

**SENTHIL SELIYAN ELANGO**  
**ID: UB3016SC17508**

**URBAN WATER MANAGEMENT**

**A Final Thesis Presented to  
The Academic Department  
Of the School of Engineering  
In Partial Fulfillment of the Requirements  
For the Degree of Bachelor Science in Civil Engineering**

**ATLANTIC INTERNATIONAL UNIVERSITY  
HONOLULU, HAWAII**

## **Table of Contents**

### **Chapter 1: Introduction**

- 1. A.Introduction

### **Chapter 2: Description**

- 2. A. Main Components of an urban water system
- 2. B.Challenges in urban water management
- 2. C.Past and current approaches to urban water management
- 2. D.Innovative approaches in urban water management

### **Chapter 3: General Analysis**

- 3. A. Waste water
  - 3. A.B.Disposal
  - 3. A.C.Incineration
  - 3. A.D.Waste management concepts
- 3. B. Waste water management
  - 3. B.A.Urban waste water disposal system management
  - 3. B.B. Waste water treatment
  - 3. B.C.Modern waste water treatment
  - 3. B.D.Urban Wastewater Management: The Outlook for the Future
- 3. C.Urban storm water management
  - 3. C.A.Advantage of Rain water harvesting system
  - 3. C.C.Types of Rain water harvesting system
  - 3. C.D.Catchment areas
  - 3. C.E.Collection system
  - 3. C.F.Conveyance System

### **Chapter 4: General Recommendation**

- 4. A.Innovation trends in urban water supply and sanitation
- 4. B.Urban Water system modeling
  - 4. B.A.Model selection
- 4. C.Optimaization

### **Chapter 5: Actualization**

- 5. A.Case Study 1: Storm Water management
- 5. B.Case study 2: Urban water supply system

### **Chapter 6: Conclusion**

### **Reference:**

## **Acknowledgements**

I would like to thank AIU academic staff for invaluable support and advice, offered throughout this study. Special thanks also go to Mr. Gilroy Newball for his interest in and review of my assignments.

Mr. Kimberly Roff is thanked for her determination in reviewing each of my program evaluations, and for offering helpful commentary along the way.

I use this opportunity to thank the members of staff of The Atlantic International University for the opportunity to design and implement an educational path for myself that suits my intellectual and professional goals and is mutually exclusive to the pursuits of others.

I want to express a special thanks to Dr. Franklin Valcin for his professional guidance through the phases of this process and to acknowledge him has one of the true pioneers of Distance Learning globally.

I am indeed grateful to the other administrative staffs of the Atlantic International University who have facilitated me with financing my education.

Special thanks also go to my family and friends for their unending support and good cheer.

## ABSTRACT

### Thesis Goals and Specific Objectives

The goal of urban water management thesis to investigate components of urban water system and careful, economic use handling of the water in urban. The first goal of this thesis is to evaluate the waste and storm water management in urban. The second goal of the thesis is to recommend storm water management strategies for urban residential areas.

The sub-objectives that lead to the achievement of these goals are:

- ✚ To explore various components of urban water supply system.
- ✚ To explore number of concepts about waste management which vary in their usage between countries or regions.
- ✚ To explore the need for storm water management and/or water conservation practices in urban residential areas.
- ✚ To explore how storm water initiatives in the urbans.
- ✚ To develop an evaluative framework based on the principles of summative/formative program evaluation, policy instrument evaluation, and community-based social marketing;
- ✚ To develop performance measures and interview questions based on the criteria identified in the evaluative framework;
- ✚ To obtain interview responses from homeowners/program participants regarding their experience with a storm water or water conservation program;

## INTRODUCTION

Urban water infrastructure typically includes water collection and storage facilities at source sites, water transport via aqueducts (canals, tunnels and/or pipelines) from source sites to water treatment facilities; water treatment, storage and distribution systems; wastewater collection (sewage) systems and treatment; and urban drainage works. This is illustrated as a simple schematic in Figure. Generic simulation models of components of urban water systems have been developed and are commonly applied to study specific component design and operation issues. Increasingly, optimization models are being used to estimate cost-effective designs and operating policies. Cost savings can be substantial, especially when applied to large complex urban systems (Dandy and Engelhardt, 2001; Savic and Walters, 1997).

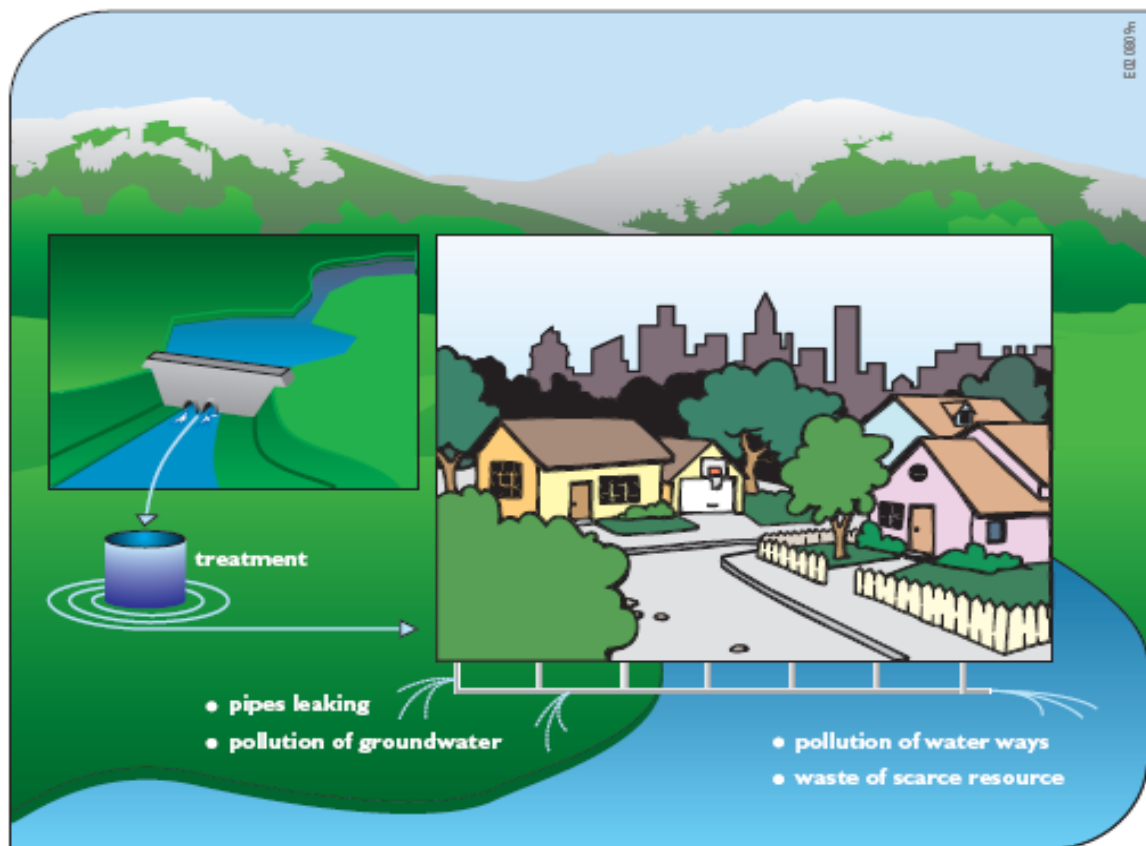


Figure. Schematic showing urban surface water source, water treatment prior to urban use, and some sources of nonpoint urban drainage and runoff and its impacts.

Most urban water users require high-quality water, and natural surface and/or groundwater supplies, called raw water, often cannot meet the quality requirements of domestic and industrial users. In such situations, water treatment is required prior to its use. Once it is treated, urban water can then be stored and distributed within the urban area, usually through a network of storage tanks and pipes.

Pipe flows in urban distribution systems should be under pressure to prevent contamination from groundwater's and to meet various user and fire protection requirements. After use, the 'wastewater' is collected in a network of sewers, or in some cases ditches, leading to a wastewater treatment plant or discharge site. In many urban areas the sewage system has a dual function. The sewers collect both wastewater from households and the runoff from streets and roofs during storm events. However, the transport capacity of the sewer network and the treatment facilities are limited. During intense rainfall, overflows from the sewage system discharge a mixture of surface runoff and wastewater to the surface waters. This has a negative impact on the water quality of urban surface waters.

