Site Design for Urban Water Management in Mexico City

by

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ABSTRACT

As the world becomes aware of the scarcity of water resources and cities struggle to meet a growing demand, we face the challenge of finding more efficient ways to manage this vital resource. Cities in developing countries face an even greater challenge as rapid population growth and demographic migration concentrate demand in already exhausted areas. Meeting this deficit has meant the expansion of hydraulic infrastructure to ever distant areas at ever increasing costs.

Water supply and disposal in the last decades has been dealt with exclusively by hydraulic engineers. They are once again attracting the interest of architects, landscape architects and planners as the effects of urban development on water resources becomes more evident. In an age of shrinking public budgets, site design can offer a competitive decentralized alternative to the massive engineering projects that would otherwise be needed to meet such demand.

This work deals with a set of tools that architects and planners can use to contribute to improving the hydraulic capacity of our cities and to restoring some of the fundamental processes of the natural environment on which they are set. It evaluates their performance in a specific context in Mexico City and explores the feasibility of their application.

Thesis Supervisor: Anne Whiston Spirn

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Table of Contents

INTRODUCTION

Water constitutes over 70% of the earth's surface; the remaining 30% consist of a mixture of soil and water with varying degrees of humidity. The idea that water is a scarce resource is a difficult one to grasp. Everywhere we look, water seems to form a considerable part of the landscape.

But fresh water is a much more limited resource. If we took away the salted water contained in the oceans, we would be left with only a fraction of the original available water. Still, fresh water can be found in great quantities frozen at the polar cones or submerged under the soil, and, to a lesser degree, at the surface in the form of rivers, ponds and lakes. In fact, only 3% of the total fresh water runs at the surface, the rest is either frozen or buried.

Civilizations have historically settled along these surface sources of water. Until the nineteenth century, the technology to subtract significant amounts of water from the underground soil without artesian pressure was not available; furthermore, low demographic concentrations made it unnecessary to complement surface water supply. Water technology was mainly concerned with diverting and controlling surface flows in order to obtain immediate benefits such as irrigation or drinking water supply, but this technology was limited to a mechanical understanding of water flows that often lacked an integrated awareness of the whole ecosystem. A well-known example of this can be found in the way that the ancient residents of Mesopotamia manipulated the flows of the Tigris and Euphrates with channels and ditches to irrigate the land in-between the two rivers. The area became so fertile and its production so vast that it enabled some of the first urban conglomerations to take form. For centuries this valley sustained the majority of the urban centers of the world at the time. This practice was nonetheless unsustainable, at least in the long term. The land which the Mesopotamian people were irrigating and farming on consisted of finely grained sands whose nutrients were steadily being washed away along with the irrigating water. The less productive the soils became, the more irrigation they needed and the more sterile the land grew. This vicious cycle ended up transforming most of this area into the desert that constitutes today's Iraq.

Examples of ruined environments such as this abound. At later stages in history technology has provided a more varied set of tools to control water to our advantage, but the way in which we have chosen to use these technologies has limited their long term benefits and has compromised the availability and quality of this resource for future generations.

Today, as population grows, water becomes increasingly scarce. All over the world, it is becoming evident that we have to re-assess our relationship with water and to recognize the liquid's inherent partaking in the ecosystem's processes. Internationally, trends are pointing towards a more rational and efficient use of water. The developing world in particular faces the challenge of a rising water demand with a stable, if not diminishing supply. The costs of water supply are and will become increasingly high as available sources of water are depleted and new ones must be found at ever-longer distances.

One of the cleanest, most economical and available sources of water is, in fact, water management. The efficiency with which we utilize this resource can sharply affect the supply of water to the population both quantitatively and qualitatively. Considered to be a problem rather than an opportunity, storm water is consistently being collected and discharged, with great costs to society, without attempting to reintegrate it into its natural cycle. This is not only wasteful and inefficient, but it has also translated itself into unexpected problems: drains that are supposed to impede floods in one area often transfer augmented flows downhill where water accumulates in unanticipated quantities; groundwater tables drop as water is not allowed to infiltrate the soil, thus jeopardizing the water supply; soil subsidence affects the stability of our buildings, and so on. Indeed, the approach that we have chosen to solve some of our problems has often resulted in great expenses and poor results. The search for other alternatives requires us to study the feasibility of treating wastewater at its source and incorporating it into the community's management; to consider utilizing softer, self perpetuating strategies that can work along and take advantage of the natural processes and result in more sustainable and cost effective choices.

This thesis seeks to apply some of the fundamental principles of hydrology as well as to study some of the bioengineering approaches to water management available today. Its setting in Mexico City can be illuminating in many ways. The city's standing as one of the largest metropolis in the world, its limited resources, growing population and particular geographic setting all represent important challenges to the sustainability of the city. In order to meet an escalating demand, the city has concentrated its resources on supply management and bulky and expensive engineering solutions that have absorbed a considerable piece of the city's budget, but that have failed, so far, to provide long term solutions.

For the purpose of this study I have chosen an area located at the western edge of the city, an area whose geologic and climatic conditions make it favorable for groundwater recharge. It is also an area that has been undergoing important development over the last 15 to 20 years and that will probably continue to grow over the next two decades. It should be noted that, contrary to the ecological reserves around the city where urban development is altogether prohibited, this area is being developed under strict regulations and the supervision of the city's authorities. Notwithstanding the commendable inclusion of environmental concerns into the project scopes, these have been included in a remedial, damage-control manner rather than as an integrated factor shaping their design.

A design approach that incorporates integrated, ecological techniques designed to make better use of water and allow its infiltration into the aquifers may significantly affect groundwater recharge rates and reduce demand of potable water for extraneous uses. This work is an attempt to evaluate some of these techniques and to exemplify their implementation under the particular physical, cultural and economic conditions of the area. It is an exploration of stormwater management devices and site design patterns that can contribute to the replenishment of the city's water resources.

The thesis is divided into four chapters and a final conclusion. The first chapter, "The Environmental History of the Basin of Mexico", sets the background that helps us to understand the dynamics of this distinct environment and the processes through which urban development shaped and has been shaped by it. This background describes first the geologic formation of the basin and the creation of this remarkable environment and second how urban settlements have developed within the basin. Finally, this chapter familiarizes the reader with the current environmental condition of Mexico City and illustrates some of the challenges and difficulties that if faces, specially in relation to water management. The second chapter explores some of the current trends in stormwater management and describes some of its fundamental principles. Next, the third chapter describes the site in greater detail and introduces the reader into some of the current development patterns occurring in that area. The fourth chapter exemplifies their application in the particular context of the site using an existing program and design as a comparative basis for the alternative approach. Finally, a set of conclusions and questions about the future development of stormwater management will close the thesis and try to evaluate some of the strengths and weaknesses of this approach as well as identify some of the challenges facing the implementation of successful stormwater management practices in Mexico City.

Chapter 1. Environmental History of the Basin of Mexico City[1]

The concept of Reading the Landscape can have different connotations. In Mexico, for example, people have referred to the landscape in a poetic context. The landscape of Mexico City has attracted the attention of writers and painters. One needs only to see the great amount of artistic interpretations that this magnificent valley has generated; Velasco's landscapes of the nineteenth century, Dr. Atl's fantastic volcanoes are only a few among many other examples. Nevertheless, especially in more recent times, we have failed to read the landscape as a living organism, a system of natural forces, as "continuous whole".[2] Somehow we have neglected to see what is so obvious because most of us were generally too busy to worry about such details. With the political, social and economic problems that we have, who cares about reading the landscape? We have too many other things to solve and the environment, as worthy of attention as it may be, does not seem to be a priority. Nevertheless, it is an integral part of the city's problems.

Figure 1.1. Jose Maria Velasco. The hacienda of Chimipa, 1893.
Source: Virtual Forum of Mexican Culture. http://www.arts-history.mx/pieza/velasco2.html

[1] In this work I will use the terms basin and valley indistinctly to describe the geography of the city.
[2] Spirn, Anne Whiston, *The Language of Landscape* (New haven, Yale University Press, 1998), 24.

Thus, in Mexico City, we seem to have made an effort not to read the landscape. Ignoring it has become almost a reflex that has proven to be, not only dangerous, but also expensive and inefficient. Here, we seek to give an overview of the conditions that have brought the city close to environmental collapse. Our final goal is to suggest alternative ways of development that could gradually re-establish some degree of equilibrium between urban development and the natural environment. An equilibrium that does not seek to freeze development altogether or invest in gigantic infrastructure projects, but one that should take advantage of the natural processes that can help us grow in a more efficient and sustainable way.

I will first seek to present a synthesis of how Mexico City's distinct environment came to be; how it was created and what characteristics made urban development feasible in the area. Further on, I will draw an account of how development has taken place in the basin, adapting itself to its surroundings, but changing them in an irreversible process. We shall see how urban development and the natural environment of the basin have influenced and limited each other and how the communities that have inhabited the Basin for over 2,000 years have contributed and been affected by this interaction. Finally, I will explore the current environmental condition of Mexico City, an urban conglomeration approaching 20 million inhabitants, especially in terms of water management. What steps are being taken to solve some of the most pressing needs without failing to take into account the overall logic of the city's ecosystem?

The Geological Formation of the Basin

The Basin of Mexico City is the outcome of a distinctive geological process in which submarine land was elevated up to 5 kilometers due to volcanic activity. This activity, in turn, is the result of the collision of the North American Plate with the Cocos Plate, which is known as the Trans-volcanic Mexican Axis. As both plates push against each other, the Cocos Plate submerges under the other causing it to melt as it reaches hot magma in a process called subduction. Because of the upward pressure, lighter gases and minerals find their way out to the surface through the gap between both plates. The volcanic landscapes that dominate this area of the country were all formed through this process and it is not coincidental that most pre-Hispanic cultures located in this area shared a common cosmic vision, a common understanding of nature.[3]

Throughout the millions of years in which new volcanic formations emerged into the surface, water flows were modified, interrupted and, finally, contained in what is now the bottom of the basin. The final form of the basin was not arrived at until relatively recent times. The Sierra Chichinautzin, which closes the basin to the south, was the last volcanic range to develop during the late Pliocene and early Pleistocene periods, from 700,000 years ago until very recent times. The Popocatepetl, for example, one of the highest peaks in Mexico, did not conclude its formation process until 900 years ago. It is noteworthy that the already sedentary population of the basin witnessed significant volcanic activity. The relative youth, in geologic terms, of this volcanic range has had enormous implications for the settling of the basin. Indeed, the capacity for water storage of the pervious volcanic rock made it possible for larger communities to settle at the foot of this mountainous area, where water was finally deposited after a long filtering process.

The basin, as we know it today, consists of 7,000 square kilometers with an elevation at its lower point of 2,250 meters above sea level. It is enclosed to the east, south and west by the Sierra Chichinautzin (or Sierra Nevada, as it is also called), the Ajusco and the Sierra de las Cruces respectively. The northern limit of the basin is much less dramatic as it consists of a series of low hills and ranges.

The surrounding hills and mountains that have constituted a topographic impediment for the expansion of urban settlements, have also provided the basin with a variety of sub-climates that range from the semi-arid areas to the north to the humid forests of the south. Indeed, great animal and plant diversity can be found at different altitudes within the basin including salt-loving halophytes from the lakebed region of Texcoco and the *Pinus hartweggii* that grow at altitudes of over 3,000 meters. These heterogeneous landscapes provided a range of resources that were vital to the constitution of urban communities at different points in time.

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[3] A more detailed analysis of the common aspects of meso-american communities inhabiting similar volcanic landscapes can be found in Espinosa Pineda, Gabriel. El Embrujo del Lago, Mexico D.F. UNAM, 1996

The Lake System

It is no longer believed that the water levels of the lakes in the Valley of Mexico have continually been diminishing,[4] but that through the formative period of the basin, water levels increased and subsided periodically. It is true, nonetheless, that all lakes are naturally prone to contract as a result of sedimentation and that, if left only to the forces of nature, the lakebed of the basin would have been gradually filled with sediment. The Lake System of the Basin of Mexico consisted of two subsystems of shallow lakes. The smaller one, located towards the north west of the basin, was formed by three small lagoons that were, perhaps, a source of water supply to cities such as Teotihuacan until the year 600 AD. The bigger and more important one was located to the west of the Basin and it is generally referred to as the Lake Region. This was, in fact, formed by three sub-basins: Xaltocan, to the north, Texcoco in the middle, and Chalco at the southermost edge of the basin. Both Xaltocan and Chalco overflowed during the rainy season to Texcoco which was the biggest of the three sub-basins and whose location at the lowest levels of the basin made it a receptacle of sedimentation from the surrounding mountains and valleys. This concentration of sediments and the lack of fresh water springs contributed to the high concentration of salt in its water.

Chalco, the most fertile region of the basin, was artificially divided into two lakes Chalco and Xochimilco and was intensively cultivated with *chinampas.*[5] In Pre-Hispanic times, when Xochimilco provided most of the agricultural produce of the basin, channels were created within the lakes to facilitate navigation. In the absence of animal labor, navigation represented the only effective means transportation device. Infrastructure devices such as dikes and were skillfully designed in pre-Hispanic times to ward Lake Xochimilco's waters from contamination from the saline waters of Lake Texcoco.

One of the most important characteristics of the lakes is their seasonal nature. Because the basin is enclosed, it does not have a continuous drain nor a continuous water

[4] Some literature suggests that the lakes have been naturally draining since their formation. According to this theory, when the volcanic ranges appeared, the existing water was retained in the basin and has been since gradually draining.
[5] The chinampa agricultural system consists of constructed islands filled with soil from the lakebed, itself fertilized every year during the rainy season by nutrients from the surrounding mountains. Although labor intensive, this system proved highly productive and provided Tenochtitlan with vast amounts of fruits and vegetables.

supply.[6] Consequently, the basin receives water in summer (from May to October) and holds it during the dry season. The provision of fresh water during summer also temporarily changed the composition of the water, making it consist almost exclusively of fresh water at the western and southern shores of Lake Texcoco where it met the lower slopes of the surrounding hills.

Figure 1.2. Illustration of the lakes of Mexico. Beginning at the north, towards the left side of the image, we can see the smaller lakes of Zumpango and Xaltocan; then Texcoco Lake with the city ofTenochtitlan at its center and finally Chalco which was later on divided into two: Chalco and Xochimilco.
Source: Lombardo de Ruiz, 1996

Today, most of the lakes have been covered by the city and only small lacustrine areas remain such as the artificially recreated ones in Texcoco and Zumpango and some of the canals of Xochimilco. However, every so often, we are reminded of our lacustrine past when some areas of the city flood after the torrential summer rains. The valley's natural propensity to flood has imposed a heavy toll on the budget of the city where extensive infrastructure has been redirect stormwater into the drainage system.

[6] In fact, there are a few small rivers that flow down from the mountainous area that can be considered

Water Recharge

Mexico City's water supply remains highly dependent on subterranean extraction. The aquifer underneath has provided water to the city since the middle of the Nineteenth century when surface streams could no longer meet water demand and the first pumping stations were inaugurated. As we will see later on, excessive water extraction has caused soil subsidence and a considerable reduction in the water levels of the aquifer. Although there is no certainty as to the extent to which the aquifer is being depleted, but long-term field measurements have shown a decline of as much as one meter per year.

The amount of water that is finally absorbed into the aquifer is conditioned by the quality of the soil – its porosity and permeability - and the concentration of rainfall within the most absorbent areas. The soil in the Basin of Mexico can be divided concentrically into three geo-technical zones: the lacustrine, the transition and the mountainous zones.

The lacustrine zone, located at the lower elevation within the valley and over the system of aquifers that form the Mexico City aquifer, consists of highly compressible clays that are highly impervious. In fact, this layer of saturated clays – sometimes several hundred meters in depth – divides the aquifer into separated chambers. Hence, water flowing into the lakebed is not filtered, but accumulates and stores on the surface; the lakes themselves were formed by the accumulation of these flows and the imperviousness of the soil.

The transition zone or piedmont immediately surrounds the lakes. This area consists, especially to the south and west of the city, of basaltic rock with high levels of porosity and permeability that contributes the most to the recharge of the aquifer. Indeed, this area collects run off water from the hills and directs it through surface streams to the lacustrine area and, through subsurface flows, to springs and to the aquifer.

Finally, the mountainous zone directs the water flow towards the basin either superficially or through subsurface flows. The hills that bound the basin to the south are, as we have mentioned before, geologically the youngest and thus, the most pervious. Young volcanic formations allow an extremely high percentage of the water to permeate down through fractures until it reaches an older geological layer (that upon which the lava of the younger volcanoes cooled and settled) that is less pervious. This inner

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perennial, but their flows also vary greatly from season to season.

geological layer collects the water in subsoil rivers and directs it in the direction of its slopes bringing it down to the fresh lakes and to springs located throughout the southern area of the basin. Subsurface flows ultimately end up recharging the aquifer under the lacustrine region. The mountainous area is indeed a sponge that contributes to the abundance of fresh water in the Chalco-Xochimilco region and to the replenishment of the aquifer.

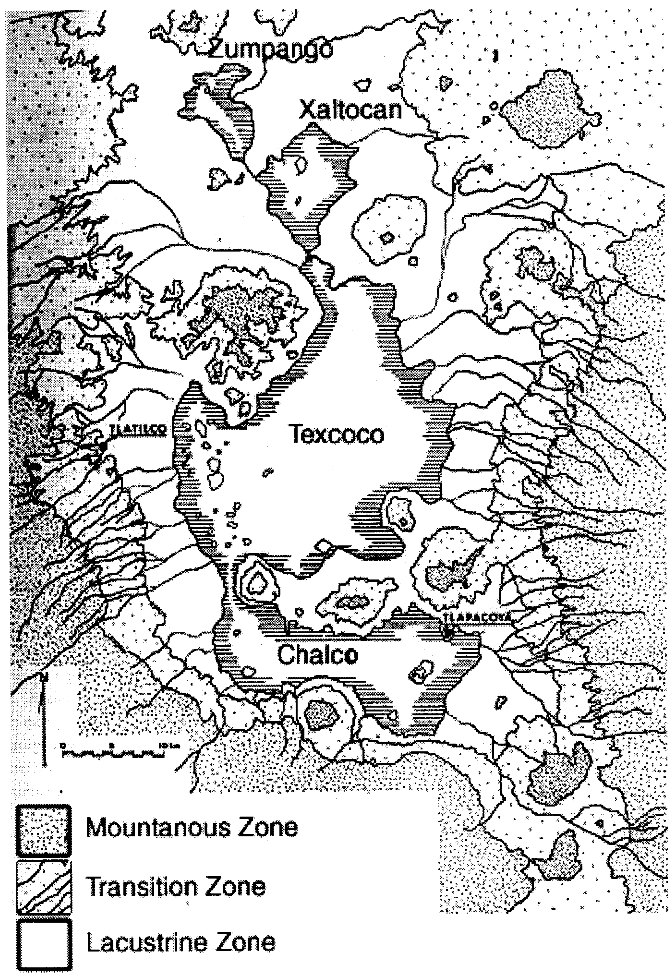

Figure 1.3. Geo-technical zones in the basin of Mexico City.
Source: Authors adaptation from Ezcurra Ezequiel et al. The Basin of Mexico, p65.

