate estimates of impervious areas, infiltration through joints in the surface or evaporation from hot surfaces. In equation (6): C = 0.04.

In Brazil there is no sample from this size of urban watershed, but with the available sample, Tucci (2000) presented the following equation:

$$C = 0.047 + 0.9 \cdot AI \tag{d.7}$$

The data used came from 11 watersheds ($R^2 = 0.92$) selected according to the following criteria:

- Watersheds with at least five events;
- Consistent values of impervious areas;
- Consistent values in relation to hydrological events.

Since Q represents the runoff coefficient for an urbanized plot, the value of 0.95 obtained mainly represents asphalt and concrete surfaces where the value is close to the upper limit.

Note that the actual runoff coefficient is not a fixed value but it can vary with the magnitude of floods (Urbonas and Roesner, 1992), the initial conditions, the characteristics of the rainfall distribution and the soil type, among others. In a rural watershed the value of the runoff coefficient does not always correspond to $C_p = 0.047$ but varies depending on the physical constraints. These equations allow us to estimate an average value.

Coefficient based on SCS: The value of C_p in equation (3) represents the runoff coefficient of a pervious surface that can be estimated on the basis of the SCS equation (SCS, 1975):

$$C_p = \left[\frac{(P - 0.2S)^2}{P + 0.8S} \right] \cdot \frac{1}{P} \tag{d.8}$$

where P is the total precipitation of the event in mm; S is the storage, which is related to the parameter characterizing the surface (CN) by:

$$S = \frac{25400}{CN} - 254 \qquad (d.9)$$

The value of CN depends on the soil type and surface characteristics. The total precipitation of the event for the Rational Method is:

$$P = I \cdot t_c \qquad (d.10)$$

where I is the intensity in mm/h and t_c is the concentration time in hours. Table I shows some values of S for various surfaces, obtained on the basis of the CN of the SCS tables (1975). The table also shows values of Co for precipitation of 1 hour and a 2-year return time for Porto Alegre (approximate risk of the average values obtained for the events in table 1). These values are in the vicinity of the adjusted value of C_p. In the Diluvio basin (Porto Alegre) most of the watersheds analysed have a predominance of soil types A, B and C, while the places with rural characteristics have soil types A and B, with a predominance of soil type A.

Owing to the high variability of this coefficient and the need to define a single standard value, a runoff coefficient of C = 0.10 was used, representing an intermediate value between soils A and B, which predominate in most of the city.

Precipitation intensity: Precipitation intensity is estimated in accordance with the duration or concentration time of the watershed and the return time. The shorter the concentration time, the greater the intensity, and the greater the mean specific flow to be adopted. Likewise, the longer the return time, the higher the natural specific flow will be. High values of natural specific flow imply a lower control volume for each place.

Considering the intensity-duration-frequency curve of the Redenção station (central area of Porto Alegre), which despite having been eliminated has a more extensive series and represents a more central area of the city, and analysing the intensity for one hour, for various risks, the equation of runoff as a function of return time gives:

$$q = 8.35 \cdot T^{0.217} \qquad (d.11)$$

Table D. 1. Values of S and $C_{n.}$

Soil type	Field	Earth streets	Farming area

A S (mm) C_D	 19.8 0.032	 52.9-79.5 0	 31.1 - 19.8 0-0.03
B S (mm) C_D	 11.2 0.158	 22.8-32.5 0-0.015	 11.91-20.7 0.025-0.14
C S (mm) C_D	 7.6 0.277	 13.5-17.8 0.049-0.108	 6.9-14.3 0.094-0.31
D S (mm) C_D	 6.3 0.34	 9.7-12.7 0.12 - 0.20	 5.0-11.9 0.14-0.42

Table D. 2. Values of C_p with $R^2 = 0.999$.

Source	**C_p**
Grass (sandy soil) ASCE, 1969	0.05 – 0.20
Grass (heavy soil) ASCE, 1969	0.13 – 0.35
Woodland, parks and sports fields, Wilken, 1978	0.05 – 0.20
Schueller equation (USA, 44 watersheds)	0.05
Urbonas et al equation (1990) (USA, 60 watersheds)	0.04
Tucci equation (Brazil, 11 watersheds)	0.047
Using Soil Conservation Service	0.025 – 0.31

In this case, using a return time of 10 years, the recommended value is 13.9 l/(s.ha). By way of example, the mean value used in the city of Seattle (USA) is 14 l/(s.ha). The specific 10-year value in Denver, USA is q_{10} = 16.7 1/s.ha.