Wastewater treatment plants remove some of the impurities in the wastewater before it is discharged into receiving water bodies or on land surfaces. Water bodies receiving effluents from point sources such as wastewater treatment plants may also receive runoff from the surrounding watershed area during storm events. The pollutants in both point and non-point discharges will affect the quality of the water in those receiving water bodies.

This thesis briefly describes these urban water system components and reviews some of the general assumptions incorporated into optimization and simulation models used to plan urban water systems. The focus of urban water systems modeling is mainly on the prediction and management of quantity and quality of flows and pressure heads in water distribution networks, wastewater flows in gravity sewer networks, and on the design efficiencies of water and wastewater treatment plants. Other models can be used for the real-time operation of various components of urban systems.

## **DESCRIPTION**

### **Main Components of an urban water system**

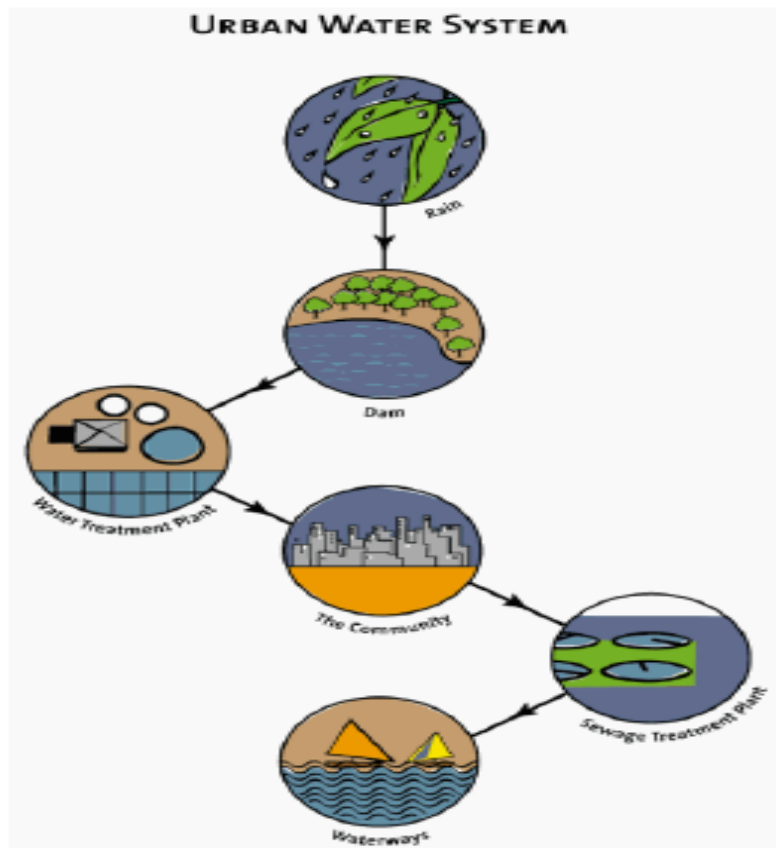
#### **Collecting water**

The entire area from which a stream or river receives its water is called a catchment. A catchment is a natural drainage area, bounded by sloping ground, hills or mountains, from which water flows to a low point.

Virtually everybody lives in a catchment, which may include hundreds of sub-catchments. What happens in each of the smaller catchments will affect the main catchment.

The water that comes out of a tap once flowed across a catchment – and that is why catchments are a crucial part of urban water systems.

The quality of the catchment determines the quality of the water harvested from it. Few communities have pristine water sources and the quality of water from most sources is at risk from activities occurring in the catchment.



### **Storing water**

In some urban water systems, the water supply is obtained directly from a river or another body of freshwater. In others, rivers are dammed and the water supply is distributed from artificial storages, such as reservoirs.

Dams are built across rivers and streams to create reservoirs to collect water from catchments to ensure sufficient supply will be available when needed. Dams also have been built for a range of purposes besides water supply, such as agriculture and hydro-electricity generation.

Water may also be released from a reservoir as an “environmental flow” to maintain the health of the ecosystem downstream of the reservoir. It is estimated that the significant reservoirs built around the world store five billion megalitres of water.

### **Transporting water**

Water is transported from catchments to communities by a variety of means including pipelines, aqueducts, and open channels or via natural waterways.

### **Treating water**

Before water is used for human consumption, its harmful impurities need to be removed. Communities that do not have adequate water treatment facilities, a common problem in developing regions, often have high incidences of disease and mortality due to drinking contaminated water. A range of syndromes, including acute dehydrating diarrhoea (cholera), prolonged febrile illness with abdominal symptoms (typhoid fever), acute bloody diarrhoea (dysentery) and chronic diarrhoea (Brainerd

diarrhoea). Numerous health organizations point to the fact that contaminated water leads to over 3 billion episodes of diarrhoea and an estimated 2 million deaths, mostly among children, each year.

Contaminants in natural water supplies can also include microorganisms such as *Cryptosporidium* and *Giardia lamblia* as well as inorganic and organic cancer-causing chemicals (such as compounds containing arsenic, chromium, copper, lead and mercury) and radioactive material (such as radium and uranium). Herbicides and pesticides reduce the suitability of river water as a source of drinking water. Recently, traces of hormonal substances and medicines detected in river water are generating more and more concern.

To remove impurities and pathogens, a typical municipal water purification system involves a sequence of processes, from physical removal of impurities to chemical treatment. Physical and chemical removal processes include initial and final filtering, coagulation, flocculation, sedimentation and disinfection, as illustrated in the schematic of Figure.

As shown in Figure, one of the first steps in most water treatment plants involves passing raw water through coarse filters to remove sticks, leaves and other large solid objects.

Sand and grit settle out of the water during this stage. Next a chemical such as alum is added to the raw water to facilitate coagulation. As the water is stirred, the alum causes the formation of sticky globs of small particles made up of bacteria, silt and other impurities. Once these globs of matter are formed, the water is routed to a series of settling tanks where the globs, or floc, sink to the bottom. This settling process is called flocculation.

After flocculation, the water is pumped slowly across another large settling basin. In this sedimentation or clarification process, much of the remaining floc and solid material accumulates at the bottom of the basin. The clarified water is then passed through layers of sand, coal and other granular material to remove microorganisms – including viruses, bacteria and protozoa such as *Cryptosporidium* – and any remaining floc and silt. This stage of purification mimics the natural filtration of water as it moves through the ground.