In terms of rainfall, the basin gradually receives a higher amount as it approaches the southwestern limits of the basin. A juxtaposition of the two maps showing the geo-technical zones together with the rainfall distribution emphasizes the importance in terms of water recharge, of the south and western extremes of the basin, where rainfall reaches up to 1500 mm and the soil is able to store, filter and transfer it into the aquifer.

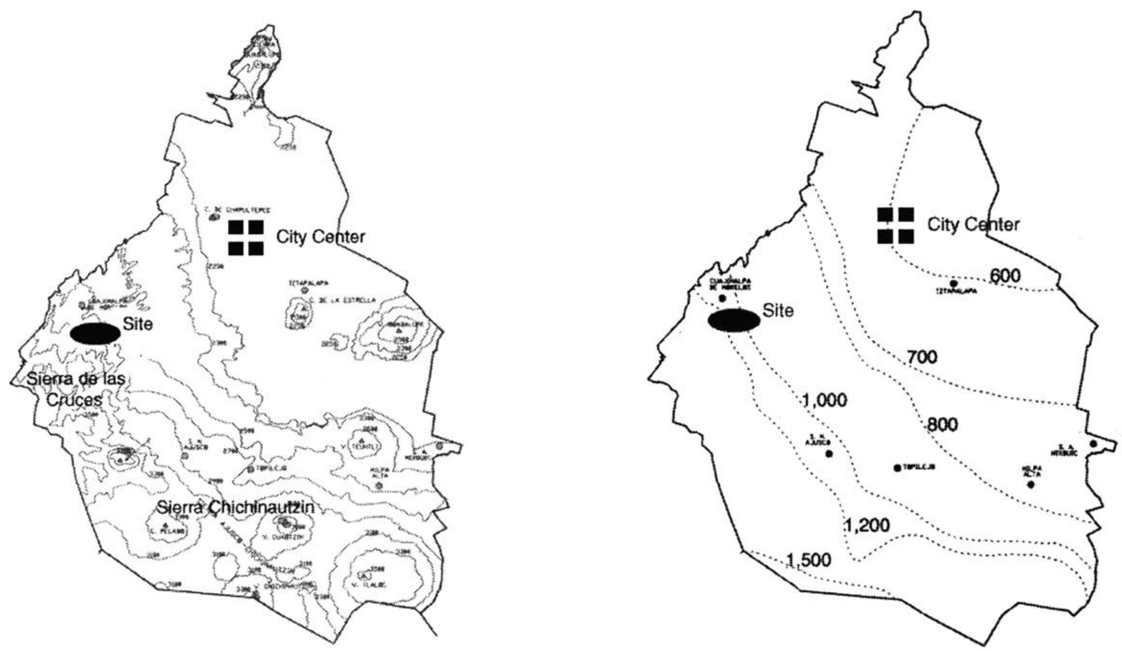

Figure 1.4. Maps of the valley of Mexico showing the topographic composition of the basin left, and the annual precipitation within the valley. Note how precipitation increases towards the south and west of the basin where the Sierras Chichinautzin and de las Cruces are located.
Source: Drafted by the author from INEGI.

Environmental History of Urban Development

Every day millions of Mexicans living in Mexico City, or *Chilangos*, as they are called, sometimes pejoratively by outsiders, hurry to their jobs, schools or other duties. We take for granted that the floor will remain where it is, that there will be water to drink, food to eat and, perhaps, a roof over our heads. However, once in a while, the city vividly reminds us of how fragile our environment is. It forces us to see what we have been trying so hard to ignore. As we turn our eyes away from these signs, they grow more violent as if they wanted to attract our attention. The 1985 earthquake was a cruel reminder of how unstable the subsoil of the city is. It took over 10,000 lives (unofficially, this figure raises to 30,000) to make us realize how unwisely the city has developed.

However, catastrophes such as this, have been succeeding each other in the City since the Basin of Mexico was first settled. Indeed, the history of the urban settlements in the basin is inherently linked to its geological, hydrological and climatic conditions. The presence of fresh water has encouraged the urbanization of the basin as much as the volcanic terrain has limited it. Historically, the basin's topographic and climatic conditions have shaped the way in which communities settled this area.

The first urban settlements occupied the lower parts of the basin, where the soil offered good productive potential, but was still sufficiently high to avoid flooding.[7] Cuicuilco, which by 100 AD had developed into an important culture and had reached a population of over 50,000 (rivaling that of Teotihuacan to the north), was suddenly buried by the eruption of the Xitle volcano. More than destruction of the city itself, it was the loss of agricultural land, covered under the lava, that eliminated the city's chances of survival. This geological catastrophe induced massive emigration to the north and consolidated the pre-eminence of Teotihuacan as the dominant force of the valley.

Teotihuacan grew from a city of 30,000 in AD 100 to 150,000 in AD 650 making it one of the largest cities in the world. Inexplicably, one century later the population had collapsed to 10,000. Although the causes for the collapse of Teotihuacan are not well known, some researchers attribute it to the exhaustion of natural resources. There is evidence pointing to the exhaustive deforestation of the area for construction purposes. Consequently, the erosion of the soils and the increase in floods and droughts could have made the agricultural lands unfertile. Other hypotheses point to a process by which subjugated cities rebelled against the system of tribute. The appropriation of natural resources would have been, in either case, the driving force for the collapse of the city.

After the fall of Teotihuacan, most of the population moved south along the moving shores of the lake system. They settled on dry land while using the highly productive *chinampa* as an agricultural strategy. This method enabled the population to

[7] The discussion that follows on the history of the basin is based on Ezcurra, Exequiel et al., *The Basin of Mexico* (New York, United Nations University Press, 1999).

rise to over 1.5 million inhabitants dispersed around the lakes and organized politically under a system of independent city-states. When the Mexicas migrated to the basin in 1325, they found a heavily populated landscape with little available land. In fact, they founded their city, Tenochtitlan, on a small island and it was only through the construction of *chinampas* that they were able to sustain themselves. Soon, however, this group of migrants gained control over the neighboring cities and had consolidated them into an empire that would control most of central Mexico.

The success of Tenochtitlan and the growth of its population increased the need for agricultural products. Besides depending on the productive *chinampa,*[8] the Aztecs set off a system of conquests that would not only give them control of the Valley, but provide them, through the imposition of tribute, with the water and food necessary to sustain its population. Some literature suggests that this organization is reflected in the Aztec religious systems with its two most important gods: Tlaloc, god of water, rain and agriculture and Huitzilopochtli, god of the sun, war and fire.[9] The war-tribute system strained the city's relation with neighboring cities to the extent that, at the arrival of the Spanish Army, Indian[10] groups such as the Tlaxcaltecas, allied with the Spanish to defeat the Aztec rule. If Cuicuilco's ruin was stemmed from a natural disaster and Teotihuacan's sudden fall was closely related to the depletion of natural resources, we could argue that, at least in part, the lack of self-sufficiency contributed to the conquest of Tenochtitlan by the Spanish.

However, even if the war-tribute system contributed to satisfy a growing demand for food, it cannot be said that the Aztecs did not understand their environment and did not take full advantage of it. The *chinampa* system, although present in the valley long before the arrival of the Aztecs, was very efficiently exploited by Tenochtitlan. The hydraulic system of the lake was also modified during this period to serve the city's needs.[11] Some literature suggests that hydraulic infrastructure was started before the Aztecs, but that it had been periodically abandoned. The Aztecs would have therefore continued a project that had begun long ago. A complex system of dikes that subdivided

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[8] Chinampas are man made islands created with the lakebed's soil and held together by branches. These are extremely fertile and contributed enormously to sustain the pre-Hispanic populations of the basin.
[9] Simon, Joel. *Endangered Mexico* (San Francisco: The Sierra Club, 1997), 81.
[10] When referring to Indians, I mean the Pre-Hispanic population of America.

the lakes and controlled the flow of water between one and other was established well before the Spanish conquered the city. These dikes, which served the double function of transport and water control were specially designed to protect the city from floods,[12] to prevent the water from Lake Texcoco from polluting with salt the waters of the other lakes, and to allow for the use of boats to transport food produce from the productive *chinampa* region of the south to the center of the city. In fact, through the construction of dikes, the Aztecs increased the area available for *chinampa* agriculture by introducing fresh water from the southern lakes of Chalco and Xochimilco and blocking the salty water from Texcoco.

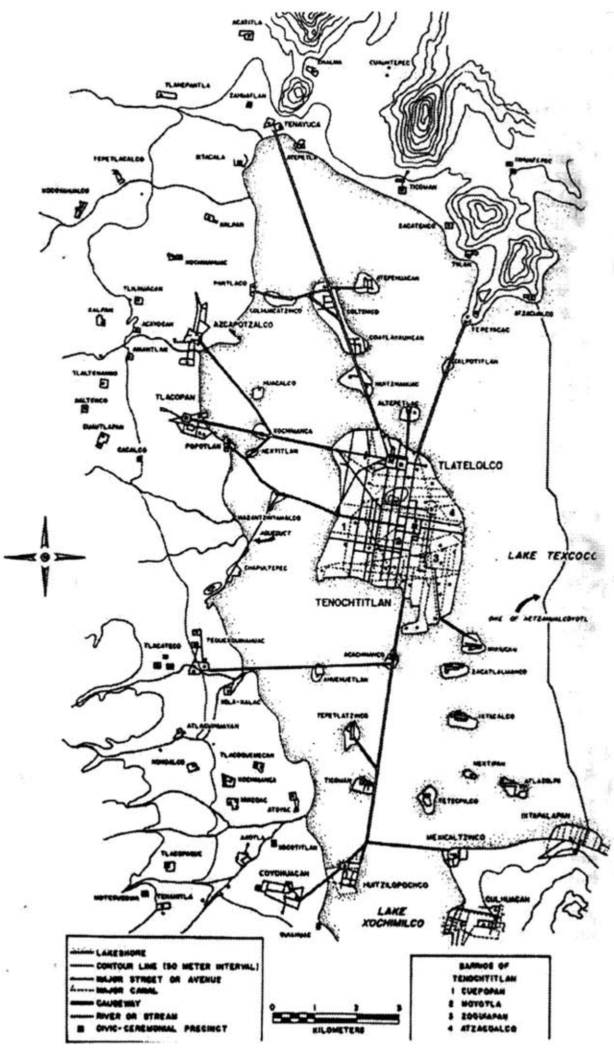

Figure 1.5. Tenochtitlan at the time of the arrival of the Spanish. The lakes appear divided by dikes/streets. Source; Ezcurra, Exequiel et al. The Basin of Mexico.

[11] Espinosa, Gabriel,.

[12] Since its foundation, the city had learnt to live with seasonal floods. However, as the city grew in power and wealth, it became important to control or limit the floods. An account of this process can be found in Espinoza, 351-372.

This understanding of the hydrologic functioning of the lake and of the productive limits of the basin was acquired by the Pre-Hispanic cultures gradually through generations. One should avoid the temptation to idealize the Aztec's relationship with their environment as one of absolute respect and responsible care. They did then, as we do now, manipulate their environment to meet their needs, but they did it sensibly enough not to alter its basic functioning. Their dependence on the lakes as a source of food rich in protein and as a means of transportation was very much ingrained in their culture and way of life.[13] Although their efforts to control the waters from the basin's lakes proved sometimes unsuccessful,[14] we can safely assume that the expertise acquired after centuries of interaction gave them a deeper understanding of their hydrologic cycles than the incoming Spanish. The Conquest was, undoubtedly, one of the most dramatic intrusions of an alien culture into an environment. Not only was the cultural system of Pre-Hispanic society completely transformed, but the ecological system of the Basin, as well as that of the rest of the continent was forever altered. Soon after the Spanish arrived, the symptoms of ecological disruption became evident as thousands of Indians contracted European diseases, such as smallpox, that were previously absent in the continent. The epidemic, fueled by the Indian's lack of antibodies, killed approximately 90% of the Indian population.[15] The introduction of grazing herds contributed to the deforestation of the landscape. As dying Indians deserted their towns and fields, more land became available for cattle or sheep. Often, cattle was introduced in areas that have been recently deforested for the construction of the Spanish towns, accelerating the erosion of the hillsides and the propensity for floods and landslides. By the end of the

[13]We should not forget that in the absence of big mammals such as horses, cattle, sheep, etc. sources rich in protein were limited to fish which could not be easily transported fresh from the distant sea. The absence of these animals contributed also to the importance of the lakes as a means of transportation and to communicate the communities that settled around the lake.

[14] This refers to the account of the construction of the Acuecuexatl aqueduct by Ahuizotl in an attempt to increase the amount of fresh water around Tenochtitlan and thus increase the city's agricultural production. The story relates how the ruler of the village of Acuecuexatl tried in vain to stop the construction alleging future catastrophes. He was executed and the aqueduct was built at great expense and effort, only to be demolished after it flooded Tenochtitlan and most of the villages around the lakes. It is not certain whether the cause of the flood was solely the aqueduct's fault or if it coincided with a specially rainy year, but it nevertheless shows how some attempts to manipulate the natural hydraulic system of the valley resulted in failure. A detailed account of the story along with its mythological significance can be found in Espinosa, Gabriel, 354-364.

sixteenth century, however, the Spanish herds had devastated the soil of the hills that circumscribe the valley.

The Spanish decided to settle their new city right over the ruins of the conquered one as a political strategy to avoid the resurgence of the conquered people, but without giving much consideration to its environmental implications. After two years of war, the city was widely damaged and most of its hydraulic infrastructure destroyed during the siege. The aqueducts no longer provided water from the wells, the dikes had been broken to allow for the Spanish brigantines to traverse the lakes and the narrow paths connecting the city with the shores were widened for horse riding. Indeed, the Spanish conception of water management, inherited from Greek and Roman thought, considered standing bodies of water unhealthy and prone to disease.[16] Through the use of animal power, they were able to satisfy their needs with agricultural products from the mainland, and they no longer needed the water for transportation; in fact, water prevented the efficient mobilization of cattle and horses throughout the valley.

The lack of need of the lakes, either as an agricultural source or as a transportation device encouraged, in turn, a mismanagement of the water system. Waste was now thrown into the lake and currents were blocked. Soon the water was, in fact, insalubrious. A vicious cycle was being established where the deforestation of the mainland and the destruction of the existing hydraulic infrastructure prompted an environmental chaos that has lasted until today. As early as 1555, the new city suffered its first flood. The barren hills no longer held the water that washed the soil into the lakes and causing its levels to rise. As deforestation continued, so did the floods such as the ones in 1580, 1604, and the more moderate, but continuous ones that lasted through 1605, 1606 and 1607. In less than one century the lakes had turned from a means of survival to a dangerous threat. In 1629, a flood killed 30,000 residents, mostly Indians living in less stable structures.

The Spanish settlers soon recognized that the hydrological system of the basin could not be consistent with their development patterns. One could not do with the other

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[15] Strong debate exists about this figure. No exact data exists to confirm the exact population number of Tenochtitlan, the Valley of Mexico, or the rest of the Indian towns. It is agreed, nonetheless, that the epidemic did reduce the Indian population dramatically.

[16] Hippocrates, for instance identified standing water as the worst kind of drinking water and stressed the important influence of water on health and well-being. Crouch, Dora. P, *Water Management in Ancient Greek Cities* (Oxford: Oxford University Press, 1993), 50.

and a race to drain the basin for good was started. By 1608, the first attempt to drain the basin was made through the "Tajo de Nochistongo", a cut through the northern hills of the basin out to the river Tula. Successive floods were followed by greater engineering endeavors that were in turn followed by more floods. By 1796, with the construction of the "Canal de Guadalupe", the lakes started to dry out. The floods continued to threaten the city, as the water continued to flow down the hills into the valley, but water levels began to shrink consistently from then on.

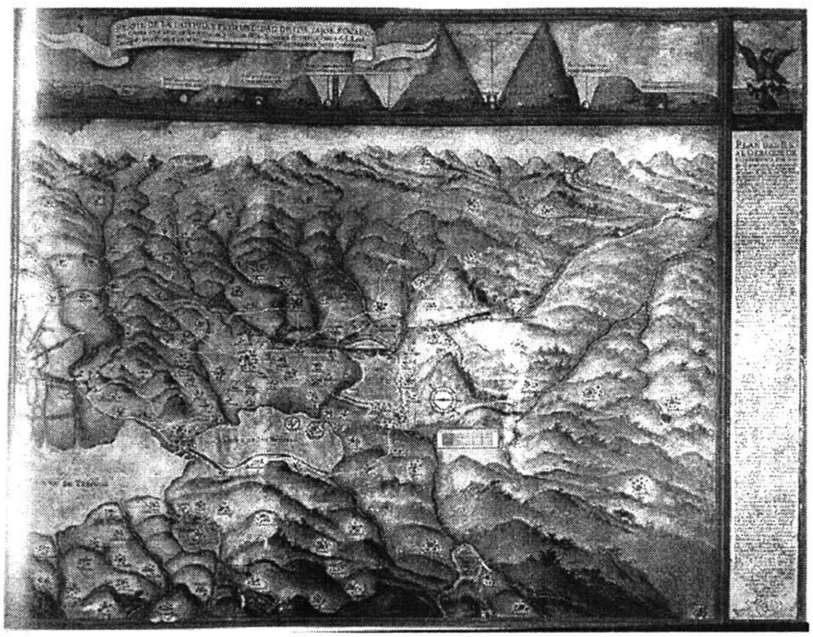

Figure 1.6. Drawing illustrating the "Tajo de Nochistongo" which drained the basin to the north.
Source: Lombardo de Ruiz 1996.

From then on and until the Mexican revolution in 1910, Mexico City gradually, but positively maintained and even strengthened its preponderance at a national level. Population growth, though, was not a problem yet. Industrialization, the great fuel for urban concentrations had not yet taken place in Mexico and the provision of medical care was too limited to allow for an important increase in population. As in the case of most Latin American cities, rapid demographic growth did not occur before the industrialization trends of the twentieth century, specially the later half of it.

Figure 1.7. View of Mexico City in 1910
from the hills at the west of the basin.
Source: Lombardo de Ruiz, 1996.