Table D. 3. Specific flow values before development

Return time (years)	**Flow (l/s.ha)**
2	9.62
5	11.9
10	13.9
25	16.9
50	19.5
100	22.5

Control volume

The control volume for small urban areas (< 2 km^2) can be estimated using the equation:

$$V = (Q_u - Q_n) \cdot t \cdot k \qquad \text{(d.12)}$$

where V is the volume in m^3; Q_n is the pre-development flow in

m^3/s; Q_u is the flow resulting from urban development; t is the duration in minutes and k = 60 for the conversion of the units.

The flow due to urban development is estimated by equation (1). The pre-development flow was estimated in the previous section from its specific flow. However, transforming equation 10 into specific volume, i.e. volume per unit of area, gives:

$$\frac{V}{A} = (0.278 \cdot C \cdot I - q_n) \cdot 60 \cdot t \qquad \text{(d.13)}$$

The runoff coefficient can be estimated in accordance with the impervious areas with C_p = 0.10 and Q = 0.95, giving the expression:

$$C = 0.10 + 0.95 \cdot AI \qquad \text{(d.14)}$$

Precipitation intensity can be represented by the equation:

$$I = \frac{a}{(t+b)^d} \qquad \text{(d.15)}$$

Substituting specific volume in the equation gives:

$$v = \left(\frac{0.278 \cdot C \cdot a}{(t+b)^d} - q_n \right) \cdot 60 \cdot t \qquad \text{(d.16)}$$

The maximum volume is obtained for the duration using the equation:

$$t = \left(\frac{q_n \cdot (t + 0.278 \cdot C \cdot a)}{0.278 \cdot C \cdot a(1-d)} \right)^{\frac{1}{(d+1)}} - b \qquad \text{(d.17)}$$

Using the precipitation data for Porto Alegre (Redenção station) volumes were obtained for return times varying from 2 to 100 years and impervious areas varying from 5 to 100%. The results are shown in table D.4. These values were adjusted to an equation with the following expression:

$$v = 2.624 \cdot T^{0.269} \cdot AI \qquad \text{(d.18)}$$

where T is given in years, AI is the impervious area as a % and v is obtained in m^3/ha. The adjustment determination coefficient was $R^2 = 0.99$.

For each return time specific equations were also adjusted, for a better representation of the results. Table D.5 shows the coefficients of the straight line and the adjustment R^2. In this case, the resulting straight line for the 10-year return time is:

$$v = 4.864 \cdot AI \tag{d.19}$$

Table D. 4. Specific volume in m^3/ha

	Return time					
Impervious area %	2	5	10	25	50	100
5	21.82	25.83	29.25	34.45	38.89	31.52
10	33.52	40.25	46.11	55.13	62.97	43.67
20	59.66	72.95	84.77	103.32	119.82	69.47
30	88.35	109.35	128.29	158.42	185.64	97.46
40	118.91	148.51	175.51	218.93	258.63	127.6
50	150.94	189.91	225.77	283.98	337.72	159.75
60	184.18	233.18	278.62	352.96	422.17	193.86
70	218.45	278.09	333.76	425.45	511.46	229.84
80	253.63	324.44	390.94	501.12	605.16	267.55
90	289.62	372.10	449.97	579.72	702.96	306.95
100	326.34	420.95	510.71	661.04	804.58	347.96

In this case, the volume required to recover the pre-existing flow for an area of 1000 m^2 with 50% impervious area is:

$$V = (1000/10000) \cdot 4.864 \cdot 50 = 24.32 m^3 \tag{d.20}$$

For a depth of 2 m, 1.23% of the total area corresponds to 12.32 m^2.

Table D. 5. Coefficient of the straight line adjusting the specific volume for each return time

Return time (years)	**a**	**R2**
2	3.1648	0.9966
5	4.0416	0.9945
10	4.8640	0.9922
25	6.2252	0.9884
50	7.5090	0.985
100	9.0490	0.981

v = a AI, where v is the specific volume in m^3 and AI is a %.