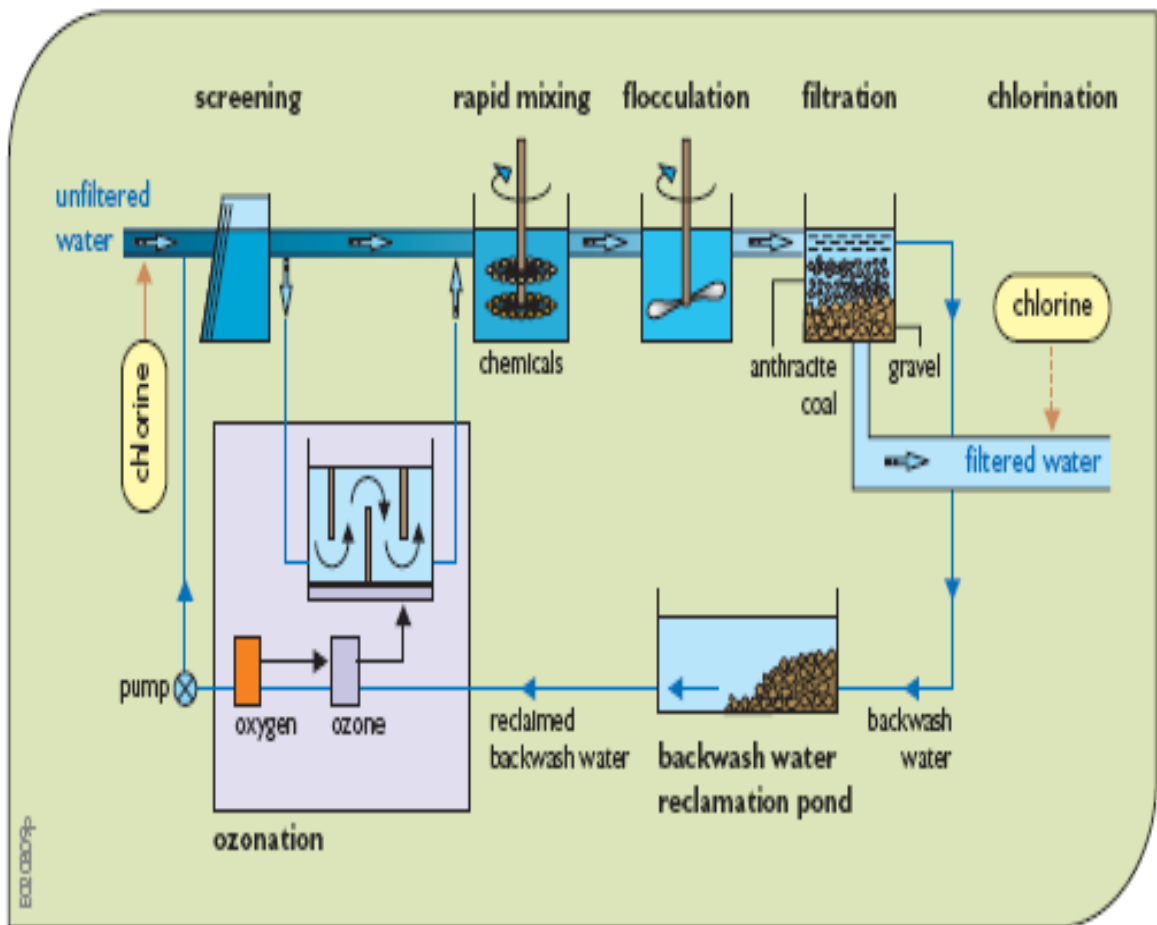


Fig. Typical processes in water treatment plants.

The filtered water is then treated with chemical disinfectants to kill any organisms that remain after the filtration process. An effective disinfectant is chlorine, but its use may cause potentially dangerous substances such as carcinogenic trihalomethanes.

Alternatives to chlorine include ozone oxidation (Figure). Unlike chlorine, ozone does not stay in the water after it leaves the treatment plant, so it offers no protection from bacteria that might be in the storage tanks and water pipes of the water distribution system.

Water can also be treated with ultraviolet light to kill microorganisms, but this has the same limitation as oxidation: it is ineffective outside of the treatment plant. Figure 13.3 is an aerial view of a water treatment plant serving a population of about 50,000. Sometimes calcium carbonate is removed from drinking water in order to prevent it from accumulating in drinking water pipes and washing machines. In arid coastal areas desalinated brackish or saline water is an important source of water for high-value uses. The cost of desalination is still high, but decreasing steadily. The two most common methods of desalination are distillation and reverse osmosis.

Distillation requires more energy, while osmosis systems need frequent maintenance of the membranes.

### **The distribution system**

After water has been treated to protect public health, improve aesthetics by removing color and taste and odour as required, it is ready to be delivered to consumers. The system of mains and pipes used to deliver the water is known as the distribution, or reticulation, system.

Treated water may be held at a treatment plant or immediately discharged into the system of mains and pipes that will transport it to consumers' taps. On the way it may be held in short-term storages, usually known as service reservoirs, which are located as close as possible to where the water will be used.

Sufficient water is required in a local area to supply periods of high demand, as on a hot summer day. From a design perspective, the needs of fire services usually determine the capacity of the system.

An important characteristic of a drinking water distribution system is that it is closed, to prevent contamination by birds, animals or people. In contrast, irrigation water is usually delivered in open channels or aqueducts.

A significant part of the water supply system lies buried underground. Out of the public eye, such infrastructure can be overlooked. It is easy to forget how valuable and essential water distribution systems are to the community. In terms of money spent on supplying water in Australia, most of it has been invested in the mains and pipes buried under the streets of towns and suburbs across the country.

Most distribution systems have developed and expanded as urban areas have grown. A map of a water distribution system would show a complex mixture of tree-like and looped pipe networks, together with valves and pumps.

Distribution systems require regular cleaning (flushing and scouring), maintenance and a program to replace pipes and other equipment as they near the end of their useful lives. Water mains can be expected to have a useful life of 40 to 100 years. Many of the pipes under the older parts of our cities may be towards the upper end of this range.

### **Challenges in Urban Water Management**

The challenges in urban water management are ample. In the developing world there is still a significant fraction of the population that has no access to proper water supply and sanitation. At the same time population growth, urbanization and industrialization continue to cause pollution and depletion of water sources. In the developed world pollution of water sources is threatening the sustainability of the

urban water systems. Climate change is likely to affect all urban centers, either with increasingly heavy storms or with prolonged droughts, or both. To address the gigantic challenges it is crucial to develop good approaches, so that policy development and planning are directed towards addressing these global change pressures, and to achieving truly sustainable urban water systems.

### **Current approach as described in international policy documents**

The ‘Dublin Statement’ (International Conference on Water and the Environment, 1992) and the ‘Agenda 21’ (UN Department for Sustainable Development, 1992) unfold a vision about how water resources are best managed, to serve the people, without damaging the environment. The ‘Dublin Statement’ formulated a number of principles that since have formed the basis for Integrated Water Resources Management (IWRM). IWRM addresses the issue of water management from a river basin perspective, since this is the scale that includes (all) relevant cause-effect relations and stakeholder interests. The principles of the ‘Dublin Statement’ are:

- ✚ Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment. Management of water resources requires linking social and economic development with environmental protection, within the river basin or catchment area.
- ✚ Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels. Decisions are taken at the lowest appropriate level, with full public consultation and involvement of users in planning and implementation.
- ✚ Women play a central part in the provision, management and safeguarding of water. Institutional arrangements should reflect the role of women in water provision and protection. Empowerment of women to participate in decision-making and implementation, as defined by them, needs to be addressed.
- ✚ Water has an economic value in all its competing uses and should be recognized as an economic good. Access to clean water and sanitation at an affordable price is a basic right of all human beings. Failure to recognize the economic value of water in the past has led to wasteful use and environmental damage.

These principles were applied to the urban environment as well and a future city was envisaged where appropriate water charges are in place, which will help reduce water scarcity and will reduce the need for developing ever more distant (and costly) sources. Waste discharge controls must be enforced and cannot be seen as reasonable trade-offs for prosperity brought by industrial growth (International Conference on Water and the Environment, 1992).

### **Innovative approaches in urban water management**

#### **The Bellagio Statement**

Several projects, programmes and approaches go a step further than the WFD. One of these is the ‘Bellagio Statement’, formulated by the Environmental Sanitation Working Group of the WSSCC in 2000. Its principles are believed to be essential for

achieving the objective of worldwide access to safe environmental sanitation and a healthy urban water system (reference):

1. Human dignity, quality of life and environmental security should be at the centre of the new approach, which should be responsive and accountable to needs and demands in the local setting.

- Solutions should be tailored to the full spectrum of social, economic, health and environmental concerns
- the household and community environment should be protected
- the economic opportunities of waste recovery and use should be harnessed

2. In line with good governance principles, decision-making should involve participation of all stakeholders, especially the consumers and providers of services.

Decision-making at all levels should be based on informed choices

- incentives for provision and consumption of services and facilities should be consistent with the overall goal and objective
- rights of consumers and providers should be balanced by responsibilities to the wider human community and environment

3. Waste should be considered a resource, and its management should be holistic and form part of integrated water resources, nutrient flows and waste management processes.

- Inputs should be reduced so as to promote efficiency and water and environmental security
- exports of waste should be minimized to promote efficiency and reduce the spread of pollution
- wastewater should be recycled and added to the water budget

4. The domain in which environmental sanitation problems are resolved should be kept to the minimum practicable size (household, community, town, district, catchment, city) and wastes diluted as little as possible.

- Waste should be managed as close as possible to its source
- water should be minimally used to transport waste
- additional technologies for waste sanitization and reuse should be developed

## **GENERAL ANALYSIS**

### **Waste water**

Waste management is the collection, transport, processing, recycling or disposal of waste materials. The term usually relates to materials produced by human activity, and is generally undertaken to reduce their effect on health, aesthetics or amenity.

Waste management is also carried out to reduce the materials' effect on the environment and to recover resources from them. Waste management can involve solid, liquid or gaseous substances, with different methods and fields of expertise for each.

Waste management practices differ for developed and developing nations, for urban and rural areas, and for residential and industrial, producers. Management for non-hazardous residential and institutional waste in metropolitan areas is usually the responsibility of local government authorities, while management for non-hazardous commercial and industrial waste is usually the responsibility of the generator.