The Twentieth Century

After the Mexican Revolution the city quickly re-established its hegemony over the nation. Politic and economic centralism and a model for national development based on industrialization encouraged the massive migration of peasants into the city. The promises of jobs in the newly created industries and the potential for a better way of life acted as a magnet. The population of the city grew at speedy rates from 1,802,679 inhabitants in 1940 to 15,440,746 in 1990 and approximately 18 million in the year 2000. The urbanization of the city went beyond the Distrito Federal into some municipalities of the Estado De Mexico constituting what today is referred to as the Metropolitan Area of Mexico City.

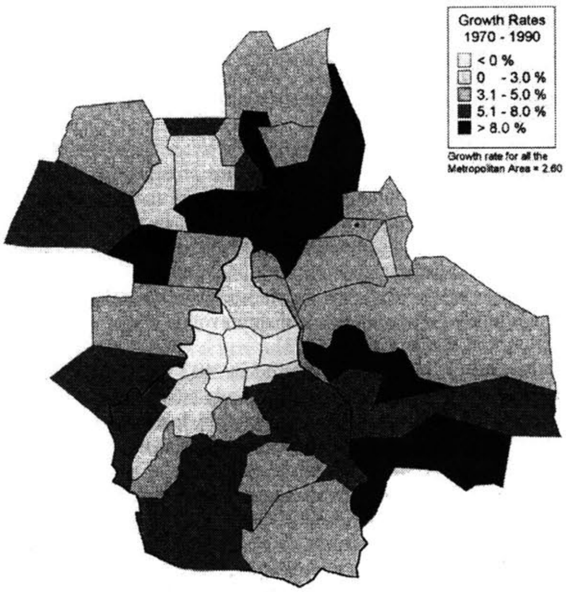

Figure 1.8. Geographic distribution of demographic growth in the Metropolitan Area of Mexico City from 1970 to 1990. Lighter tones represent lower growth rates. Note how the highest rates are located along the periphery of the Distrito Federal, in the Estado de Mexico. The historic center of the city is currently undergoing negative population growth.
Source: Pick, James, 1997.

Growth rates were finally reduced during the 1980s (perhaps in the aftermath of the 1985 earthquake). It reached its highest rate in the 1950s and 1960s at 5.1% annually and has decreased down to 1.36% in the year 2000. The spatial distribution of this growth is still, to say the least, disturbing. While some areas of the city are experiencing no growth at all, others, particularly around the edges of the city, are still growing at rates higher than 8%. The city has grown in size with alarming alacrity. The supply of mass public transportation fueled the urban expansion. During the first decades of the century, migrants settled within the urbanized area, close to the center of the city where most of the jobs were. The higher prices of these areas were compensated by the lower costs of transportation. The provision of affordable public transport, from the 1930s on, offset this equilibrium and encouraged the construction of large new settlements at the fringes of the city. Population densities were sharply reduced, from close to 20,000 people per sq. km in 1920 to 14,000 in the 1980s. This, of course, at the cost of urbanizing a larger area of the basin, from 240 sq. km in 1953 to 1,200 in 1990. A fivefold growth in a period of only 37 years. The growth of the city reflected, at least initially, the success of the economic policy of the new regime. The national improvement of health care, the sharp increase in industrial productivity and the provision of urban infrastructure, among other factors, made such a concentration possible. It also had, as we well know, some very important environmental consequences; some even threatening the survival of the city itself.

Throughout the last 30 years, as some alarming facts have begun to surface, some attempts have been made to lessen the impact of urbanization. The realization of the importance of the aquifer, the high costs of pumping water from outside the basin, the subsidence of the soil and its effect on the city's architectural heritage and the health cost associated with air pollution have increased the degree to which the city, government and residents alike, are willing to undertake some of the necessary steps to ameliorate the devastated condition of Mexico City's environment.

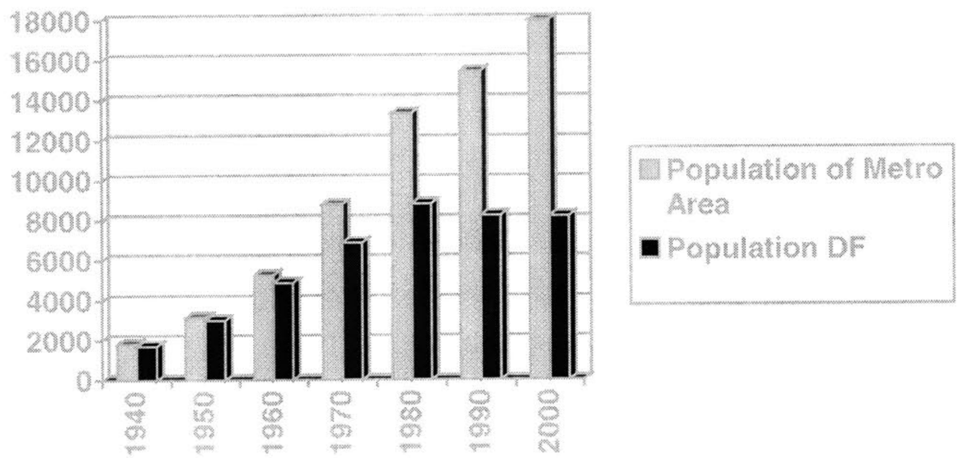

Figure 1.9. Demographic growth during the second half of the twentieth century in the Metropolitan Area of Mexico City.
Source: INEGI

Environmental Consequences and Solutions Undertaken

The environmental consequences of centuries of neglect are, of course, paramount. Perhaps, one of the most debated and addressed of these has been atmospheric pollution. The enormous expansion of the city, added to the basin's particular geography, have made Mexico City one of the most polluted cities in the world. The visibility of this problem has, on the other hand, encouraged the city and federal authorities to make a significant effort to improve the air quality. In the year

2000, the situation has been, at least partially, improved by both the implementation of a series of policies designed to limit the use of automobiles and by the introduction of new fuel technologies.

New technologies will probably facilitate the further improvement of air quality in Mexico City, in fact, the automobile industry is making significant progress in developing cleaner and more efficient engines. On the other hand, the problem of water supply and drainage and its effects on soil subsidence is not only being insufficiently addressed, but is one that can only grow more complex over time. Soil subsidence, for example, is one outcome of irresponsible water management. As early as 1944, Mexican hydrologist, Nabor Carrillo had inferred the link between soil subsidence and the consolidation of deep layers of clay as a result of a drop in hydraulic pressure caused by excessive pumping. The city sank 4.4" between 1948 and 1951 and 4.75" between 1951 and 1954.[17] In 1954, the authorities finally recognized the problem and banned the extraction of water in the central part of the city where buildings were beginning to collapse over the sinking soil. Subsidence has diminished, but not completely stopped. By 1970 the sinking had stabilized to 2.5"/year, but heavy damage had already been done to both the city's infrastructure and private buildings. The drainage system, for example, was no longer capable of sending waste water away without the help of pumping stations and a new deep drainage system had to be built to further down to take the flow away from the city (See Figure 1.8).

The costs of soil subsidence have been extensive. Drains and sewers fracture under the sinking soil and release untreated water into the subsoil and down into the aquifer; as the soil that supports them collapses, buildings slant, and water mains that distribute the water fracture and release the liquid into the ground. Surprisingly, one of the main sources of recharge of the aquifer, calculated at 16 cubic meters per second or over 24% of the total water supply, is that of water from leaking main pipes all over the city.[18] The city's historic heritage is also threatened, as buildings such as the Cathedral, built in the 17th and 18th Centuries, have to be externally supported to avoid its collapse.

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17 Ezcurra 65.
18 Ezcurra 82.

The steps taken to solve the problem of subsidence in the city have only gone half way. Pumping was, indeed, banned from the central parts of the city, but, to satisfy the water requirements of the population, water is being intensely pumped in other areas. In Nezahualcoyotl, for example, a large, low income neighborhood at the south east of the city, subsidence has not only continued, but it has increased to over 15"/year. This raises the issue of equity since most of the area where water is being pumped is home to lower income groups.

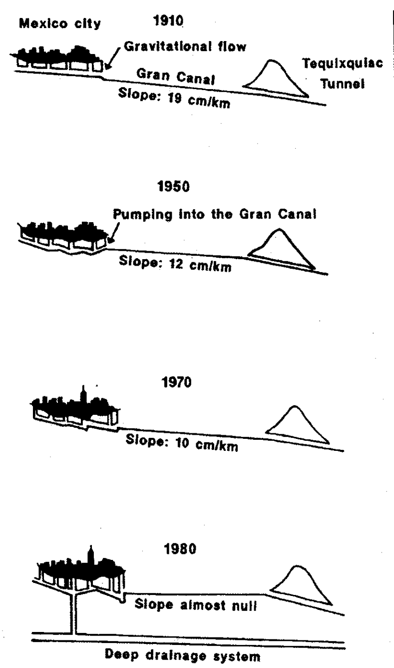

Figure 1.10. Effects of soil subsidence over the drainage infrastructure of the city. Source. Ezquerra,

The city has also taken steps to secure the recharge of the aquifer. National parks in the outskirts of the city have been created and developments are required to increase the percentage of pervious surfaces. However, enforcing these policies has been difficult; squatters often invade the new parks and new limits have to be re-drawn every few years. Developers often evade the regulations concerning pervious surfaces and the city has not had the capacity or the budget to enforce and monitor some of these policies.

In terms of water supply and demand, the situation seems even more discouraging. Having altered the hydrological system of the basin, the city is unable to sustain itself without exporting untreated waste waters and importing drinking water at great expense. The environmental inefficiency of the city has transcended the limits of the basin and threatens to severely impact other areas as well. Water management policies have been divided into two different and totally unconnected components: water supply and drainage. Until recently, there seemed to have been no attempt to seek a balance between the two. Larger and deeper drains, with ever increasing capacity, were carved out of the basin to the north while dams and pumping stations were being built to bring more water into the city. It is true that a city of the size of Mexico City could hardly be self-sufficient in terms of water management, but the extent to which we have ignored the basin's own water potential has indeed proven expensive.

In 1990, in order to meet the demand for drinking water of a little over 15 million people, 63 cubic meters per second had to be drawn from different sources. Of these, 42 were extracted from the aquifer, 1.5 were taken from surface flows within the basin and the remaining 19.5 were pumped into the valley from the Lerma and Cutzamala systems. Hence, continuous pumping has annulled the artesian pressure of old water springs and the overall water level of the aquifer is gradually diminishing. On the recharge side, the main annual input of water into the basin is estimated at 744.2 million cubic meters of which a maximum of 50% is captured and filtered to the aquifer[19]. This means a recharge of about 11 cubic meters per second exclusively from rainfall. Anther source of recharge, as we have already mentioned, is that which occurs from leaks in the water distribution system at 16 cubic meters per second. Both sources add up to only 27[20] cubic meters per second. This means that we have a deficit of 15 cubic meters per second that are being consumed, but not replaced. There is no certainty about the quantity of water that the aquifer holds and there is no analysis of the real costs of systematically reducing the city's water reserves.

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[19] Ezcurra and INEGI present this figure which may appear high, specially at an urban setting such as Mexico City. It is important to remember though, that the basin comprises 7,000 sq. km. Out of which 1,400 are urbanized.

[20] Ezcurra 84.

What we do know is the cost of supplying the water that is not drawn from within the basin. The 19.5 cubic meters of water per second brought up to the valley at a cost of US$ 0.20 per cubic meter[21] results in a daily expenditure of US$ 654,000 a day. It is important to mention that, because the aquifer is already being exploited beyond its capacity, any future requirements will have to be met through outside sources. Hence, the percentage of the water supply brought from outside the basin, 30% in 1990 cannot but grow if an alternative model for water management is not implemented.

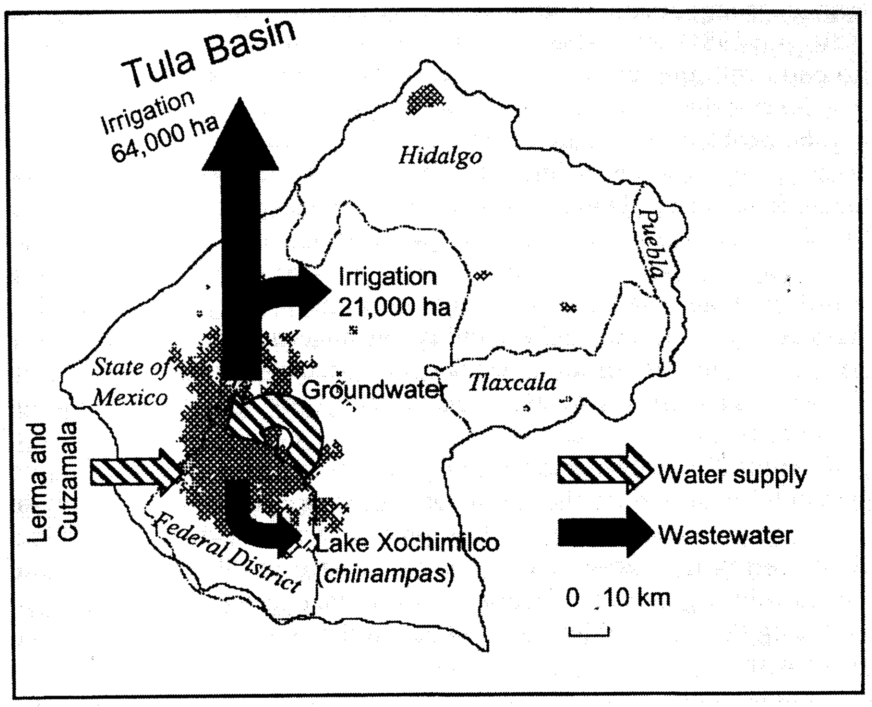

Figure 1.11. Drinking and waste water sources and final destination. Source: Ezquerra.

Stormwater and sewage rainage is, if considered as an isolated process, much cheaper than water supply. Although it also requires some pumping, its cost only represents one tenth of the previous figure. This amount nonetheless does not include the costs of wastewater treatment and the environmental costs associated with the pollution

[21] This figure was calculated out from an analysis of costs in Ezcurra, p. 147. It takes into account the different heights from where the water is drawn and the cost of the power required to pump it in 1995 dollars. It does not include, however, the capital infrastructure and land consumption costs of the Cutzamala system.

of other areas.[22] More importantly, though, it does not include the opportunity costs of minimizing the need of bringing drinking water from outside sources.

The city's water treatment capacity, currently working at only 50% of its capacity treats only 7% of the total wastewater generated. This represent 4.3 cubic meters per second which are used for industrial purposes and for the recharge of semi-artificial lakes such as the ones in Chapultepec, Aragon, Cuemanco and Xochimilco. The irony lies, I believe, in that the cost of water treatment has been calculated at about US$ 0.20 per cubic meter. Exactly the same than that of pumping the water from the Lerma and Cutzamala systems and much lower than the costs of water from the fourth phase of the Cutzamala, which, including capital investments can be as high as 1 dollar per cubic meter per second. It is true though, that waste water is currently being used for irrigation in the Mezquital Valley, north of Mexico City. A valley that would otherwise be dry and unfertile is capable of producing a significant amount of agricultural produce. However, the high levels of pollutants of the untreated water, turns this disposal method, that would otherwise be laudable into a health hazard. Other, more successful projects include the re-flooding of an area of the former lake Texcoco. This "artificial" lake is used as a water treatment plant for irrigation and industrial purposes. One unexpected benefit of the lake has been the significant reduction of the suspended particles' content of the air. In fact, when the dominant northeast winds blew over the dried lakebed, a considerable amount of dust swept the eastern edge of the city, contributing significantly to the air pollution of the area. Moisture and temperature measurements over the last ten years have shown an increased humidity which, in turn, stabilizes temperature and helps prevent thermal inversion during winter. The benefits of this project on air quality has encouraged projects to increase the area of the artificial lake and to re-vegetate other areas. The authorities are beginning to recognize the interrelation between environmental factors where an effort to improve one part of the ecosystem can have positive influences over another.

One field that has been partially overlooked by the city's water authority DGCOH,[23] is the impact of urbanization on water management. The city's concern in this

[22] The government of the Federal District is currently facing the possibility of paying close to 45 million dollars a year to neighboring states for polluting the waters of rivers such as the Tula, located in the state of Hidalgo.

regard has been limited to the protection of recharge areas such as the Ajusco[24] and to a few regulations stipulating a percentage of pervious areas within new developments. As commendable as these policies might be, the limited involvement of the DGCOH in the planning of the city represents a missed opportunity to incorporate comprehensive stormwater management practices within the new developments around the city. The traditional political preference for costly mega projects as well as the government's disdain for non-structural solutions is reflected in the 1997-2000,[25] Water Management Master Plan[26] which does not include any site design considerations. More than two thirds of the budget of the plan is concentrated on "Improvements and Expansion" which consist of hard engineering, infrastructure projects such as the expansion of the Cutzamala system, new pumping stations, and distribution pipelines. Even if all of these projects were necessary, the master plan's budget analysis recognizes the poor effectiveness of such projects. According to their own figures, the cost of every cubic meter per second of water provided by the "Improvements and Expansion" section of the budget would be of 2,038 million pesos; the same amount of water would cost the city 206 and 488 million pesos by investments in preventing leaks and treating water for reuse respectively.[27]

Today, we are still paying for bad investment decisions. One of the projects in the Improvements and Expansion section of the Master Plan, was the completion of an Aquaferico, an aqueduct that would run throughout the southern edge of the city to distribute some of the water coming through the Cutzamala system from the State of Mexico. The system was constructed to carry as much as 20,000 liters per second; today, because of the resilience of residents in the State of Mexico to give the city more of its water, it only carries 300 liters per second.[28] Another such example is a treatment plant

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[23] Direccion General de Construccion y Operacion Hidraulica.
[24] The protection of this area at the south edge of the city dates back to the 1980s when it was proclaimed a National Park. This area is a very significant source of water for the aquifer and its conservation has become an important water management strategy.
[25] One should notice the lack of continuity of the agency's programs. It is disturbing that the agency's direction is appointed by the mayor and thus changes with every administration.
[26] DGCOH. *Plan Maestro de Agua Potable del Distrito Federal 1997-2000*, (Mexico D.F. 1997).
[27] Figures taken from the cost effective analysis in table 7.2 of DGCOH.
[28] According to Reforma (Fecha), residents of Temascaltepec, fearing being left with water resources have protested against the construction of the fourth phase of the Cutzamala project that would direct the "unutilized " flows to the Metropolitan Area. There have even been threats menacing to sabotage the project if it continues construction.

for exclusive development of Santa Fe. In this case, the master plan of the area demanded a facility that could take wastewater and treat it to irrigate the development's green areas. Due to financial and political difficulties, the plant as well as the distribution pipes required, which are at a 90% completion, are still unable to work. The concentration of water management into one single, centrally controlled project has often, as in the case of these examples, proven ineffective and expensive. A more decentralized approach could have proven to be more financially feasible. For example, a developer of a housing project in the Santa Fe area assures me that their company has already contributed their share to the water treatment plant programmed for the area.[29] Nevertheless, they have not been able to use it even after more than five years of occupancy. In fact, the housing development is large enough to justify its own water treatment plant. Even if the economies of scale involved in building a larger plant were significant, the distribution network required to transport the water from the generating point to the plant and back to the consumer would greatly increase its financial and environmental costs.[30] Furthermore, a series of smaller plants privately owned and operated could represent considerable public savings. The city's role in this case would be limited to monitoring the quality of the treated effluent as well as give financial incentives and information to the parties involved in the construction and operation of such plants.