Waste management methods vary widely between areas for many reasons, including type of waste material, nearby land uses, and the area available.

## **Disposal**

### **Landfill**

Disposing of waste in a landfill involves burying waste to dispose of it, and this remains a common practice in most countries. Historically, landfills were often established in disused quarries, mining voids or borrow pits. A properly-designed and well-managed landfill can be a hygienic and relatively inexpensive method of disposing of waste materials. Older, poorly-designed or poorly-managed landfills can create a number of adverse environmental impacts such as wind-blown litter, attraction of vermin, and generation of liquid leachate. Another common byproduct of landfills is gas (mostly composed of methane and carbon dioxide), which is produced as organic waste breaks down anaerobically. This gas can create odor problems, kill surface vegetation, and is a greenhouse gas.

Design characteristics of a modern landfill include methods to contain leachate such as clay or plastic lining material. Deposited waste is normally compacted to increase its density and stability, and covered to prevent attracting vermin (such as mice or rats). Many landfills also have landfill gas extraction systems installed to extract the landfill gas. Gas is pumped out of the landfill using perforated pipes and flared off or burnt in a gas engine to generate electricity.

Many local authorities, especially in rural areas, have found it difficult to establish new landfills due to opposition from owners of adjacent land. As a result, solid waste disposal in these areas must be transported further for disposal or managed by other methods. This fact, as well as growing concern about the environmental impacts of excessive materials consumption, has given rise to efforts to minimize the amount of waste sent to landfill in many areas. These efforts include taxing or levying waste sent to landfill, recycling waste products, converting waste to energy, and designing products that use less material.

### **Incineration**

Incineration is a disposal method that involves combustion of waste material. Incineration and other high temperature waste treatment systems are sometimes described as "thermal treatment". Incinerators convert waste materials into heat, gas, steam, and ash.

Incineration is carried out both on a small scale by individuals and on a large scale by industry. It is used to dispose of solid, liquid and gaseous waste. It is recognized as a practical method of disposing of certain hazardous waste materials (such as biological medical waste). Incineration is a controversial method of waste disposal due to issues such as emission of gaseous pollutants. Incineration is common in countries such as Japan where land is more scarce, as these facilities generally do not require as much area as landfills.

Waste-to-energy (WtE) or energy-from-waste (EfW) are broad terms for facilities that burn waste in a furnace or boiler to generate heat, steam and/or electricity. Modern combustion technologies maintain the advantages of incineration without its numerous disadvantages, while providing a clean energy source. Installation of a "boiler" such as the RCBC (rotary cascading bed combustor) allows the consumption of problem waste as fuels for the generation of electricity. Municipal solid waste, sewage, sludge, "dirty coals", and coal byproducts, are cleanly and efficiently

consumed for energy production with emissions well within strict regulatory standards. The fly ash byproduct is inert, and can be mixed with compost.

Tridel SA, a public corporation, is a modern waste-to-energy plant in Lausanne, Switzerland. It provides both electrical and thermal energy, totaling about 60 MW. It uses an oscillating firebed. The emitted gases are treated to reach as low as about 10% of the permitted values of pollutants as regulated by the severe Swiss legislation, except for NO<sub>x</sub>, which is held at 50%. The water used is collected mostly from roofs and paved areas and all waste water conforms to strict standards. Solid waste is mostly treated clinker plus washed fly ash and is almost inert, occupying about 10% of the volume of the original compacted municipal waste and other sources. Heavy metals, including mercury, are extracted and sent by rail for recycling. A unique feature is that much of the waste arrives by rail, through a purpose-built 4 km tunnel; as the plant is built about 250 m higher than the lake, this avoids the pollution from numerous trucks per day climbing the steep hill. Environmentally, Tridel SA supplies almost 10% of the electricity consumed in its catchment area at full output, from a renewable fuel. Economically, it is viable.

### **Waste management concepts**

There are a number of concepts about waste management which vary in their usage between countries or regions. This section presents some of the most general, widely-used concepts.

### **Waste hierarchy**

The waste hierarchy refers to the "3 Rs" reduce, reuse and recycle, which classify waste management strategies according to their desirability in terms of waste minimization. The waste hierarchy remains the cornerstone of most waste minimization strategies. The aim of the waste hierarchy is to extract the maximum practical benefits from products and to generate the minimum amount of waste.

### **Extended producer responsibility**

Extended Producer Responsibility (EPR) is a strategy designed to promote the integration of all costs associated with products throughout their life cycle (including end-of-life disposal costs) into the market price of the product. Extended producer responsibility is meant to impose accountability over the entire lifecycle of products and packaging introduced to the market. This means that firms which manufacture, import and/or sell products are required to be responsible for the products after their useful life as well as during manufacture.

### **Polluter pays principle**

The Polluter Pays Principle is a principle where the polluting party pays for the impact caused to the natural environment. With respect to waste management, this generally refers to the requirement for a waste generator to pay for appropriate disposal of the waste.

## **Urban Wastewater Management: The Outlook for the Future**

Urban wastewater management is at a critical juncture in the United States and elsewhere. Methods must again change in response to urban development, population growth, and diminishing natural resources. Based on information in recent literature, current research focuses, and trends in the engineering and regulatory community, three aspects of wastewater management are becoming increasingly important now and will continue to be important in the foreseeable future development of wastewater management. The three aspects are decentralized wastewater management (DWM), wastewater reclamation and reuse, and heightened attention to wet-weather flow (WWF) management. Currently, consideration of these three aspects in wastewater management planning is improving the functionality of wastewater systems and creating sustainable alternatives to the traditional centralized SSSs.

The reduction in recent years of federal grant money for the construction of wastewater collection and treatment systems required municipalities to search for cost-effective wastewater management alternatives. In addition, federal legislation (e.g., the 1977 amendments to the Clean Water Act) required communities to consider alternatives to the conventional centralized sewer system, and financial assistance was made available. The requirement that municipal and industrial discharges identify cost-effective wastewater management solutions has curtailed the sometimes blind selection of centralized SSSs for newly urbanizing areas. And as stated earlier, since World War II newly urbanizing areas have been constructed with lower density than the historical urban areas for which centralized sewer systems were originally designed. The applicability of centralized management concepts in these less-densely populated urbanizing areas is questionable. The factors of cost-effectiveness and appropriateness have contributed to the development of alternative wastewater management methods including DWM technologies. Decentralized wastewater management (DWM) is defined as the collection, treatment, and reuse of wastewater at or near its source of generation. A significant improvement in the newer decentralized technologies compared to the decentralized privy vault-cesspool system of the nineteenth century is the ability to integrate seamlessly and effectively with water-carriage waste removal. From the public's perspective, the primary deterrent to implementation of alternative wastewater management technologies has been the fear of a life-style change. Most individuals desire wastewater management to be unobtrusive, convenient, and not to require significant maintenance efforts on their part. The newer decentralized technologies have been developed to integrate easily with traditional plumbing fixtures and do not require a significant life-style adjustment. Essentially, the core components of DWM are the same as centralized collection and treatment systems, but the applied technologies are different. Water carriage is still prevalent, but the wastewater is treated on site or near the site and not transported to a central treatment facility. Decentralized systems currently serve approximately 25 percent of the U.S. population, and approximately 37 percent of new development. DWM systems have been shown to save money, to promote better watershed management, and to be suitable for a variety of site conditions. Research has improved the operation and management of septic tanks and developed innovative and improved on-site treatment technologies, e.g., intermittent and recirculating packed-bed filtration. The result has been the increased implementation of DWM in developing urban fringe areas, the same areas where centralized SSSs would likely

have been implemented two decades earlier if federal funding could have been easily secured. From the policy making and regulatory perspective, the most prominent concern about DWM is the lack of a body of authority with the appropriate powers to operate, manage, and regulate the system in the same manner as a centralized system. Creating such a managing body would require changing the status quo that has existed for many years, something many think is not possible. The primary difficulty in the near future for DWM is anticipated to be overcoming the years of institutional inertia built up in favor of centralized SSSs. One additional issue hindering the implementation of DWM technologies is the limited basic design requirements available. Because of the newness of the current decentralized technologies, engineering textbooks and manuals do not yet have adequate coverage of the concepts. A period of several years is needed until the necessary information is widely available and the ideas become incorporated into standard engineering practice.