Our attitude towards water management needs change. The low price of water does not represent at all, its costs. Although it is imperative to provide drinking water, even to the poorest sectors of our society, its price should more accurately reflect its cost. Indeed, water is currently cheap to all: rich and poor alike. It is, in fact, the poorest sector of the economy, the one that does not get piped water, that pays a disproportionately high price for the liquid. Redistributing water subsidies to help only those who need it the most could increase resources for water treatment projects while discouraging waste.

The current use of water really reflects how damaging these policies have been. In 1990, 40% of the drinking water, that is approximately 27 cubic meters per second, were used for nothing other than flushing our toilets. We literally flushed over US$ 654

[29] Private conversation with Civil Engineer Miguel Angel Ruiz
[30] According to Janus Niemczyowicz, *Integrated Water Management Background to Modern Approach with Two Case Examples* in Field, Richard et al, *Integrated Stormwater Management* (Ann Arbor, Lewis

million every day, in bringing clean, potable water to the city. According to Dora Crouch, already in antiquity, the Greek societies divided the water into three types to be used for different purposes: drinking, washing and irrigating. The scarcity of drinking water made this culture recognize its value and conceive of strategies for its most efficient use.

Current trends in real estate development incorporate large portions of land under one developer which are large enough to incorporate water treatment facilities and sound water management practices into its design. Given a more rational water price, a set of public financial incentives and the inherent environmental benefits of these practices, design would then be encouraged to incorporate the latest trends in water management. The City could then compensate the costs of those incentives by freeing resources from water supply or drainage. We have yet to come with ways to distribute equitably the costs of hydraulic infrastructure, and here I include site planning and bio-engineering devices as well as traditional engineering projects, while encouraging public participation and private investment.

Publishers, 1993) on site plants can be designed to treat only pollutants found in that source to a standard that can vary depending on its final use.

Chapter 2. New Trends in Stormwater Management

Water management is certainly not a new concept. The ability to control water has been an important tool for the development of society, perhaps as much so as the ability to control fire. Cities have been historically founded close to sources of water, water that has been used not only for human consumption, but also for irrigation, transportation and industrial purposes. Crouch sustains that as early as the eight century B.C. the Greeks were choosing the location for their colonies around the Mediterranean according to geologic formations that would guarantee access to sources of water for which they had already developed technologies in the mainland.[1] Hydraulic technology has also played a key role in the limitation of urban capacity. An urban center could maintain and increase its population as long as it developed the necessary technologies to supply water: Greeks mastered the art of collecting water from the karst geologic formation, Romans engineered aqueducts and tunnels to transport it from distant sources and so on. The scientific and technological advances made since the eighteen century have significantly altered every aspect of human life and urban development; the provision of water is no exception. Mechanic pumps, disinfectants, stronger and more efficient pipes supply water from otherwise unobtainable sources. In Mexico the percentage of the population with piped water has increased from 18% in 1930 to 86% in 1998.[2]

We have reached a time though, in which we can objectively evaluate the application of these technologies and their consequences. We have recently become aware of the costs related to the degradation of the environment. According to the Mexican Federal Government, the economic losses related to environmental degradation and the depletion of non renewable resources ascends to 10.6% of the Gross National Product.[3] Environmental sensibility must therefore become a main criterion for evaluating the cost-effectiveness of future infrastructure projects.

The stormwater management strategies that follow are intended to fulfill most of the functions that most hard engineering projects fulfill, but with a beneficial impact on the environment and an opportunity for important collateral benefits. These strategies seek to utilize natural processes in an advantageous way, in fact they constitute a crucial ingredient

[1] Crouch. P. 66.
[2] INEGI.

of the strategy itself. The understanding of some of these basic processes becomes key to the appropriate implementation of these strategies. I will briefly mention how this fundamental processes work and how they are impacted by urbanization. For further study, please refer to Bruce Ferguson, Introduction to Stormwater, 1998.

Stormwater Fundamentals

According to Ferguson, the undisturbed environment includes soil and vegetation that "absorb rain and make it part of a living organism"[4]. Each component of the ecosystem plays a role in the water cycle: soils filter and contain the water to different degrees according to their structure and quality; plants absorb water through their roots, break up soil particles and add material to it when it decomposes; animals such as earthworms excavate the soil allowing plant roots to penetrate it and water to filter through. Throughout this slow process water is filtered and its nutrients are fed upon by vegetation and microorganisms as it flows towards an underground aquifer, a stream or the oceans.

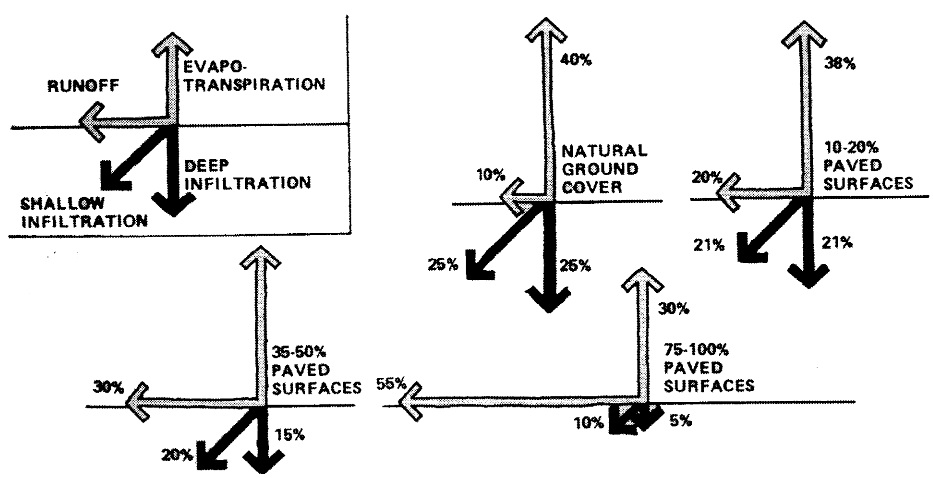


Figure 2.1. Water cycle under undeveloped and developed conditions.
Source: Tourbier, 3.

Runoff, on the other hand, is the movement of water that has been unable to infiltrate the soils whether because the soil was too impervious or because it was already saturated with water. Runoff, also flows towards streams, rivers or oceans, but it does so at

[3] Semarnat.
[4] Ferguson, Bruce K. Introduction to Stormwater. New York, John Wiley and sons, Inc, 1998. p.1

the surface and at a much higher speed than underground water thus it short- circuiting most of this cleansing process.

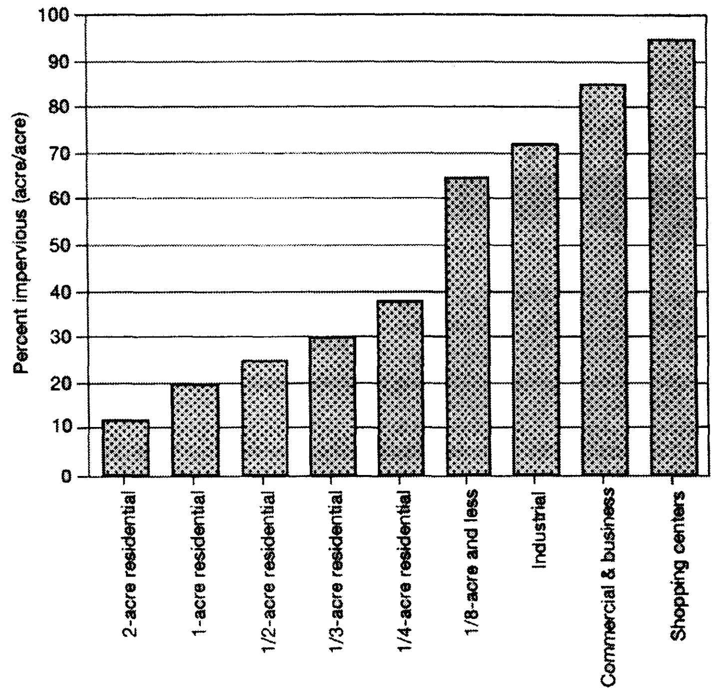


Figure 2.2. Impervious cover as a function of contemporary land use.
Source: Ferguson. Introduction to Stormwater, 5.

Urban development has increased impervious surfaces dramatically. It seals the soil and eliminates its capacity to infiltrate water. By doing so, impervious surfaces not only increase the amount of runoff, but also decrease the amount of water flowing underground and so warrants the gradual depletion of aquifers. On the surface, rivers and streams get sudden inflows of water during storm events, but do not get enough water from underground flows to sustain a constant current during drier seasons. Stream bank erosion, poor water quality and flooding are some consequences of these rapid flows. "Impervious cover produces the worst kind of hydrologic worlds: it enlarges storm flows into destructive bursts and, at the same time, it withdraws the resource of base flows"[5] It is no coincidence that flows from 50 or 100 year storms are currently succeeding each other every 5 or 10 years.

[5] Ferguson. p.5.

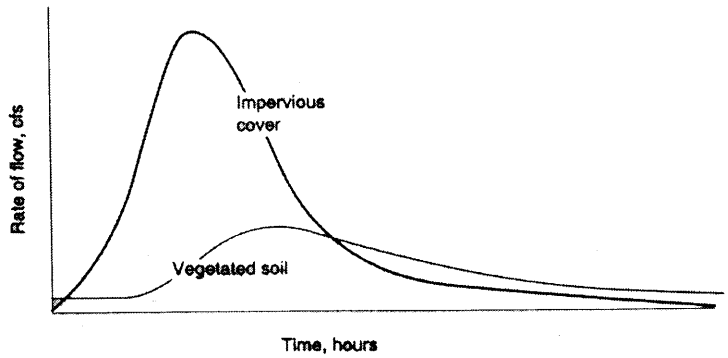


Figure 2.3. Contrasting peak flows in vegetated and unpervious soils.
Source: Ferguson, Introduction to Stormwater, 6.

Water quality has been remarkably damaged by the urbanization process. Water no longer gets cleaned and filtered by soil particles and bio-mass, but it now carries other pollutants such as oil, fuel, organic suspended solids, rubber, and chemical nutrients such as phosphorous and nitrogen. The reduced water quality threats to pollute clean sources of drinking water such as rivers, lakes and aquifers.

Slowing down water as it travels through the surface provides the opportunity of naturally removing some pollutants. Mechanical treatment plants mimic the biological processes that exist in nature to remove pollutants from the water, but they do so in a compacted area where the processes are packed down and monitored. As useful as these treatment facilities may be, they do not repair the water cycle nor can they serve different functions at the same time. Bio-engineering techniques that control natural processes in a replicated natural setting can obtain the same reliability as mechanical plants, but can also offer additional benefits such as habitat for wildlife, human recreation, improved air quality and flood control. Such strategies can and should be included in addition or as a viable alternative to mechanical processes.

In the following pages I will briefly describe each strategy in a general way. An application example of each that incorporates the particular characteristics of the site will follow in the next chapter together with a set of conclusions regarding their behavior and feasibility within the context of Mexico City.

Classification of Stormwater Management Strategies

The natural water cycle is composed exclusively of four factors: rainfall, the amount of water that falls during a particular storm event; evapotranspiration, the water which is absorbed by vegetation or that is evaporated back to the atmosphere; infiltration, the water that filters down into the soil; and runoff, the water that flows through the surface until it reaches a sea, lake or ocean.

The quality of the soils, the vegetation, and the amount of rain are tightly interrelated and complete a natural balance that unrestricted urban development has often shattered. This effect could be summarized by the reduction of the capacity of the soil to infiltrate and a subsequent increase in runoff. Problems associated with this include floods, erosion, decreased or increased river flows and water pollution among others.

Stormwater management should seek to restore this balance. New developments should include preventive measures to limit their impact on the water cycle as well as design components that compensate for the decreased infiltration capacity of the area and manage the increase in water runoff. These different approaches can be described as Preventive and Corrective Measures.

Preventive Measures

These are the steps taken to minimize the impact of a given development in its environment through the configuration and lay out of its components. A few general principles include the clustering of the development into the minimum possible area in order to reduce paved surfaces and infrastructure and maximize green, undeveloped areas; the location of the development within the size so that environmentally or socially sensible areas are not affected; the reduction of road widths; and the selection of appropriate materials, vegetation species and construction techniques, but there can be as many as the imagination and creativity of the designer allows. The specifics of the site and the development that will occupy it should inspire and limit the application of preventive measures.

Corrective Measures

As I have stated earlier, corrective measures are the ones designed to reduce the impact that a particular design is expected to have on the water cycle. They should therefore respond to the particular characteristic of a given development: the greater the percentage of covered or impacted soil, the greater the amount of corrective techniques that would be needed to restore the water balance.

The main objectives of stormwater management, infiltration compensation and runoff management will serve as a basis for the following classification. Most of these devices, however, fulfill both functions to some degree as well as other ones that should also be evaluated as additional benefits such as aesthetic values, real estate marketability or educational opportunities.

1.- Infiltration Compensation Measures:

1.1 Swales.

Swales are open channels whose objective is the conveyance of water. Depending on its design, a swale can reduce runoff peak flows and water velocity as well as improve water quality, encourage infiltration and support a wide range of plant and animal species. A swale's hydraulic capacity is defined by its section, cover material and slope, all of which should be designed for a given storm event. Swales can be included in long linear patterns (see application) such as street edges and following topographic contours in order to avoid slopes higher than 10% that can result in erodible velocities. The pollutant removal capability of a 200 feet long swale with velocities of no more than 0.5 fps can be as high as 80% for suspended solids.

1.2 Dutch drains or ditches.

These are long, rectangular trenches whose bases are covered with crushed stone or gravel with high water storage capacity. The top layer that covers the gravel must be of a highly pervious material such as vegetation, perforated concrete, loose pebbles or an iron grid. Besides storing water for further conveyance or infiltration, and depending on the filtering capacity of the base and top materials.

1.3 Perforated pipes.

These are pipes that are buried in the ground and that allow infiltration through perforations along its perimeter. Concrete perforated pipes are usually used in Mexico for landscape drainage. If the soil's permeability is not enough to significantly reduce the flow within the pipe, an additional Dutch drain can be incorporated with the perforated pipe running through its center. Because of the greater velocity of the flow within the pipe, the infiltration capacity is lower than that of swales or ditches, but the conveyance capacity can be greater.

1.4 Infiltration ponds.

Infiltration ponds are water bodies on pervious land. Water stored on these ponds should be able to permeate the soil on its base and sides. Pond size can be calculated for different storm events, but it is generally economically unfeasible to design them for extreme events. An outlet can be manipulated to allow for water levels control that can be particularly valuable for runoff control purposes; in this case the pond can be emptied before a storm event, thus increasing its capacity to store the event's water. Great attention should be given to avoid accumulation of sediments that can reduce percolation rates, specially during construction; vegetation can help maintain the soil's porous structure. A sedimentation pond working in conjunction with an infiltration pond or trench can reduce this risk.

1.5 Subsurface infiltration basins.

Similar in nature to infiltration ponds, but constructed in areas where limited space is available, under the ground. These basins consist of a constructed chamber filled with open-graded aggregate and lined with a fabric that allows the percolation of water into the soil. The advantageous underground location allows other for other uses to take place at the surface (streets, buildings, etc.), but increases significantly the costs of construction.

1.6 Infiltration wells.

These are vertical cavities in which water is injected and to the soil. Infiltration wells can perforate impermeable layers of the subsoil and reach more permeable ones, but the contact area with the soil is limited to the wells section at its base, its sides, generally cased, impede lateral infiltration. The greater pressure of water though, either injected by gravitational or mechanical means, thrusts the water into the soil and maximize the soil's potential absorption capacity. The limited area of the well's base is highly susceptible to sediment clogging so it is imperative to use a sediment filtering device. The cost and efficiency of wells vary according to the soil's characteristics, the level of complexity of the well itself and its location in relation to the aquifer.

1.7 Terraces.

The manipulation of the topography into terraces can significantly reduce water velocity and increase the time in which water is in direct contact with the soil thus increasing infiltration. Important considerations for the construction of terraces are the consolidation of the deeper layers of the soil and the inclusion of best management practices (BMPs) during construction to avoid erosion and sedimentation. An added benefit of terraces, specially in steep topographies are decreased erosion, increased accessibility and usability to the site. The costs involved in grading the site though can be significant, and an accurate analysis of the soil's capacity to resist sloughing, even under saturated conditions, is indispensable to warrant stability.

1.8 Permeable pavements

Road and parking pavements constitute the majority of impervious surfaces in contemporary developments. The inclusion of permeable paving materials can significantly increase infiltration and, consequently, reduce runoff. Permeable pavements include porous asphalt and cement, open celled pavers such as lattice or castellated and brick, pebbles or gravel set in an unconsolidated fashion. The 10% increase in price of these alternatives can be amply offset, if considered in the design from the beginning, by savings in storm drainage systems. These pavements are particularly suitable for low traffic, residential streets and parking lots.

2.- Runoff Control Management

2.1 Dry detention Basin.

These basins are designed to slow down the rate of flow of surface runoff thus reducing peak flows during storm events. The storage capacity of these basins is maximized by their seasonal nature where water is only stored for short periods of time and released as soon as the flow downstream recedes. The basin should ideally be empty before a storm event. A detention basin must be calculated to store water for a given storm event and to release when all the flows in the watershed have decreased. Failure to do so can result in augmented floods downstream. One of the advantages of dry detention basins is that they can be set in areas used for other purposes such as sports fields and parking lots.

2.2 Extended Detention Basin / Wetlands.

These are similar to the previous basins, but they hold water throughout the year; their outlet is placed at a higher level than the bottom of the pond. The constant water flow allows for a greater wildlife variety as well as an improvement of the water quality via phyto and bio remediation. Wetlands, for example are wildlife-rich detention basins with slow and even water flows that can significantly reduce contaminants loads. Their pollutant removal efficiency though is dependant on the continuity and regularity of water flows. Infiltration may be undesirable if water inflows during the dry season are not enough to compensate losses through infiltration.

2.3 Sedimentation Ponds

Sedimentation ponds are almost exclusively used in combination with other structures; their key objective is to settle sediments at its base and block them from flowing through. Consideration should be given to the design and location of the pond in order to avoid strong winds or wildlife that could stir the sediments. Sediments at the base of the ponds should be removed consistently to avoid reducing the pond's hydraulic capacity.

2.4 Spreaders.

Spreaders are artificial topographic formations designed to fulfill two main functions; avoid channelization by spreading the water into a wide sheet flow and delay and slow down surface runoff. Sheet flow and reduced velocity may further increase infiltration as well as protect the soil from erosion.

2.5 Stream Buffers

Stream buffers are areas along a river that serve as a cushion between the river ecosystem and that of urban or agricultural areas. The riparian vegetation filter nutrients and pollutants that would otherwise enter the river and creates a linear link connecting various habitats. A healthy stream buffer contributes to a slower flow and to the stability of the river's banks. Its width depends on the topography of the site and on the ultimate function of the buffer, a sensible width is 30 meters on each side of the stream, but steep topographies and a wildlife habitat and connector might need widths of up to 100 meters. In Mexico City, stream buffers are federally owned and their sizes depend on the size of the stream itself. Streams under 5 meters wide have a 5 meter buffer and those over 5 meters have a ten meter buffer. Stream buffers are generally divided into an inner area or stream side zone where land use should be restricted to mature vegetation and footpaths; the middle zone which should consist also of mature vegetation, but where stormwater management practices can be placed as well as recreational foot and bike paths; and the outer zone which can include residential lawns and landscapes and recreational amenities.

2.6 Wet Meadows

Wet meadows are characterized by moist to saturated soils with standing water present for only brief periods during the wet season. Vegetation is generally limited to herbs, grasses and sedges. Wet meadows have a great capacity for pollutant and sediment removal and can work in conjunction with other practices.

Chapter 3. Site Analysis of Case Study
A New Residential Development in Santa Fe, Mexico City

The following case study is intended to be a demonstration of an integrated stormwater management approach in site design. The alternative configuration shown on the next chapter responds only to this concern and ignores other, equally valid, environmental, financial, social and aesthetic issues. Thus, it should not be considered as a substitute proposal but as a display of a set of tools to achieve a specific end.

Santa Fe Sub-center

The areas located at the south and western edges of the city are extremely important to the recharge of the city's aquifer. They receive up to 1200 mm of rain every year and has a rugged volcanic geology that allows great water infiltration. Nevertheless and in spite of the unfavorable topography of the area in real estate terms, they have undergone extensive urban development, particularly in the last fifteen years. The location of Santa Fe, immediately bordering the higher income neighborhoods west of the city, makes it a natural recipient of the centrifugal expansion of the urban fabric.

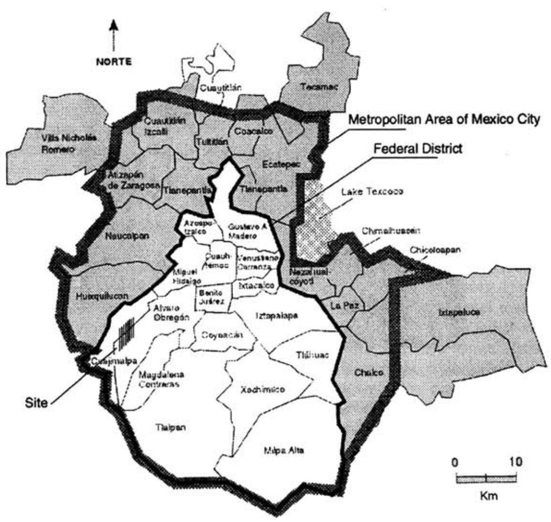
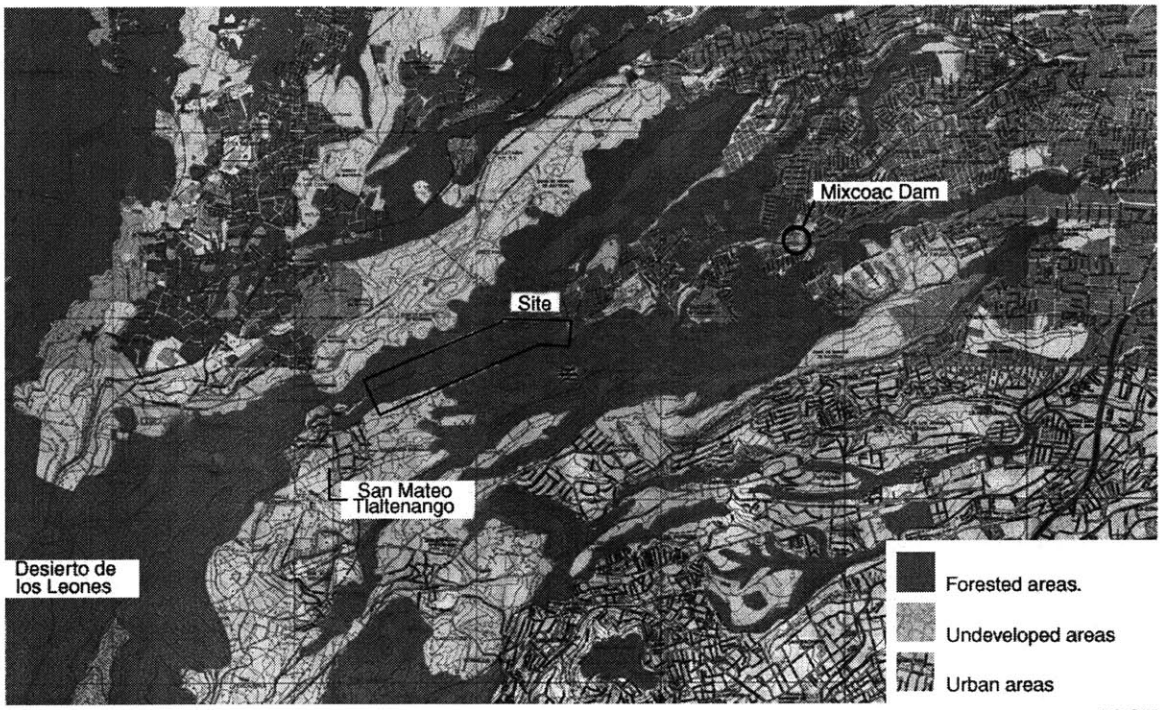
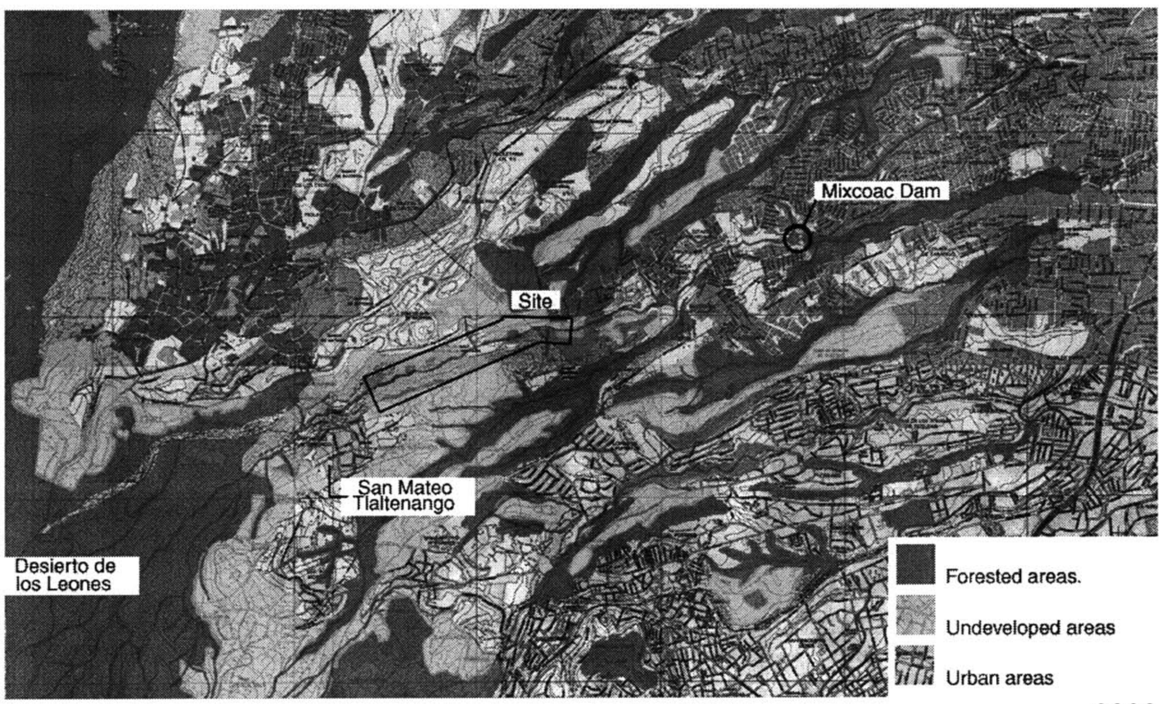


Figure 3.1.
Map of the Metropolitan Area of Mexico City with the border of the Federal District and the location of the site.
Source: National Research Council, Mexico City's Water Supply, p.5.

Santa Fe, a mega-project that includes universities, high end residential, corporate offices and the largest shopping center in Latin America has been the core of the city's programmed urban expansion at the western edge of the Federal District.



1985



2000

Figures 3.2 and 3.3 show the progression of the urban mass into the forested areas of the Sierra de las Cruces from the year 1985 to the year 2000.
Source: Author.

The site's setting.

The site is located at the southernmost edge of Santa Fe, a few hundred meters east of the semi-rural town of San Mateo Tlaltenango. The 236 acre site is itself a long, narrow valley enclosed by steep topography at its north and south edges. The Mixcoac River that runs through the middle of the site is one of only three perennial rivers in the Federal District. It originates in the Desierto de los Leones National Park, in the Sierra de las Cruces hill range, some six kilometers west of the site, and runs eastwards towards the city, for another 6.5 kilometers until the Mixcoac Dam stops its flow and redirects it toward the city's drainage system

Figure 3.4. Aerial view of the site towards the east with the city on the background. The river is visible at the lower right corner.
Source: DINE http://www.dine.com.mx/dsrrllo.htm

The river's elevation, from level 3,000 above sea level (a. s. l.) to 2,400 a. s. l. results in an slope of close to 5 %, a median flow of 3 m^3/s and a maximum hydraulic capacity of 10 m^3/s. In 1941 the Mixcoac dam, with a capacity of over 800,000 m^3, was built to prevent the flooding of the city; no attempt was then made to incorporate the water into the city's water supply system. Today, urbanization has caught up with the location of the dam; the increase of impervious surfaces and drains and the encroachment of built structures at the river's banks upstream have resulted in augmented flows and erosion, with subsequent floods and landslides, which have caused considerable damage. Even though the dam itself has been able to withstand the increased flow, city officials are beginning to recognize the need to extend the stormwater infrastructure further away from the city's core.

The particularly harmful storm of June 25, 1998, when the river carried a flow of 24 m^3/s gave rise to a governmental initiative to study the river's hydrology and the state of its banks. The report emphasizes the necessity to protect the river's buffer from invasion and garbage disposal and to impede the intrusion of raw sewage from illegal drains into the river's bend. It proposes the strict enforcement of the publicly owned 15 feet (5 meters) buffer and its possible expansion of another 15 feet; the fencing off of the river to avoid garbage disposal; the construction of gabion dams to avoid further erosion and the construction of a raw sewage pipeline along the river's buffer.

The location of the site, immediately bordering the dense urban fabric of the city downstream and the semi-rural landscape upstream, makes it an ideal candidate to implement water reclamation and infiltration strategies. It is the last stage before the river enters the urban area where implementing these measures grows more difficult, requiring perhaps population relocation and intense water monitoring The semi-rural areas west of the site contribute relatively little to the pollution of the water; the city's policies to impede raw sewage from entering its flow may further reduce its pollution.

The implementation of a comprehensive stormwater management strategy can substitute costly engineering projects that often, as is the case of the Mixcoac dam, serve only one purpose and fail to take advantage of the potential benefits that a sustainable design might offer. The water of the Mixcoac river should no longer be perceived as a threat to the city, but as an opportunity to attenuate its severe water deficit.

The site's projected development

One of Santa Fe's prime residential neighborhoods is being developed along the basin of the Mixcoac River, at the southernmost edge of the subcenter's area. A case study of this particular site will provide this work with a framework with which we can compare the performance of traditional development patterns against a design that concentrates on incorporating stormwater management practices. This development is perhaps one of the greenest developments in the city devoting close to 45% of the entire site exclusively to open, green and forested areas (See table 3.1). The potential hydrologic impact that urban development in this areas has on the rest of the city highlights the necessity to design deliberately to avoid erosion, maximize groundwater recharge and preserve, if not improve, surface water quality. The green areas integrated into a development in this area should be designed and located in relation to their performance towards these issues and the overall ecology of the site. A development such as this, which markets itself as a green oasis, should not miss the opportunity to integrate its natural features into the overall biological, hydrological and environmental functioning of the ecosystem in which it lies. Furthermore, in a city such as Mexico City where nature is indeed a commodity, this approach could have a positive effect on the marketability of the project.

As shown in Table 3.1, the large size of the 205 single family lots consumes over 52 acres of land, forcing the developer to limit the area devoted to undeveloped forest to only 29.82 acres. The calculation of impervious areas under this site configuration results in 41.29% of impervious areas.[1] The "green" development therefore performs poorly in hydrologic terms.

[1] The impervious percentages of each type has been assumed by the author after calculating standard construction practices in Mexico. In the case of single family residential lots, for example, the author assumes that houses will have a total area of 7,000 sq. f. of which 4000 would be on the ground floor. Additionally, a house in this development would have a parking area of at least 1,000 sq. f. suitable for 4 or 5 automobiles and 1,000 sq. f. of terraces and walkways. Added together, these impermeable surfaces would result in 50% of the total lot. The remaining 15% as well as the percentages for green areas were arrived at after calculating the SCS's runoff coefficient for grassed residential areas in Bruce Ferguson, Introduction to Stormwater, p67.

Table 3.1.

Area and density analysis of the proposed development plan.

Type	**units**	**Area (sqf)**	**Area (ac)**	**ND U/ac**	**Lot/unit**	**Impervious %**	**Total imp**
Single fam (2-3)	205	2,278,189.57	52.30	3.92	11,113.12	0.65	1,480,823.22
Multifam-low (2-3)	40	483,630.33	11.10	3.60	12,090.76	0.6	290,178.20
Multifam-med (7-13)	182	1,158,075.83	26.59	6.85	6,363.05	0.45	521,134.12
Multifam-high (18)	294	343,203.79	7.88	37.31	1,167.36	0.45	154,441.71
Services		470,445.50	10.80			0.7	329,311.85
Street		694,236.97	15.94			0.9	624,813.27
BUILT UP		**5,427,781.99**	**124.60**	**52.61%**			**3,400,702.37**
Streetscape		1,041,355.45	23.91			0.35	364,474.41
Green Area Sport		1,978,085.31	45.41			0.25	494,521.33
Undeveloped		1,298,843.60	29.82			0	-
TOTAL OPEN		**4,318,284.36**	**99.13**	**41.86%**	**TOTAL IMPERVIOUS**		**4,259,698.10** **41.29%**
TOTAL	**721**	**10,316,976.30**	**236.85**	**3.04**			
Federal Area River		470,445.50	10.80				
TOTAL SITE	721	11,047,222.75	253.61	2.84			

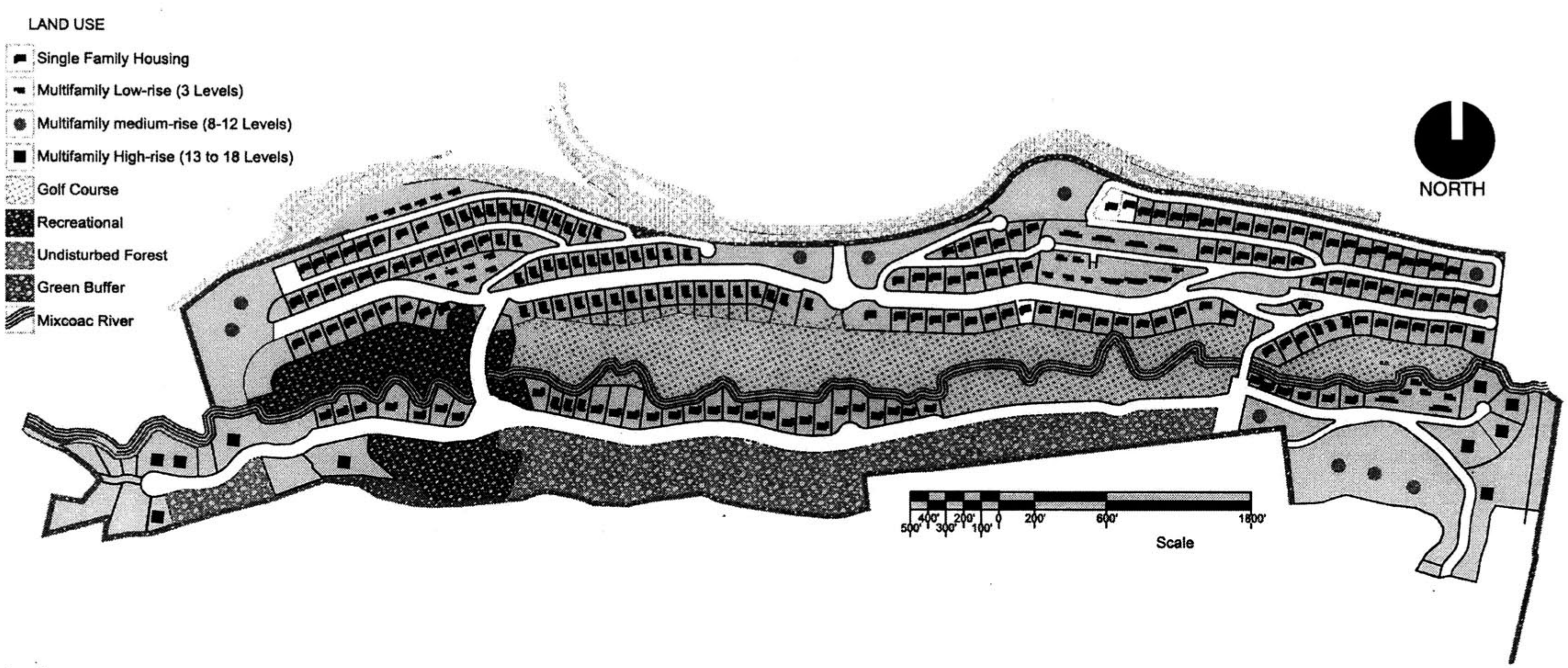


Figure 3.5. Plan of the Existing Development Proposal.
Source: Dine.