The second wastewater management concept that will be important in the future is wastewater reuse. Wastewater reuse generally occurs on site or at the end of a centralized collection and treatment operation. The development of local and on-site wastewater reuse technologies will further encourage the use of DWM technologies. DWM, coupled with wastewater reuse, has the potential to be a highly cost-effective wastewater management method in less densely populated urbanizing areas. Increased reuse of wastewater at the end of a centralized collection and treatment operation will reduce the demand for water resources, but will not, in general, promote the use of alternative wastewater management options. Difficulties with wastewater reuse include public perception of selected uses for the reclaimed wastewater and the need to find economic uses of reclaimed wastewater and waste products. Currently, reuse is more attractive economically in the industrial setting than in the residential setting. But with growing populations and the future demands on potable water in residential areas, wastewater reuse will likely become more economical in residential areas.

Managing the quantity and quality of wet-weather flow (WWF) is the final issue expected to significantly influence the development of wastewater management in the future. In the nineteenth and early twentieth centuries, WWF was viewed as a mechanism to cleanse the urban area of built-up filth on roadways and in the sewers. WWF gradually became viewed as wastewater when centralized SSSs developed into the wastewater management technology of choice in the early twentieth century. Separate storm-water discharges were observed to pollute waterways and create nuisance conditions. Even with some early recognition, it has taken the better part of the twentieth century for the importance of WWF in water quality degradation to become thoroughly documented. Currently, all wet weather induced discharges (e.g., combined-sewer overflow (CSO), sanitary-sewer overflow (SSO), and separate storm-water discharges) are known to have detrimental effects on receiving water. In the late 1960s and throughout the 1970s, regulations were enacted in response to the documented effects of WWF on water quality degradation. The initial step was the 1972 passage of the Federal Water Pollution Control Act Amendments, which established policies for controlling wastewater discharges in an effort to protect water quality and acknowledged storm water as significant. The extension of the National Pollution Discharge Elimination System (NPDES) to include municipal separate storm-water discharges in the 1990s is having a significant effect on urban wastewater management. The requirement of municipal and industrial storm-water control and the current direction of combined-sewer overflow (CSO) and sanitary-sewer overflow

(SSO) policies suggest the need to reconsider past wastewater management methods and technologies that were developed before storm-water discharges, CSO, and SSO were water quality concerns.

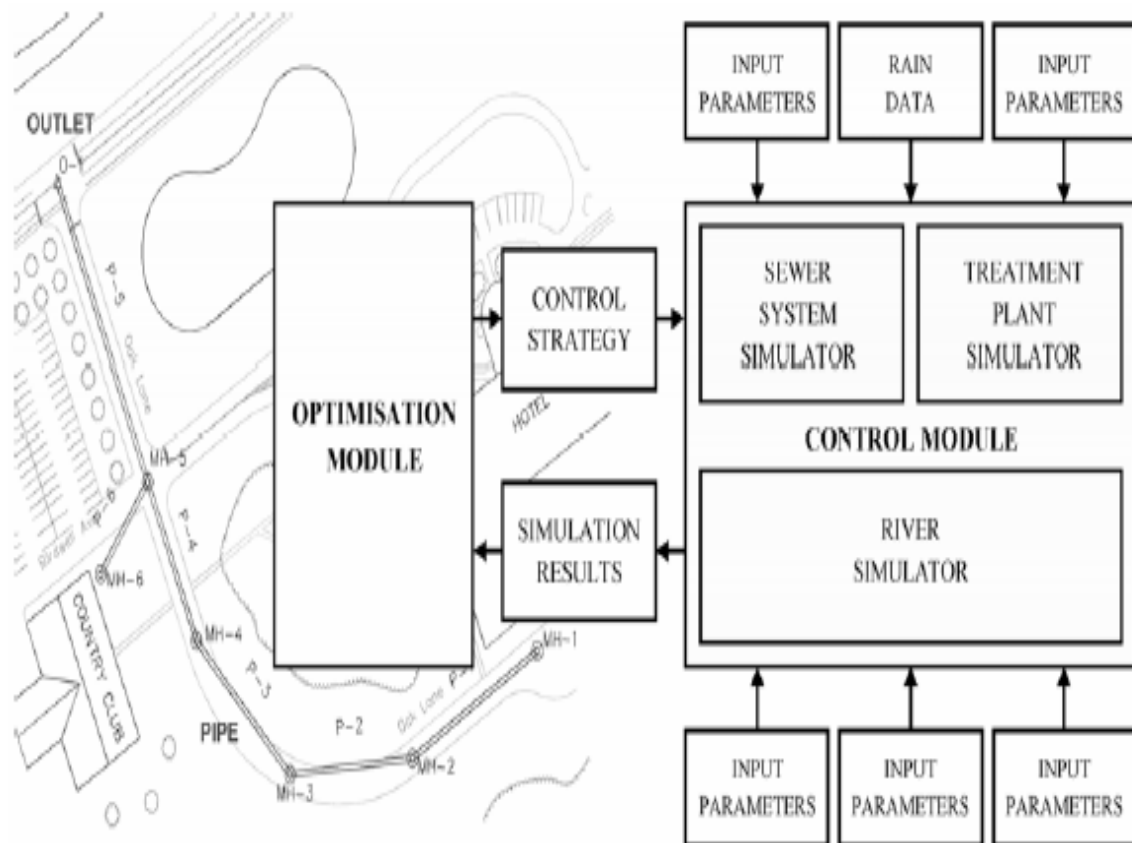
Due to the widespread problems of CSO, there has been a massive effort to control or eliminate CSOs at the municipal, state, and federal level. The improved understanding of combined-sewer systems (CSS) has renewed the interest in the use of centralized CSSs in the United States and elsewhere under specific conditions. Lessons learned from past combined system problems have enlightened current engineers and improved the operation of existing systems. For example, CSSs can be planned for newly urbanizing areas of the appropriate density to take advantage of new construction to provide adequate inline and offline storage and increased capacity at the wastewater treatment facility. In addition, new construction of wastewater treatment facilities could be coordinated with the new CSSs to accommodate the increased sludge-handling capacity required. The improved storage capacity coupled with improved storm-water management would theoretically reduce CSO frequency.

The SSO problem has also come under scrutiny over the past decade. Most SSOs are a result of excessive groundwater infiltration and storm-water inflow (I/I) causing the sewer system to be overwhelmed. Overflow structures provide the necessary relief to protect the integrity of the collection and treatment system, but have an adverse effect on the receiving water. During wet weather, a sanitary sewer conduit taking on excessive I/I essentially operates as a combined sewer. Millions of dollars in fines against a municipality can accumulate for SSO violations. Investigations into the causes of the SSO and the implementation of corrective actions could also cost millions of dollars. The level of funds required to address and correct SSO problems suggests the need to reduce wet-weather induced I/I in future wastewater management methods.

Studies in the past have compared the performance of centralized combined- versus separate-sewer systems. The results from the studies have shown combined and separate systems to discharge similar quantities of pollutants over the long term, suggesting that neither has environmental advantages. This is similar to the conclusions of Rudolph Hering's report to the National Board of Health in 1880. The need for a careful economic comparison between combined and separate systems is vital now that sanitary advantages are not as apparent. An unbiased comparison of combined and separate systems has renewed the interest in CSSs. Heaney et al., for example, reported that CSSs may discharge a smaller pollutant load to the receiving water than separate systems in cases where the storm water is discharged untreated and the sanitary wastewater is treated effectively. They presented an example in southern Germany where CSSs were being designed with extensive infiltration components to reduce the inflow of storm water to the drainage systems, reducing the frequency and magnitude of CSO events. CSSs are also used in Switzerland and Japan with similar results. In the United States, similar micro-management techniques are being used to improve the performance of CSSs. Proper planning of micro-management concepts, especially localized storm-water detention, will improve the performance of new CSSs, making them more attractive in the future.

## **Urban waste water disposal system management**

Urban waste water disposal systems are very complex hydraulic engineering systems comprising a number of spatial elements with characteristic parameters (natural part of the basin, urbanized city space), hydrographic network with the receptor, climatic and hydrographic characteristics of the basin, sewage system and the structures within it, waste water treatment facilities, culturological and sociologic properties of the people living in the basin etc. Extremely complex and specific issues of the urban waste water disposal systems, due to their complexity, and multidisciplinary character, as well as due to a large number of influential parameters, are nowadays, successfully solved in the developed countries by the integral management with the application of the modern computer system and technologies. By the integral solution of the urban space problems, sewage system, waste water treatment facilities and the receptors (figure ), using the existing historical or current data bases, modern simulation and optimization models, careful planning and production of appropriate scenarios, nowadays the optimal high-efficiency strategies are attained in the world, their basic goal being the «hygienic» disposal of waste waters, that is maximal reduction of waste water outlets and of harmful effects on the recipients and the environment, with minimization of capital investments and operational costs.