Stormwater Management Deficiencies of the Existing Design.

There are three main concerns in regard to stormwater management that should be carefully addressed when designing for this specific site: the forested areas along the ravines, the steep topography of the site and the importance of the preservation of the stream. These three issues are interrelated and should be addressed in a comprehensive way. Figure 3.6 shows the topography of the site in three different categories: slopes of 35% or higher where construction would cause sever erosion and deforestation; slopes between 15% and 35% more suitable for development and areas with slopes lower than 15%.

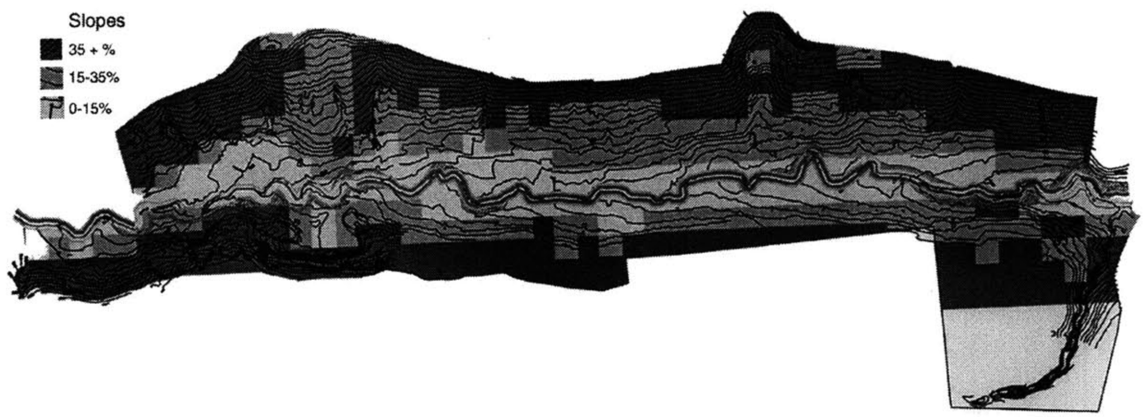


Figure 3.6. Topography of the site.
Source: Drafted by the author with information provided by DINE.

As we can see, the flatter areas of the site are located at the center of the valley, along the river; the topography grows steeper towards the crest of the ravines. The vegetation of the site coincides with its topography; the most forested areas occupy those slopes over 15% and the flatter areas along the river are vegetated by bushes and grasses in what has been, for the last 15 years, a golf course. Because of this desire to maintain the golf course for market reasons, the developer was forced to occupy the steeper and more forested areas at the edges. At the same time, the large area of single family lots of over 11,000 sf each pushes the development further up into the steepest ravines. The large area of single family lots contributes to feed the perception of a low density development with a high percentage of natural areas, but it is in fact this characteristic of the design that contributes the most to the deforestation and subsequent erosion of the ravines. Figure 3.7 shows the steeper areas of the site, with slopes of 40% or higher, over which development is being proposed.

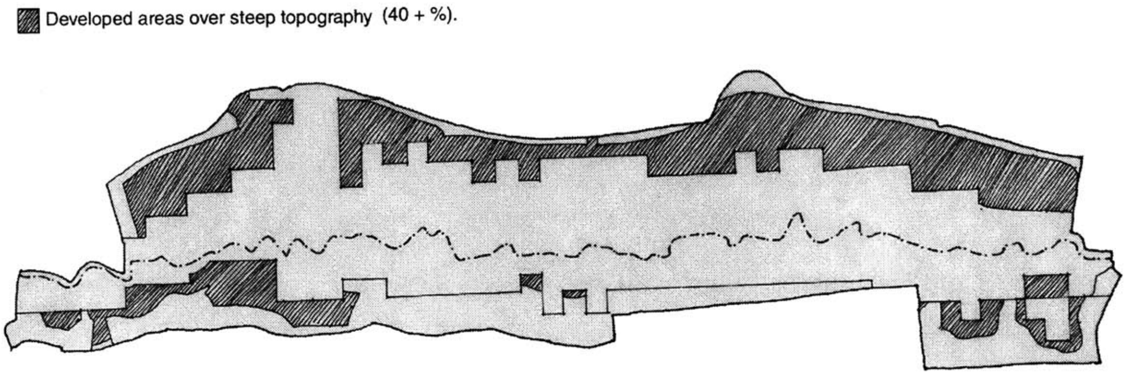


Figure 3.7. Encroachment of the development over steep topography.
Source: Author

The infrastructure requirements to provide access and services to each lot grow in relation to the size of the individual lots. Complicating the matter further, the construction of single family houses over this topography forces the designer to provide single loaded streets in order to be able to access each lot at its highest elevation and limit excavation. Even with narrow streets of only 18 feet wide, the total area of the roads (excluding parking, streetscape and sidewalks) ascends to 15.94 acres. This and other potential threats that the configuration of the development can pose on the hydraulic balance of the site are identified in Figure 3.8.

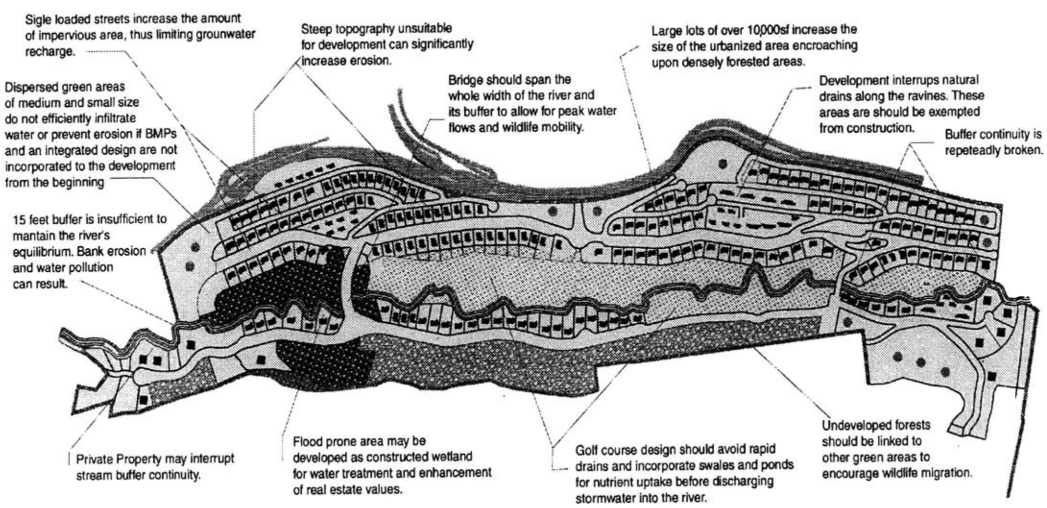


Figure 3.8. Identification of potential hazards of the proposed design.
Source: Author.

The extended distribution of the single lots throughout the site also has consequences on the river. As shown in figure 3.8 the river's buffer is endangered by the proximity of the houses. The legal buffer of 15 feet, which is federal property, is respected, but it is hardly sufficient in view of the increase runoff and erosion that such development can generate. The affected hydrology of the river can severely disrupt the river's health and result in bank erosion and flooding. The golf course can be incorporated into the river's buffer and reduce its vulnerability as long as it is purposefully designed to alleviate flow discharge and increase nutrient uptake.

The calculation of the runoff and erosion impact of the design can offer a valuable tool in determining the performance of the development in regard to a hydrologic criteria. Table 4.2 is a comparative analysis of runoff under the predevelopment condition and under two development scenarios: the existing design and an alternative one that seeks to minimize its impact. We should acknowledge however that these calculations do not include the progressive nature of hydrologic and environmental unbalances. The partial deforestation of the site can have significant immediate consequences, but it can also have long term effects that are difficult to forecast.

Chapter 4. Site Design for Stormwater Management

A comprehensive design that seeks to limit or control the impact on the ecosystem should be carried out from the first stages of the development. Consideration should be given to appropriate land use, density and accessibility. The planning authorities' regulations usually set limits to land use and establish maximum densities and percentages of pervious land to be maintained. The land use plan in Santa Fe, Mexico City has some of the more stringent environmental requirements in the city, especially those that affect groundwater recharge. A percentage that ranges from 25 to 60% of the development's site has to be devoted to green areas. These regulations however, do not consider the qualitative characteristics of those areas nor do they consider their real infiltration capacity. The compliance with these regulations, designed at a regional scale, can have a dramatically different impact when considering the specific environmental dynamics of each site. It is therefore necessary to consider each and every development as a distinctive piece whose site is inherently ingrained in the larger ecosystem and to monitor and evaluate its performance. For this, it may be necessary to focus the regulatory agencies' attention on the potential performance of a given development rather than on its compliance with a set of generic limitations that may or may not have the desired outcome.

The case study selected for this work exemplifies the performance inconsistencies between two site designs with the same program. While preserving the program, net density and typologies, the alternative site design makes stormwater management the main objective of the plan. A coherent process for the integration of stormwater management practices into a design can be as follows:[1]

1. Survey of the site. An extensive site analysis that would include all the natural features of the site such as geology, hydrology, vegetation and climate. This first step is one frequently ignored by most developers and underestimated by designers. It is crucial though, to obtain current and reliable data that can inform the design process. Incorrect, obsolete or imprecise information may

[1] This methodology follows closely the one presented by Tourbier, 11.

lead to an unsuccessful design that can not only translate into a waste of resources, but also into a potential hazard. At this stage, it is also important to set the degree of impact on the environment which we consider permissible. This is, how much can we impact the ecosystem before actually impairing its chances of survival or regeneration

2. Determination of feasible land use. This part of the development process considers the maximum potential economic profit for the developer. The programming and intensity of land use should be determined as much by the objectives set on the previous stage as by the project's economic potential. A balance between the two is necessary if someone is to develop the site at all, if the objectives are too rigid, no developer would consider investing in the site or they would be encouraged to avoid implementing any stromwater management strategies. The role of the city government at this stage is crucial; the use of information and incentives can make the difference between a location being desirable or impossible to develop.
3. Conceptual site design incorporating **preventive measures**. At this stage a design that incorporates preventive measures such as avoiding erodible or flood prone areas is evaluated.
4. Integration of **corrective strategies** and evaluation. Corrective measures are incorporated into the design in order to achieve a specific desire outcome where preventive measures were not enough.
5. Preliminary site design for stormwater management. At this stage the design's performance is evaluated and its costs estimated. If the economic costs are too great or the performance too poor, alternative configurations should be sought until the desired outcome is produced.
6. Final Design. The final proposal should include the selected design as well as a detailed account of the appropriate maintenance and construction techniques required.

For the case study at hand we have already provided the information required in steps 1 and 2. We do not consider however, that the site analysis is as detailed and documented as it should be nor that the program designed by the developer is necessarily the most adequate for the site. Surely, a site analysis with soil studies over different areas of the site, a correct determination of the exact depth of the water table, a plant and animal species survey and other site characteristics should be carried out before the design process just as the developer's program should be able to adapt to better fit into the site. The site analysis of the previous chapter and the program defined by the developer will have to serve, for the time being, as a framework for the redistribution of the program within the site.

4.1 Conceptual design incorporating preventive measures.

Main Concerns

1. Avoid construction on steep topography and forested areas.
2. Maintain river buffer and increase its width.
3. Maintain as much of the natural drainage as possible
4. Minimize impervious surfaces.

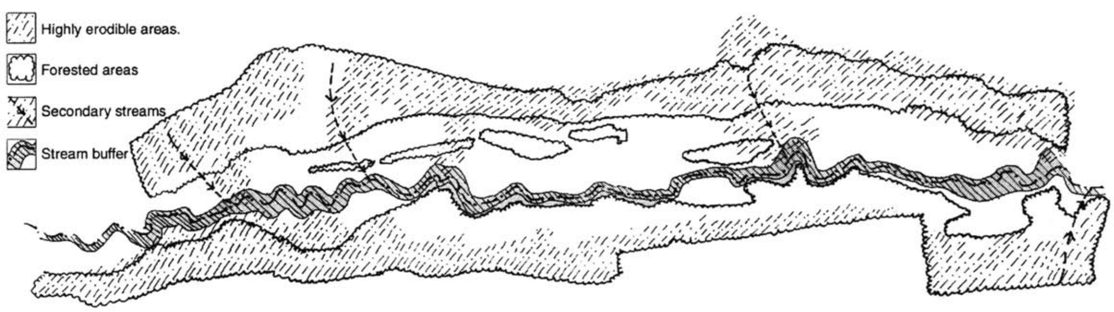


Figure 4.1. Plan of the site with areas where construction should be avoided or limited in order to minimize the environmental impact of the development.
Source: Author

Development requirements.

1. Maintain number of units (net overall density) and typologies (e.g. number of high-rise, mid-rise, low-rise and single family residences). (See table 3.1).
2. Maintain golf course as a central feature and maximize residential frontage towards green areas.
3. Maximize real estate values.
4. Minimize capital investment.
5.

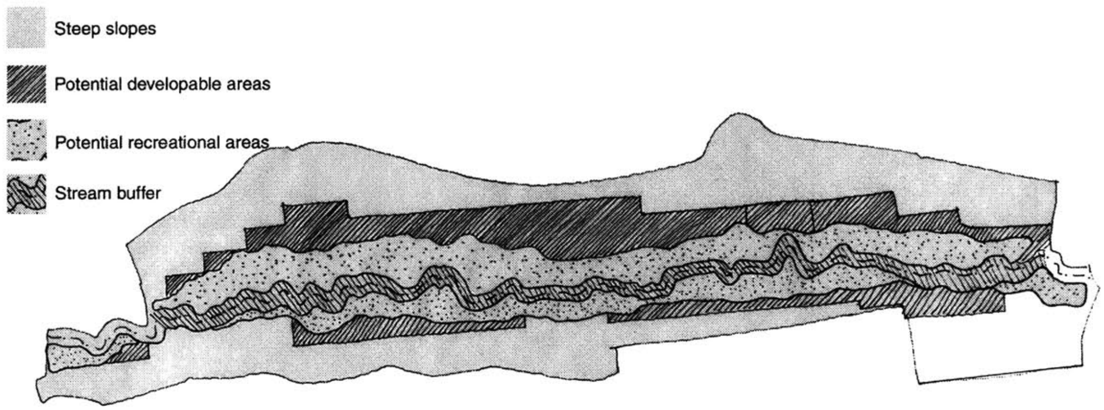


Figure 4.2. Plan of the site with the potential location of developable and recreational areas.
Source: Author.

Preventive Measures.

1. Cluster development: smaller lots that occupy less space, but are still able to accommodate the desired typologies.
2. Concentrate green areas that were otherwise spread over private residential gardens and maximize their potential stormwater management efficiencies.
3. Maximize road efficiency by double loading.
4. Restrict location of the houses within their lots to maximize pervious areas.
5. Identify appropriate areas for each different use within the site in order to maximize the potential benefits of the extensive open areas.

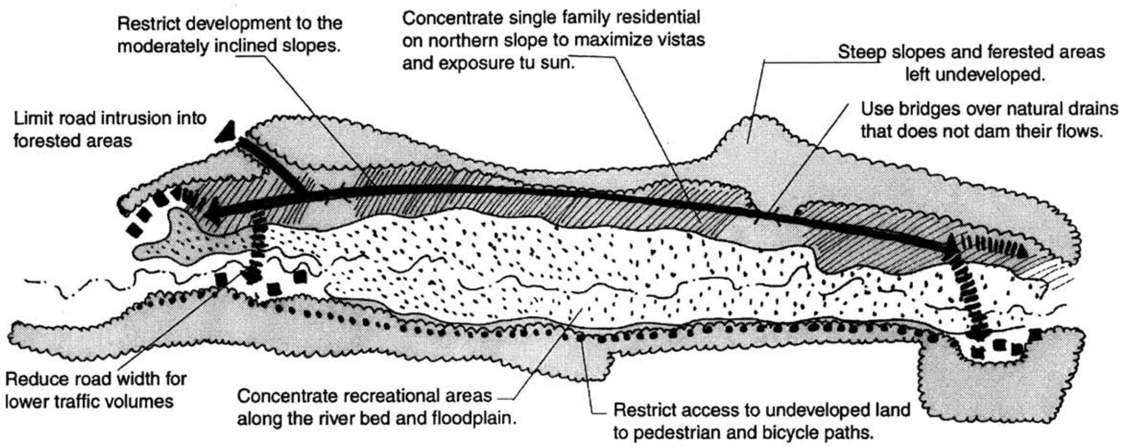


Figure 4.3. Conceptual plan of preventive measures and development configuration.
Source: Author.

A more detailed site analysis that includes soil and hydraulic conditions within different areas of the site as well as a detailed survey of the river would be essential to guarantee the performance of the project. The following site plan, Figure 4.4, reconfigures the existing project into a design that incorporates the preventive measures mentioned above. As I mentioned before it is not a design intended to substitute the previous one, but an exploration of the applicability of these strategies on a traditional development in this particular area of the city.

As shown in table 4.1, the overall density of the site has been maintained at 3.04 units/acre, but here we reduce the area of single family lots from 12,000 sq.f. to 6,000 sq.f allowing for a more compact development that limits the intrusion into steep and forested areas. At the same time it allows every house to face either a forested area or the golf course itself and severely shortens the acreage devoted to roads and streetscape, which can translate into important financial benefits for the developer. Lots of 6,000 sq.f. are common in high-income developments and have been used previously by the same developer; the perceived higher density of this subdivision can be reversed by the adjacency of extensive green areas.

Mid-rise and high-rise buildings are also compacted into smaller lots, but are given direct access to forest and golf course areas, thus maintaining the sense of amplitude of the previous plan. It would be important to incorporate structured parking in order to limit impervious areas. Furthermore, surface parking is highly unfeasible both because of the steep topography of the site, which would require extensive excavations and because of the market requirements of this kind of real estate product.

Green areas in this lay-out are clearly defined as those left in their natural state and those artificially landscaped. The natural forests at the top of the ravines are safe from erosion and inflow of sediments from the adjoining construction site because there are uphill. The golf course and other green areas located at the center of the site can safely incur in some sediment deposition during the construction phase if later landscape construction redevelops and restores the entire area. The most important characteristic of the central green zone would be its ability to serve a multiplicity of functions at the same time. Parts of the golf course could in fact store water during storm events to prevent floods downstream. Ponds and swales could be incorporated into the landscape design to improve water quality as much as for aesthetic reasons. A comprehensive landscape design that takes advantage of the hydraulics of the site can contribute significantly to reduce the extensive water requirements of the golf course and limit maintenance and irrigation expenses.

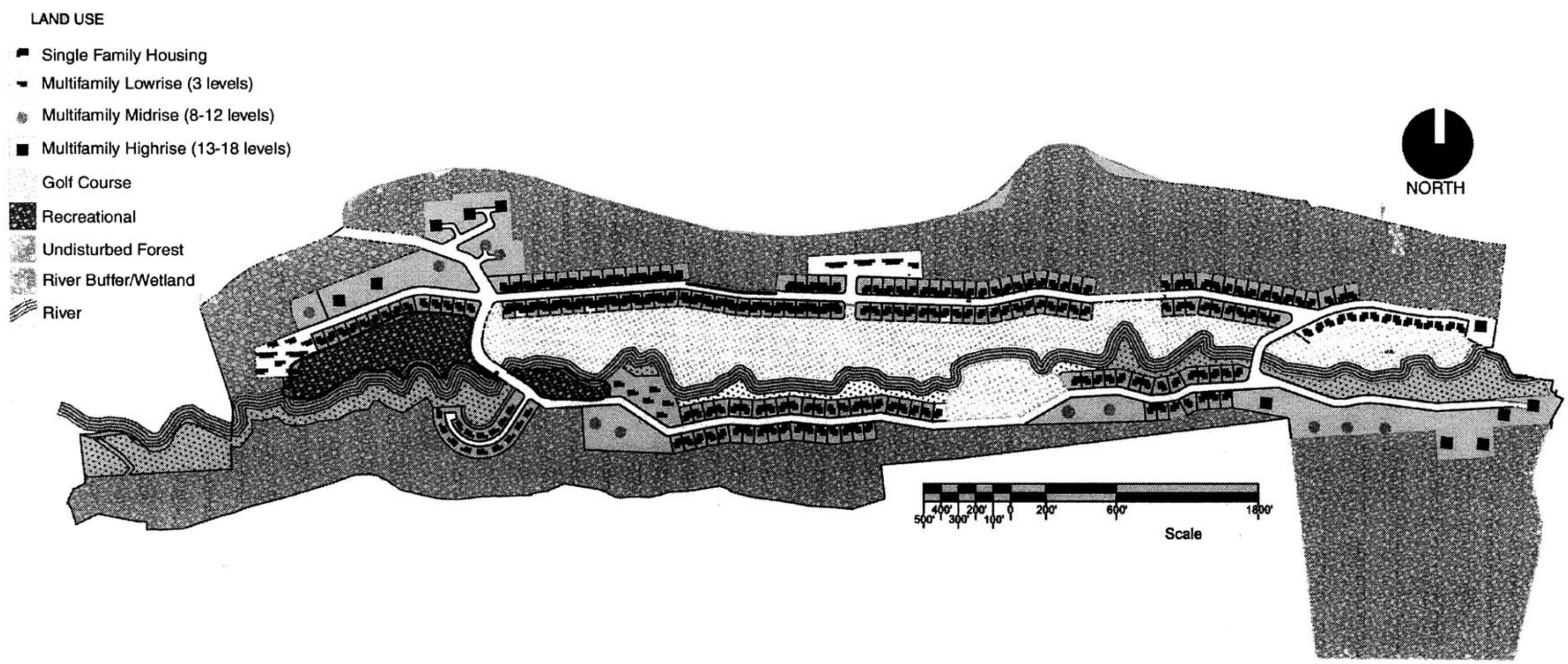


Figure 4.4. Integration of preventive measures into the development.
Source: Author

Table 4.1 Area and density analysis of the proposed development plan

Type	units	Land Area (sqf)	Area (ac)	ND U/ac	Lot/unit	Impervious %	Total impervious
Single fam (2-3)	205	1,231,677.72	28.28	7.25	6,008.18	0.65	800,590.52
Multifam-low (2-3)	40	302,691.94	6.95	5.76	7,567.30	0.6	181,615.17
Multifam-med (7-13)	182	385,819.91	8.86	20.55	2,119.89	0.45	173,618.96
Multifam-high (18)	294	355,260.66	8.16	36.05	1,208.37	0.45	159,867.30
Services		470,445.50	10.80			0.7	329,311.85
Street		255,952.61	5.88			0.9	230,357.35
TOTAL BUILT	**721**	**3,001,848**	**68.91**				**1,875,361**
Ponds/Wetlands		595,640.00	13.67			0.25	148,910.00
Streetscape		389,347.00	8.94			0.25	97,336.75
Green Area Sport		1,468,589.00	33.71			0.25	367,147.25
Undeveloped		4,861,551.97	111.61			0	
TOTAL OPEN		**7,315,127.97**	**167.93**		**TOTAL IMPERVIOUS**		**2,488,755**
							24.12%
TOTAL	**721**	**10,316,976**	**236.85**	**3.04**			
Federal Area River		470,445	10.80				
TOTAL SITE	721	11,047,223	253.61	2.84			

The results, I believe, are quite compelling. By increasing the densities in the developed areas, almost doubling it in single family lots, we can increase the area devoted for forest preservation from 29.82 acres (see Figure 3.1) to 111.61 acres. In this configuration, the area not longer consumed by the development is maintained as undeveloped forest. Using the same coefficients as those used in table 3.1, the impermeable surfaces of the new configuration is reduced to only 24.12%, almost half of that in the previous one.

Figure 4.5 illustrates a section of a residential street in an area with slopes of over 30%. Instead of being forced by the topography into providing single loaded streets, short segments of the road can be terraced, adjusting better to the topography without increasing its width substantially.

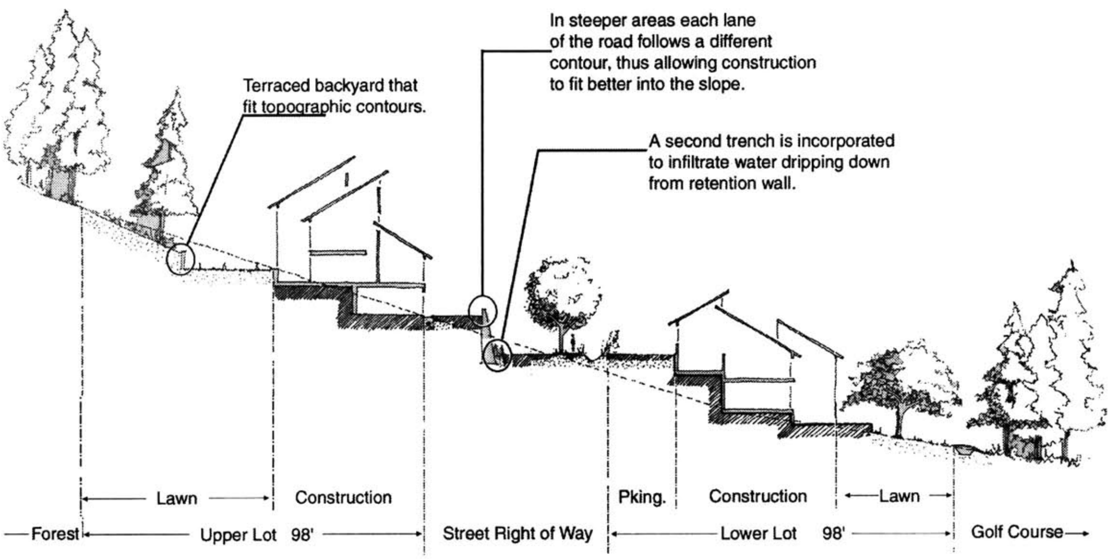


Figure 4.5. Street section in 30% slopes.
Source: Author.

Evaluation of Performance of Proposed Development.

Given the stormwater management focus of this work, we will limit this evaluation to the measurement of runoff and groundwater infiltration under predevelopment conditions and under the existing and proposed design. For this analysis, we have used the hydrologic soil groups of the SCS (U.S. Soil Conservation Service) in Ferguson[2] for soil group B (soils with moderate infiltration rates when thoroughly wetted with well to well-drained soils that may have experienced urbanization, but have not been significantly compacted) and surface covers similar to those of the development: woods; bushes and grasses; lawns; streetscapes and pavements; and roofs. This selection was done after considering the soil type of the area in question and matching it to those of the SCS. Although they may not precisely reflect the actual condition of the site, I believe that they do offer a reliable approximation that, if any, tends to be conservative.

[2] Introduction to Stormwater, 66

The precipitation used corresponds to the storm of July 28, 1998 that caused severe damage to the town of San Mateo Tlaltenango, adjoining the site to the west. July is in fact the month with the highest precipitation rate, thus the following calculations would be appropriate only for the rainy season. During drier months, the differential impact would be much smaller and would be altogether void in the absence of rain.

Runoff

Table 4.2 Comparative analysis of runoff performance of site designs.

Predevelopment Condition	**Area**	**Coefficient**	**Runoff-area**	**Precipitation July in inches**	**Runoff**	
Woods	170.53	0.45	76.74			
Bush/Grass	18.948	0.48	9.10			
Lawn	47.37	0.61	28.90			
Total	**236.85**		**114.73**	**8.64**	**991.27**	
						No Impact

Existing Design	**Area**	**Coefficient**	**Runoff-area**	**Precipitation July in inches**	**Runoff in inches-acre**	**Increase in %**
Woods	29.82	0.45	13.42			
Bush/Grass	45.41	0.48	21.80			
Lawn	59.65	0.61	36.38			
Streetscape	23.91	0.89	21.28			
Roads/Rooftops	78.07	0.98	76.51			
Total	**236.85**		**169.38**	**8.64**	**1463.48**	
				Impact	**472.21**	**47.64%**

Stormwater Management Design	**Area**	**Coefficient**	**Runoffarea**	**Precipitation July in inches**	**Runoff**	
Woods	111.61	0.45	50.22			
Bush/Grass	33.71	0.48	16.18			
Lawn	25.87	0.61	15.78			
Streetscape	8.94	0.89	7.95			
Roads/Rooftops	43.05	0.98	42.19			
Wetlands/Ponds	13.67	0.61	8.34			
Total	**236.85**		**140.67**	**8.64**	**1,215.39**	
				Impact	**224.12**	**22.61%**

Infiltration

The calculation of groundwater infiltration can be a complicated process. We cannot simply equate infiltration loss to increase runoff because some of the runoff produced by either of the alternatives will be subjected to evaporation and evotranspiration as well. All these variables affecting water infiltration into the ground can significantly alter absorption rates within a given area. Because we have no specific data on the infiltration capacity of this site, we have taken values that are generic to the basin of Mexico. We know that the geology of this area is particularly suitable for infiltration, therefore we can suppose that the infiltration percentage is, if anything, conservative. According to the DGCOH report, the water cycle in the basin of Mexico breaks up in the following way:

Evapotranspiration	57.40%
Evaporation	1.30%
Infiltration	19.85%
Runoff	21.50%
Total	**100%**

Knowing the value for runoff, we can now isolate the other three variables and calculate their respective percentages. In this way we can assume that evaporation constitutes 73.07% of the total precipitation minus runoff, evaporation 1.30% and infiltration 25.27%.

Evapotranspiration	57.40%	73.07	
Evaporation	1.30%	1.65	
Infiltration	19.85%	25.27	78.50%
Runoff	21.50%		
Total	100%	**8.64**	

Transferring to cubic meters:

	Runoff in m^3	Differential	25.27 % prevented infiltration in m^3	Net differential During July in m^3	Per unit in development
Existing Design	150,509.24				
		48,563.68	12,140.92		
Predev. Condition	101,945.56			**6,378.61**	**8.85**
		23,049.25	5,762.31		
Stormwater M. Design	124,994.82				

A net differential during the month of July of 6,378 cubic meters can translate into 16.8%[3] of the total residential water demand of the whole development for a month. This figure may be too conservative if we take into account that the DGCOH break up of the hydraulic cycle was calculated on urban areas where infiltration is considerably reduced and runoff enhanced. A much greater figure could in fact be obtained had the data considered the favorable infiltration conditions of this area.

4.2 Integration of Corrective Strategies

Once an overall plan is determined, we can start to incorporate strategies that will bridge the gap between a project's environmental objectives and the actual performance of the preliminary design. One could include as many devices as it is financially feasible. In this case, we have chosen to demonstrate a few strategies within the most impacted area of the site, that is, the streets and the residential lots. Figure 5.5 and 5.6 show a transversal section and plan of the housing units and the street on an area with a 15% slope.

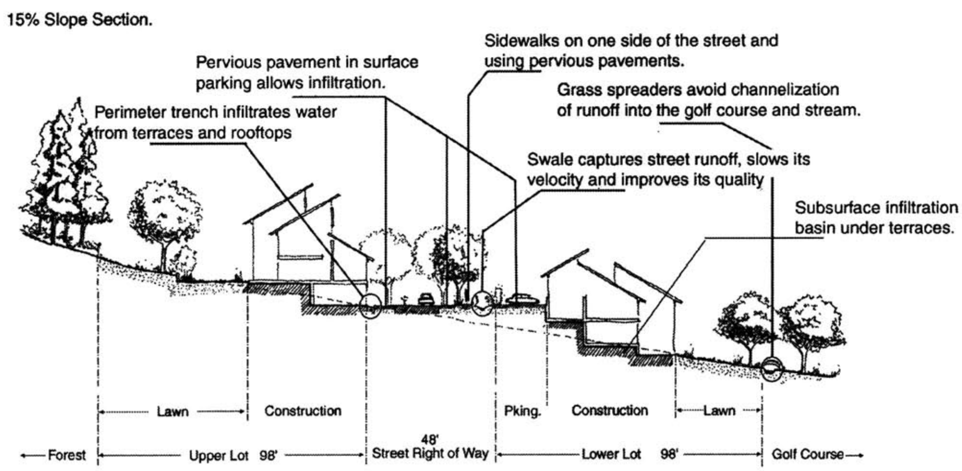


Figure 4.6. Street section at a slope of 15% shows the different corrective strategies applicable.
Source: Author

[3] This figure assumes 5 persons per unit. A total of 3605 inhabitants whose demand of 350 liters a day accounts for 37,852 cubic meters a month.

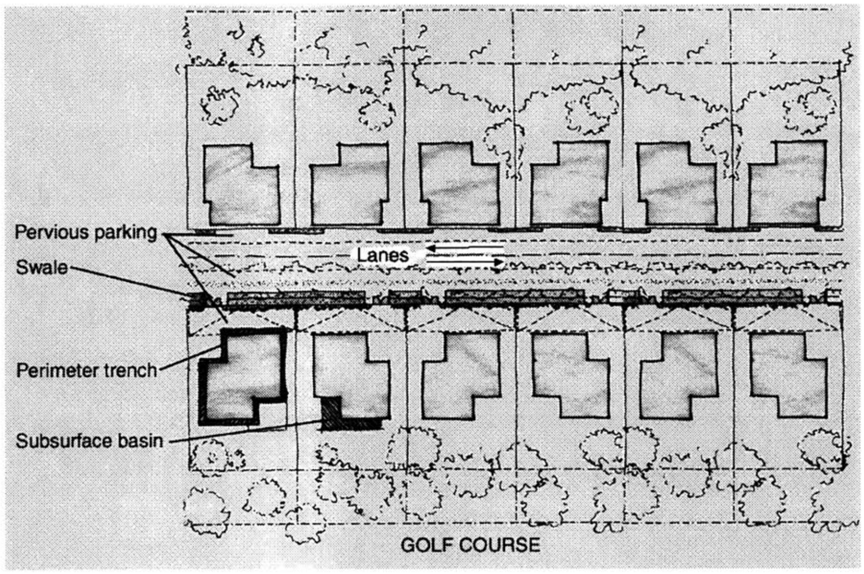


Figure 4.7. Street Plan showing corrective strategies.
Source: Author

In this example, a variety of bioengineering strategies are integrated into the design. The use of swales, trenches, spreaders, pervious pavements and subsurface infiltration basins are all designed to achieve our environmental and hydraulic objectives. We will not attempt to design all of these devices, but rather provide a brief example of its application within the site. The following devices have been designed to "correct" the impact of a given area within the overall site, thus "subtracting" the negative impact of those areas. Our conceptual objective would be to reach zero impact (pre-development condition) or better still, enhance the infiltration capacity and runoff storage of the site. The strategies have been organized in groups that seek to correct a given area.

Street Right of Way and Parking / Swale

In this case a 7 f wide swale was designed to carry the runoff from the entire section of the street and from the parking area of the lower house into a collector that would direct the flow towards the river. The swale's linearity adapts well to that of a street and its capacity to remove suspended solids warrants a clean flow to the river. Two main factor should be included in the calculation of a swale's section: the expected inflow determined by a given storm event and the swale's hydraulic capacity.

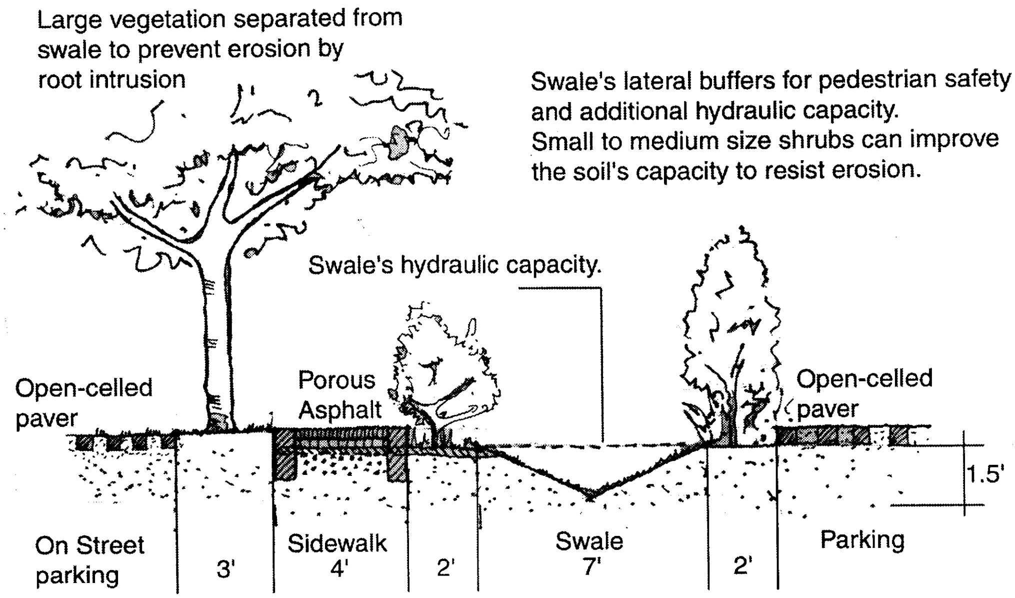


Figure 4.8. Section of swale.
Source: Author

Factors determining

Area: the area of the watershed draining into the swale. In this case a 68 feet wide (48 f of the right of way + 20 f of the lower house's parking area) and 1,000 feet long (this number allows for a collector every 2000 f or 30 house fronts) watershed gives us an area of 68,000 sq.f.