The basic characteristic of the modern solutions of the urban waste water disposal systems is a high level of influence of information and communication technology in the definition of the final solutions and in their application. Nowadays, no one is able to anticipate the speed and scope of the development of information and communication technologies with certainty, but their influence in the future will surely be very important.

The influence of the sewage system on the waste water treatment facility, and on the receptor due to the uncontrolled overflow of waste waters is very significant. Because of the high oscillations of hydraulic and biological load, especially at unbalanced sewage systems, particularly the efficiency of the biological part of the waste water facility is reduced and the large problems occur in its operation. The experiences of the developed countries demonstrate that there is no efficient protection of the water resources without efficient planning, dimensioning, organization, management and the work of the sewage system itself, and the modern solution of urban waste waters disposal systems and protection from pollution are based on this fact.

### **Wastewater Treatment**

The wastewater generated by residences, businesses and industries in a community consists largely of water. It often contains less than 10% dissolved and suspended solid material. Its cloudiness is caused by suspended particles whose concentrations in

untreated sewage range from 100 to 350 mg/l. One measure of the strength of the wastewater is its biochemical oxygen demand, or *BOD*<sub>5</sub>. *BOD*<sub>5</sub> is the amount of dissolved oxygen aquatic microorganisms will require in five days as they metabolize the organic material in the wastewater. Untreated sewage typically has a *BOD*<sub>5</sub> concentration ranging from 100 mg/l to 300 mg/l. Pathogens or disease-causing organisms are also present in sewage. Coliform bacteria are used as an indicator of disease-causing organisms. Sewage also contains nutrients (such as ammonia and phosphorus), minerals and metals. Ammonia can range from 12 to 50 mg/l and phosphorus can range from 6 to 20 mg/l in untreated sewage.

As illustrated in Figures 13.7 and 13.8, wastewater treatment is a multi-stage process. The goal is to reduce or remove organic matter, solids, nutrients, disease-causing organisms and other pollutants from wastewater before it is released into a body of water or on to the land, or is reused. The first stage of treatment is called preliminary treatment.

Preliminary treatment removes solid materials (sticks, rags, large particles, sand, gravel, toys, money, or anything people flush down toilets). Devices such as bar screens and grit chambers are used to filter the wastewater as it enters a treatment plant, and it then passes on to what is called primary treatment.

Clarifiers and septic tanks are generally used to provide primary treatment, which separates suspended solids and greases from wastewater. The wastewater is held in a tank for several hours, allowing the particles to settle to the bottom and the greases to float to the top. The solids that are drawn off the bottom and skimmed off the top receive further treatment as sludge. The clarified wastewater flows on to the next, secondary stage of wastewater treatment.

This secondary stage typically involves a biological treatment process designed to remove dissolved organic matter from wastewater. Sewage microorganisms cultivated and added to the wastewater absorb organic matter from sewage as their food supply. Three approaches are commonly used to accomplish secondary treatment: fixed-film, suspended-film and lagoon systems.

Fixed-film systems grow microorganisms on substrates such as rocks, sand or plastic, over which the wastewater is poured. As organic matter and nutrients are absorbed from the wastewater, the film of microorganisms grows and thickens. Trickling filters, rotating biological contactors and sand filters are examples of fixed-film systems.

Suspended-film systems stir and suspend microorganisms in wastewater. As the microorganisms absorb organic matter and nutrients from the wastewater, they grow in size and number. After the microorganisms have been suspended in the wastewater for several hours, they are settled out as sludge. Some of the sludge is pumped back into the incoming wastewater to provide 'seed' microorganisms. The remainder is sent on to a sludge treatment process. Activated sludge, extended aeration, oxidation ditch and sequential batch reactor systems are all examples of suspended-film systems. Lagoons, where used, are shallow basins that hold the wastewater for several months to allow for the natural degradation of sewage. These systems take advantage of natural aeration and microorganisms in the wastewater to renovate sewage.

Advanced treatment is necessary in some systems to remove nutrients from wastewater. Chemicals are sometimes added during the treatment process to help remove phosphorus or nitrogen. Some examples of nutrient removal systems are

coagulant addition for phosphorus removal and air stripping for ammonia removal. Final treatment focuses on removal of disease-causing organisms from wastewater. Treated wastewater can be disinfected by adding chlorine or by exposing it to sufficient ultraviolet light. High levels of chlorine may be harmful to aquatic life in receiving streams, so treatment systems often add a chlorine-neutralizing chemical to the treated wastewater before stream discharge. Sludges are generated throughout the sewage treatment process. This sludge needs to be treated to reduce odours, remove some of the water and reduce volume, decompose some of the organic matter and kill disease-causing organisms. Following sludge treatment, liquid and cake sludges free of toxic compounds can be spread on fields, returning organic matter and nutrients to the soil.

Artificial wetlands and ponds are sometimes used for effluent polishing. In the wetlands the natural diurnal variation in the oxygen concentration is restored. Furthermore, artificial wetlands can reduce the nutrient content of the effluent by the uptake of nitrogen and phosphorus by algae or macrophytes. The organic matter may be harvested from the ponds and wetlands.

A typical model for the simulation of the treatment processes in wastewater treatment plants is the Activated Sludge Model (Gujer et al., 1999; Henze et al., 1999; Hvitved-Jacobsen et al., 1998). Activated sludge models predict the production of bacterial biomass and the subsequent conversion of organic matter and nutrients into sludge, CO<sub>2</sub> and N<sub>2</sub> gas.

### **Modern wastewater treatment**

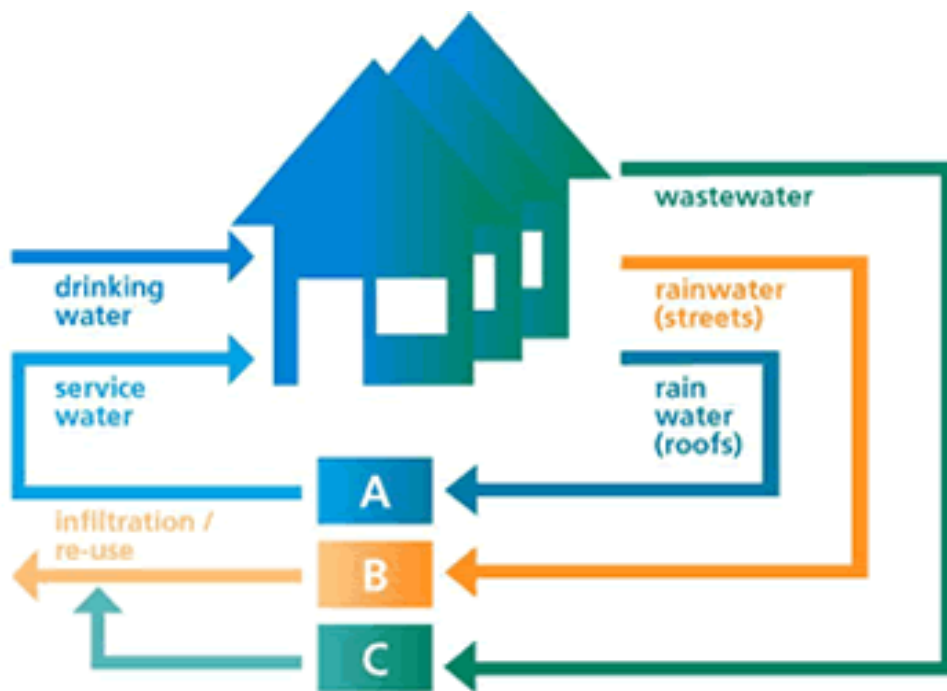
The basic principle treating the highly concentrated wastewater occurring in small volumes only is based on separating the domestic wastewater flow applying modern, low-energy membrane technology.

By advanced anaerobic technology (high-performance digestion) the concentrate flow is directly metabolized into biogas (methane, carbon dioxide) for energy generation. The filtrate flow, which is free of solids, is purified in modern wastewater membrane bioreactors. This anaerobic process step works with a high biomass concentration producing only little amounts of secondary sludge.