Runoff: a "runoff factor" should be incorporated to each different part of the watershed according to its capacity to generate runoff itself determined by the soil's infiltration capacity, the amount and type of vegetation cover and other factors such as temperature. In this case we have used the U.S. Soil Conservation Service's table in Ferguson for Urban Areas with soils with moderately low runoff potential for three different kinds of cover: impervious pavement, pervious pavements such as open-celled pavers and vegetation.

Inflow: the calculated storm event. In this case a 25-year storm event of 85.6 mm/hr or 23.71 i/hr

Weighted Average Runoff factor (WARF):

Total width of watershed	68 f	% of area	Runoff Factor	WARF
Street (impervious pavement)	16 f	23.53	0.98	0.2306
Parking (pervious pavement)	36 f	52.94	0.49	0.2540
Vegetation cover	16 f	23.53	0.39	0.0918
				0.5764

Area = 68 f X 1000 f = 68,000 sf = **1.56 acres**

Applying the Rational Formula **Q=CiA**, where Q = expected flow in cfs, C=WARF, i = inflow in i/hr and A = area in sq.f.

Q = 0.5764 X 23.71 X 1.56 = **21.32 cfs**

Factors determining hydraulic capacity.

Area of the swale A = (7 f X 1.5 f) /2 =	**5.25 sq. f**
Wetted perimeter Wp (for friction). =	**7.61 sq. f.**
Slope along swale S	**4%**
Roughness coefficient[4] **n**	**0.04**
Hydraulic radius R (R=A/Wp)	**0.6898**

Applying Mannings Equation $Q = 1.49/n \; R^{2/3} \; S^{1/2} \; A$ we calculate capacity and verify that velocity is under 5 fps for grassed swales.

$$Q = (0.6898^{2/3})(0.04^{1/2})(5.25) = 30.23 \text{ cfs}$$
$$\text{Velocity} = Q/A = 30.23 / 5.25 = 4.06 \text{ fps}$$

Result: the swale's hydraulic capacity of 30.23 cfs exceeds the expected flow of 21.32 and the flow's expected velocity of 4.06 fps is lower than the maximum of 5 fps for this kind of soil and vegetation.

In this case and for this specific climate, soil and topography, a 7 feet swale could carry the runoff from the adjoining right of way as well as that from private parking areas, which add up to 68 feet. Only 10.25% of the watershed is therefore occupied by the swale (7 out of 68 feet) or 14.5% of the right of way. Given the two functions of the swale, runoff conveyance and landscape feature, the percentage of area required for it is not significant. A committed maintenance, though, is required to avoid accumulation of debris and litter that can lessen the swale's performance.

Parking Areas / Pervious Pavements

One of the most common and least expensive stormwater management devices is the use of pervious pavements. These are especially effective in low traffic areas where the pavement need not support excessive weight and friction such as parking areas both inside the properties and along the right of way. Although runoff does generate from this surface, especially under severe short storm where the flow is too large and sudden to percolate the ground, the use of pervious pavements can result in percolation rates almost as high as those of residential lawns.

[4] Roughness Coefficient taken from Tourvier p. 31A. It applies to swales vegetated with grass.

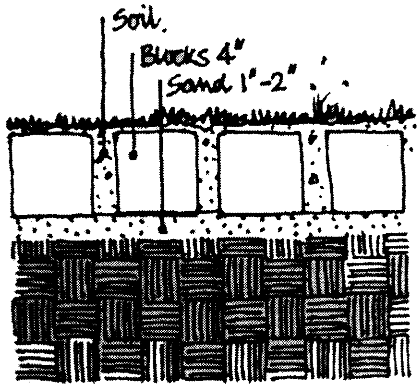


Figure 4.9. Pervious Pavement.
Source Tourbier, 1.5.

In Mexico they are most commonly found as concrete lattices that are set over a layer of sand, the orifices are then filled with soil and grass. It is important that, during the construction process, care is taken to avoid compacting the soil over which the lattice will be placed. Failure to do so can result in almost null percolation rates.

Roof Runoff /Trench and Infiltration Basin

Having reduced the impact of the road and the parking areas with the swale and with the use of pervious pavements, we now can try to do the same with the constructions themselves. For this a peripheral trench that captures roof runoff is proposed around each house. The trench would concentrate runoff, and slowly convey it to a subsurface infiltration basin located under a terrace. Excess water could then be directed through a spill up drain to other storage devices such as ponds or wetlands located throughout the golf course.

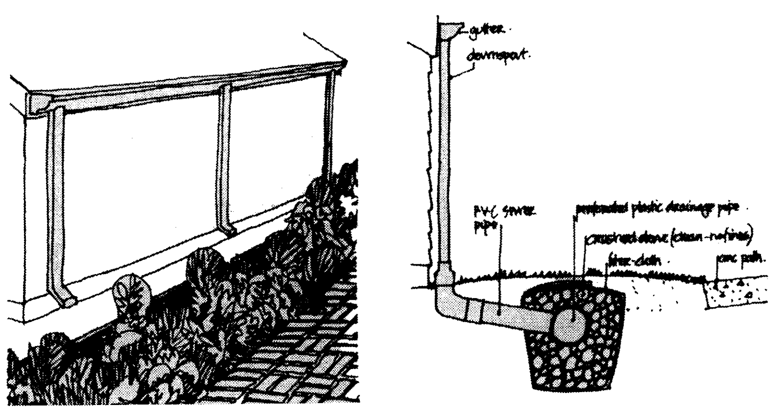


Figure 4.10. Infiltration trench located at the perimeter of each house.
Source: Tourbier 1.2

The location of the subsurface basin under a terrace facing the golf course takes advantage of the need to adapt the construction to the slope of the terrain. Aggregate material inside could consist of waste construction material common in Mexico such as broken brick, tezontle (a very light volcanic gravel) or cleaned gravel, thus reducing its construction costs.

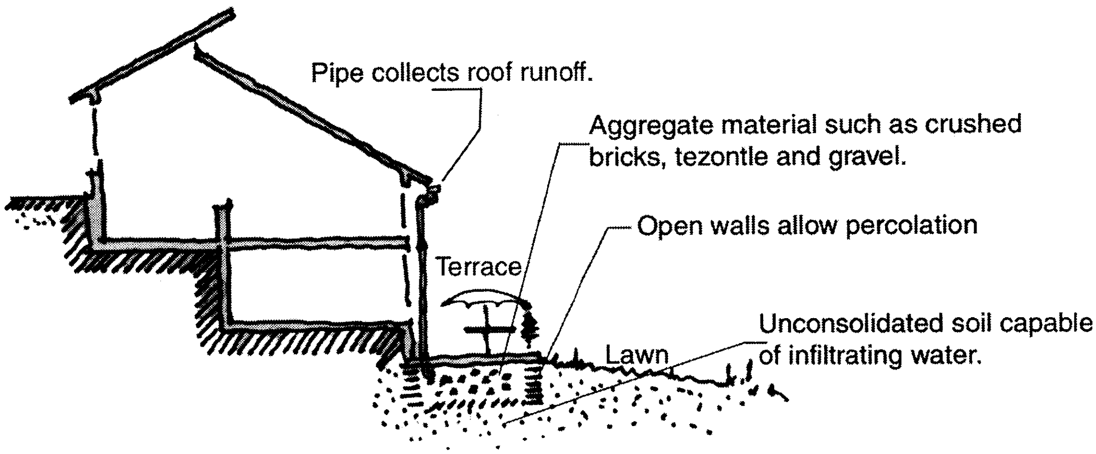


Figure 4.11. Subsurface infiltration basin.
Source: Author

The size and capacity of both the trench and the subsurface basin can be varied according to the hydraulic objectives set by the developer or the city's authorities. The advantage of a development such as this, where many residents share a large common area such as the golf course is that they can also share the cost of implementing common storage ponds. Indeed, the golf course can be designed in such a way that it encourages water treatment and infiltration as well as recycling and utilizing runoff from the whole development. Furthermore, as we have mentioned before, this site may be the last stage before the river enters the dense urban area where garbage disposal practices and illegal raw sewage drains pollute its water increasing the costs and difficulties for utilizing it. Such devices as constructed wetlands, ponds and swales can consume some of the area devoted to the golf course, but it can also add to its value and beauty. Figure 4.12 is an attempt to illustrate how the use of green areas along the golf course can gradually improve the river's water quality, encourage groundwater infiltration and storage water for irrigation.

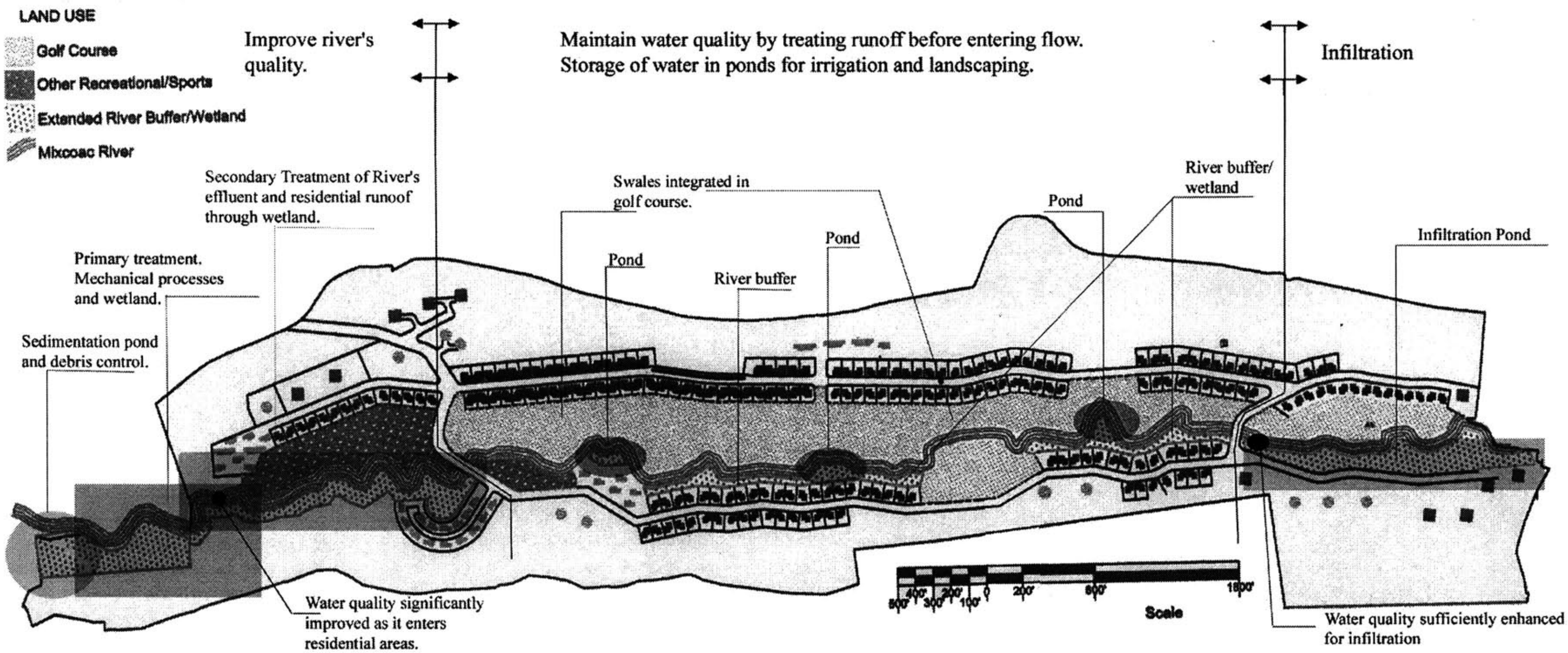


Figure 4.12. Stormwater management and infiltration devices along golf course.
Source: Author

Golf Course as the River's Kidney.

The opportunity to integrate stormwater management and infiltration strategies within the golf course should not be missed. An overall strategy could follow the following pattern:

1. Improvement of river's quality. At the upstream limit of the site, a primary treatment plant such as the one already planned by the developer, will screen off some of the roughest water pollutants coming from San Mateo Tlaltenango and other settlements upstream. The costs of primary treatment plants represents only 10 to 15% of the total costs of water treatment up to tertiary quality. Because this part of the site is partially isolated from the developed areas, artificially created wetlands could be used to further the process of purification without endangering its residents. According to water pollutant standards, a 2000 feet wetland could remove, depending on its design and maintenance, as much as 80% of pollutants such as suspended solids, nitrogen and phosphorous.

2. Maintain water quality and store water for irrigation. After the previous phase, once the water quality is satisfactory for landscaping and irrigation purposes it could be stored in ponds that would not only fulfill this functional application, but that would also contribute to the beautification of the golf course's landscape. The storage of water in ponds might require an impermeable liner to avoid loosing water through infiltration. The golf course propensity to discharge nutrients and pesticides into the stream could be reduced by incorporating swales along the golf course, between holes which would convey runoff and remove part of these nutrients.

3. Maximize infiltration. At the downstream edge of the pond, before the water leaves the site, an area can be devoted to create a seasonal infiltration basin that would fill during the rainy season in summer, but that would be available for recreational purposes throughout the other seasons of the year. We can assume that, if proper consideration is given to the water treatment function of all these features, water quality would be suitable for infiltration.

Although there are many variables that affect the performance of these strategies such as size, proportion, vegetation types, climate and many others, there are performance standards based on empirical data that suggests pollution removal rates as high as 98% for fecal coliforms, 78% for total suspended solids, 75% for nitrogen and 50 for phosphorous.[5] However, strict maintenance guidelines and construction processes would have to be observed to obtain systems with high performance levels.

The degree to which these strategies can treat and directly infiltrate water is somewhat dubious. Most sources provide an ample range of performance rates based on empirical data gathered mostly in the United States. Mexico has yet to compile this information and make it available to all parties involved in the urban development process in order to facilitate their implementation.

[5] Figures taken from U.S. EPA, Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment, U.S. EPA, CERI, Cincinnati, OH.

Conclusions

The water management problem in Mexico City can certainly not be solved only through site planning. The infrastructure that the concentration of almost twenty million people requires goes well beyond what natural ecosystem can provide. Engineering has helped us bridge the gap between what nature can provide and what our urban patterns actually require. We are no longer however exclusively concerned with the quantitative solution of our problems, but have to consider how those solutions will perform over time and what their consequences, both in social, and environmental terms, will be. Mexico City must start to search for ways to ameliorate, if not solve, the dilemmas of water management in a comprehensive way that incorporates not only the Distrito Federal or the Metropolitan area, but also the bordering states that form part of the hydraulic system of the city. This is an effort that escapes any one discipline.

The use of the stormwater management techniques would have a positive effect on the city's groundwater recharge, as is shown by the case explored in these pages. The residential development's drinking water requirements (including irrigation of private lawns, but not that of the golf course and public green areas) amounts to 1,261 m^3 /day. The existing project prevents the infiltration of 404.69 m^3 /day, which represents 32.09% of the development's daily water needs. The implementation of preventive measures exclusively –configuration of built and green areas, without considering the impact of corrective measures—would reduce the loss of infiltration by more than half, to 192 m^3 /day, or 15.22% of its water needs. The implementation of corrective measures could further reduce the gap between this figure and pre-development infiltration rates, or even improve these with the use of induced infiltration strategies.

Despite their efficiency and relative low-cost, these strategies are hardly ever implemented in Mexico City. Although market studies have established that "green" developments can generate higher revenues, projects such as the one studied here already offer extensive green areas. Their hydraulic efficiency though, may not increase the marketability of the development. In a broader context, the extremely low cost of water in the city makes attempts to implement these techniques and reduce water use economically unappealing. Thus direct economic incentives for developers are lacking. The challenge of creating an environment that encourages stormwater management practices and that shares its costs more evenly, must then be taken up by the city and its government. As a major reversal in regulatory practices for Mexico City, a comprehensive regulatory body needs to focus not only on quantitative standards such as the size of green areas or the number of trees, but on qualitative performance. As Ian McHarg has said, "in general, any benefits that do occur –usually economic—tend to accrue to the private sector, while remedies and long range costs are usually the responsibility of the public domain"[1]. The financial gains accrued by the developers of these areas must be offset against the environmental losses to the common realm, and it is the public authorities' duty to strike a balance between the two.

This thesis has focused on the favorable effects that stormwater management can have on infiltration, using one of the new developments in the Santa Fe area as a case study. Nevertheless, when these effects are taken to the broader scale of the city, the picture is less rosy. The city's daily water supply amounts to 65 m^3 /second, or 5,616,000 m^3 /day, so the 6,378.61 m^3 of supplemental infiltration that the second development option would allow during the rainy month of July is equivalent to only 0.0224% of the city's daily water expenditure. Building the stormwater management option would allow the aquifer to recharge only a tiny percentage of the city's total needs. Thus, the use of stormwater management practices in urbanizing areas would prevent the further degeneration of the aquifer's recharge capacity, but they should not be understood as the solution to a water supply problem of colossal proportions.

The solution explored here cannot, then, be but partial. The city's main problem is not the regulation of high-end residential development, but creating sustainable urban development for a population whose poverty makes environmental concerns secondary. So far, attempts to ensure the ecological soundness of new settlements –most of the irregular and unregulated—have met with failure. There is an urgent need to enhance the attractiveness of open, green, hydraulically efficient areas for the poorer communities themselves. The city has so far relied on restrictive regulations in order to "protect" nature: fencing in dams, rivers and ravines –as is recommended in the 1998 DGCOH

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[1] Ian McHarg, Design with Nature, Philadelphia: The Falcon Press, 1969, 65.

report on the protection of the Mixcoac river[2]. Green areas are thus seen not only as alien to the communities, but as obstacles to their greater welfare. Especially telling is the case of San Mateo Tlaltenango, bordering the site of this study, where the designated land use is "semi-rural", in order to limit the growth of the urban mass. Although this measure has limited the marketability of this area, it has not prevented its irregular densification. The unrealistic expectations of the city's land use plan prevents the residents of San Mateo from profiting from their location, and does not allow for a better, more rational design for the inevitable densification of this area.

Recent trends in water management[3] points toward decentralization, based on the idea of capturing, treating and reusing water as close to the source as possible, and for the benefit of the local population. This, perhaps, is one of the solutions to the problems sketched above, where a community such as that of San Mateo could use, administer and benefit from the green areas along the Mixcoac River, where urban growth would mean greater economic opportunity within a more rational, environmentally sounder plan, and where the community is encouraged to police and monitor the correct implementation of environmental guidelines. One thing is certain: Mexico City needs to broaden its vision and explore more diverse and more flexible avenues in order to better manage its hydraulic resources.

[2] DGCOH, Report on the state of the banks of the Mixcoac River after the storm of July 25, 1998.
[3] For a more detailed description of these, see Janus Niemczynowicz, Integrated Water Management Background to Modern Approach with Two Case Examples in Field Richard et al Integrated Stormwater Management, 1993.

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