In the anaerobic high-performance digestion with integrated micro filtration, the organic mass is converted from highly-concentrated primary and secondary sludge by the microbial mineralization chain into CH<sub>4</sub>, CO<sub>2</sub> and NH<sub>4</sub>. Due to the high concentration present, ammonia nitrogen can be economically recycled from the sludge fermentation procedure.

As already mentioned, the filtrate flow with the organic compounds dissolved in it undergoes anaerobic purification. This occurs in a high-performance bioreactor with biomass enrichment via membrane technology. The filtrate flow generated is hygienically harmless and reaches bathing water quality. It can be directly infiltrated into the ground or be used as process water.

After the second membrane separation stage, remaining nitrogen and phosphorus compounds are taken from the solids-free wastewater, whereby the precipitation product can also be recycled as a fertilizer.



## Storm Water Management

In most urban areas, population is increasing rapidly and the issue of supplying adequate water to meet societal needs and to ensure equity in access to water is one of the most urgent and significant challenges faced by decision-makers. With respect to the physical alternatives to fulfill sustainable management of freshwater, there are two solutions: finding alternate or additional water resources using conventional centralized approaches; or better utilizing the limited amount of water resources available in a more efficient way. To date, much attention has been given to the first option and only limited attention has been given to optimizing water management systems.

Among the various alternative technologies to augment freshwater resources, rainwater harvesting and utilization is a decentralized, environmentally sound solution, which can avoid many environmental problems often caused in conventional large-scale projects using centralized approaches.

Rainwater harvesting, in its broadest sense, is a technology used for collecting and storing rainwater for human use from rooftops, land surfaces or rock catchments using simple techniques such as jars and pots as well as engineered techniques. Rainwater harvesting has been practiced for more than 4,000 years, owing to the temporal and spatial variability of rainfall. It is an important water source in many areas with significant rainfall but lacking any kind of conventional, centralized supply system. It

is also a good option in areas where good quality fresh surface water or groundwater is lacking. The application of appropriate rainwater harvesting technology is important for the utilization of rainwater as a water resource.

### **Advantages of Rainwater Harvesting**

- ✚ Rainwater harvesting can co - exist with and provide a good supplement to other water sources and utility systems, thus relieving pressure on other water sources.
- ✚ Rainwater harvesting provides a water supply buffer for use in times of emergency or breakdown of the public water supply systems, particularly during natural disasters.
- ✚ Rainwater harvesting can reduce storm drainage load and flooding in city streets.
- ✚ Users of rainwater are usually the owners who operate and manage the catchments system, hence, they are more likely to exercise water conservation because they know how much water is in storage and they will try to prevent the storage tank from drying up.
- ✚ Rainwater harvesting technologies are flexible and can be built to meet almost any requirements. Construction, operation, and maintenance are not labor intensive.

### **Types of Rainwater Harvesting Systems**

Typically, a rainwater harvesting system consists of three basic elements: the collection system, the conveyance system, and the storage system. Collection systems can vary from simple types within a household to bigger systems where a large catchments area contributes to an impounding reservoir from which water is either gravitated or pumped to water treatment plants. The categorization of rainwater harvesting systems depends on factors like the size and nature of the catchment's areas and whether the systems are in urban or rural settings. Some of the systems are described below

#### **Catchment Areas**

**Rooftop catchments:** In the most basic form of this technology, rainwater is collected in simple vessels at the edge of the roof. Variations on this basic approach include collection of rainwater in gutters which drain to the collection vessel through down-pipes constructed for this purpose, and/or the diversion of rainwater from the gutters to containers for settling particulates before being conveyed to the storage container for the domestic use. As the rooftop is the main catchment area, the amount and quality of rainwater collected depends on the area and type of roofing material. Reasonably pure rainwater can be collected from roofs constructed with galvanized corrugated iron, aluminium or asbestos cement sheets, tiles and slates, although

thatched roofs tied with bamboo gutters and laid in proper slopes can produce almost the same amount of runoff less expensively (Gould, 1992). However, the bamboo roofs are least suitable because of possible health hazards. Similarly, roofs with metallic paint or other coatings are not recommended as they may impart tastes or color to the collected water. Roof catchments should also be cleaned regularly to remove dust, leaves and bird droppings so as to maintain the quality of the product water (see figure 1).

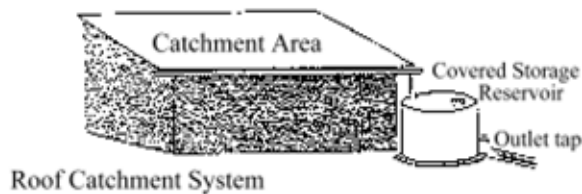


Figure 1: Rooftop Catchment System.

Land surface catchments: Rainwater harvesting using ground or land surface catchment areas is less complex way of collecting rainwater. It involves improving runoff capacity of the land surface through various techniques including collection of runoff with drain pipes and storage of collected water. Compared to rooftop catchment techniques, ground catchment techniques provide more opportunity for collecting water from a larger surface area. By retaining the flows (including flood flows) of small creeks and streams in small storage reservoirs (on surface or underground) created by low cost (e.g., earthen) dams, this technology can meet water demands during dry periods. There is a possibility of high rates of water loss due to infiltration into the ground, and, because of the often marginal quality of the water collected, this technique is mainly suitable for storing water for agricultural purposes. Various techniques available for increasing the runoff within ground catchment areas involve: i) clearing or altering vegetation cover, ii) increasing the land slope with artificial ground cover, and iii) reducing soil permeability by the soil compaction and application of chemicals (see figure 2).



Figure 2: Ground Catchment System

✚ Clearing or altering vegetation cover: Clearing vegetation from the ground can increase surface runoff but also can induce more soil erosion. Use of dense vegetation cover such as grass is usually suggested as it helps to both maintain an high rate of runoff and minimize soil erosion.

✚ Increasing slope: Steeper slopes can allow rapid runoff of rainfall to the collector. However, the rate of runoff has to be controlled to minimize soil erosion from the catchment field. Use of plastic sheets, asphalt or tiles along with slope can further increase efficiency by reducing both evaporative losses and soil erosion. The use of flat sheets of galvanized iron with timber frames to prevent corrosion was recommended and constructed in the State of Victoria, Australia, about 65 years ago (Kenyon, 1929; cited in UNEP, 1982).

✚ Soil compaction by physical means: This involves smoothing and compacting of soil surface using equipment such as graders and rollers. To increase the surface runoff and minimize soil erosion rates, conservation bench terraces are constructed along a slope perpendicular to runoff flow. The bench terraces are separated by the sloping collectors and provision is made for distributing the runoff evenly across the field strips as sheet flow. Excess flows are routed to a lower collector and stored (UNEP, 1982).

• Soil compaction by chemical treatments: In addition to clearing, shaping and compacting a catchment area, chemical applications with such soil treatments as sodium can significantly reduce the soil permeability. Use of aqueous solutions of a silicone-water repellent is another technique for enhancing soil compaction technologies. Though soil permeability can be reduced through chemical treatments, soil compaction can induce greater rates of soil erosion and may be expensive. Use of sodium-based chemicals may increase the salt content in the collected water, which may not be suitable both for drinking and irrigation purposes.

### **Collection Devices**

Storage tanks: Storage tanks for collecting rainwater harvested using guttering may be either above or below the ground. Precautions required in the use of storage tanks include provision of an adequate enclosure to minimize contamination from human, animal or other environmental contaminants, and a tight cover to prevent algal growth and the breeding of mosquitoes. Open containers are not recommended for collecting water for drinking purposes. Various types of rainwater storage facilities can be found in practice. Among them are cylindrical ferrocement tanks and mortar jars. The ferrocement tank consists of a lightly reinforced concrete base on which is erected a circular vertical cylinder with a 10 mm steel base. This cylinder is further wrapped in two layers of light wire mesh to form the frame of the tank. Mortar jars are large jar shaped vessels constructed from wire reinforced mortar. The storage capacity needed should be calculated to take into consideration the length of any dry spells, the amount of rainfall, and the per capita water consumption rate. In most of the Asian countries, the winter months are dry, sometimes for weeks on end, and the annual average rainfall can occur within just a few days. In such circumstances, the storage capacity should be large enough to cover the demands of two to three weeks. For example, a three person household should have a minimum capacity of  $3 \text{ (Persons)} \times 90 \text{ (l)} \times 20 \text{ (days)} = 5400 \text{ l}$ .

Rainfall water containers: As an alternative to storage tanks, battery tanks (i.e., interconnected tanks) made of pottery, ferrocement, or polyethylene may be suitable. The polyethylene tanks are compact but have a large storage capacity (ca. 1 000 to 2 000 l), are easy to clean and have many openings which can be fitted with fittings for connecting pipes. In Asia, jars made of earthen materials or ferrocement tanks are commonly used. During the 1980s, the use of rainwater catchment technologies, especially roof catchment systems, expanded rapidly in a number of regions, including Thailand where more than ten million 2 m<sup>3</sup> ferrocement rainwater jars were built and many tens of thousands of larger ferrocement tanks were constructed between 1991 and 1993. Early problems with the jar design were quickly addressed by including a metal cover using readily available, standard brass fixtures. The immense success of the jar programme springs from the fact that the technology met a real need, was affordable, and invited community participation. The programme also captured the imagination and support of not only the citizens, but also of government at both local and national levels as well as community based organizations, small-scale enterprises and donor agencies. The introduction and rapid promotion of Bamboo reinforced tanks, however, was less successful because the bamboo was attacked by termites, bacteria and fungus. More than 50 000 tanks were built between 1986 and 1993 (mainly in Thailand and Indonesia) before a number started to fail, and, by the late 1980s, the bamboo reinforced tank design, which had promised to provide an excellent low-cost alternative to ferrocement tanks, had to be abandoned.

### **Conveyance Systems**

Conveyance systems are required to transfer the rainwater collected on the rooftops to the storage tanks. This is usually accomplished by making connections to one or more down-pipes connected to the rooftop gutters. When selecting a conveyance system, consideration should be given to the fact that, when it first starts to rain, dirt and debris from the rooftop and gutters will be washed into the down-pipe. Thus, the relatively clean water will only be available some time later in the storm. There are several possible choices to selectively collect clean water for the storage tanks. The most common is the down-pipe flap. With this flap it is possible to direct the first flush of water flow through the down-pipe, while later rainfall is diverted into a storage tank. When it starts to rain, the flap is left in the closed position, directing water to the down-pipe, and, later, opened when relatively clean water can be collected. A great disadvantage of using this type of conveyance control system is the necessity to observe the runoff quality and manually operate the flap. An alternative approach would be to automate the opening of the flap as described below.

A funnel-shaped insert is integrated into the down-pipe system. Because the upper edge of the funnel is not in direct contact with the sides of the down-pipe, and a small gap exists between the down-pipe walls and the funnel, water is free to flow both around the funnel and through the funnel. When it first starts to rain, the volume of water passing down the pipe is small, and the \*dirty\* water runs down the walls of the pipe, around the funnel and is discharged to the ground as is normally the case with rainwater guttering. However, as the rainfall continues, the volume of water increases and \*clean\* water fills the down-pipe. At this higher volume, the funnel collects the clean water and redirects it to a storage tank. The pipes used for the collection of rainwater, wherever possible, should be made of plastic, PVC or other inert substance,

as the pH of rainwater can be low (acidic) and could cause corrosion, and mobilization of metals, in metal pipes.

In order to safely fill a rainwater storage tank, it is necessary to make sure that excess water can overflow, and that blockages in the pipes or dirt in the water do not cause damage or contamination of the water supply. The design of the funnel system, with the drain-pipe being larger than the rainwater tank feed-pipe, helps to ensure that the water supply is protected by allowing excess water to bypass the storage tank. A modification of this design is shown in Figure 5, which illustrates a simple overflow/bypass system. In this system, it also is possible to fill the tank from a municipal drinking water source, so that even during a prolonged drought the tank can be kept full. Care should be taken, however, to ensure that rainwater does not enter the drinking water distribution system.

## **GENERAL RECOMMENDATION**

### **Innovation Trends in Urban Water Supply and Sanitation.**

Parallel with growing urban population drinking water demand especially in mega cities in the developing countries, is growing quickly and takes increasing part of total water resources of the world. In spite of the fact that urban population uses only small amount of available water for consumption, delivery of sufficient water volumes constitutes a difficult logistic and economical problem. In spite of grate efforts during several decades, still about 1.2 billion people in the developing countries lack access to safe drinking water supply. By the year 2050 an estimated 65% of the world population will live in areas of water shortage (Milburn, 1996). Newer sources (Knight, 1998) say that the pace of population growth is slowing down and if this trend will be continuing "only" 25 - 40 % of population will face shortages of fresh water.

There is a fundamental connection between present state in water supply, sanitation, organic waste management and agricultural development worldwide. While sustainable provision of water and sanitation for growing population is in itself an outstanding challenge, the new target is to develop technologies and management strategies that can make organic residuals from human settlements useful in rural and urban agriculture for production of food. Content of nutrients in excreta of one person is sufficient to produce grain with all nutrition necessary to maintain life of just one person.

Thus, theoretically, there is no reason for hunger for anybody. Thus, it can be stated that the need of increased agricultural production requires new developments in sanitation and solid waste handling technology to make recycling of nutrients from households to agriculture possible. Thus, methods of sanitation and handling organic solid wastes become a fundamental parts of water management challenge representing a crucial interface between type of sanitation, state of the environment, health of populations and food production.

Traditional methods used in water resources development and in supply of sanitation

were and still are unable to satisfy fast growing needs of developing countries. The problem with supply of water and sanitation to growing urban agglomerations has, according International Water Resources Association already grown to the scale of a problem number one in the world (Milburn 1996). Solution of this problem depends on research and introduction of innovative technologies in water sector and on long-term national planning and development using technical, behavioral and legislative means. The new challenge is to adopt already emerging technical solutions as well as logistic and organizational methods and turn present problems to opportunities. It is clear that it may be possible to increase agricultural production without increasing the use of fossil fertilizers provided that sanitation technology could be made capable of recycling nutrients from households to agriculture. Water and sanitation system solutions known from developed countries are not only to expensive in investments and running costs to majority of developing countries but also does not possess ability to recycle nutrients.

General outline of the complex solution and its necessary elements have been already defined and it is clear that such solutions will require rethinking and innovation in entire water and sanitation sector. It is also clear that the majority of developing countries will, even in spite of possible future economical development, not copy water and sanitation solutions known from developed world. At stake is to much: economical burden of such solutions versus possibility to increase agricultural production without use of fossil fertilizers and subsequent land degradation. The general goals of the future complex solution have been formulated and several elements is already under development. It is clear that in order to alleviate problems with water supply it is necessary to develop methods for multiple and/or quality dependent water use in households and introduce more efficient economical incentives to save water. It is also clear that some countries must come back to ancient habits to collect and use storm water for non-consumptive water uses. For example roof storm water may be used after separation of runoff from first minutes if the rainfall using simple mechanical devices.

Development of new technologies and innovative total water system solutions for urban areas is needed to satisfy present human needs with respect to living standards and the present environmental goals. These future system solutions will encompass water supply, quality-dependent water consumption, reuse of rainwater, on-water-borne sanitation and new methods of wastewater re-use in agriculture. Decreasing availability of clean water implies that water-borne sanitation is not feasible solution for any country not equipped with effective wastewater treatment, and especially not for countries in dry climate conditions. Two important tasks can be listed in connection to sanitation issue: first of all safe, cost-effective and socially acceptable water saving and safe sanitation alternatives or dry-sanitation technologies should be further developed and implemented, for the second it is necessary to facilitate smooth, long-term transition in which water-borne and dry sanitation solutions exist parallel in the same city. Since sanitation is mostly lacking not in central parts of cities but in suburban areas, introduction of dry sanitation may bring rapid and low-cost alternative to satisfy the needs of those less wealthy. Wider introduction of dry sanitation (including separation sanitation) solutions will require increased research

efforts to adapt already developed solutions to the varying local cultural and economical conditions of developing countries. The challenge in this context to create socially and economically acceptable technologies of agricultural uses of nutrients present in human excreta.

Methods of safe and hygienic utilization wastewater from water-borne sanitation systems that are present in central parts of many large cities in developing countries have been discussed for a long time, but still there is no generally accepted way for utilization of wastewater in agriculture. The problem may be technically addressed in two ways: the first one is to introduce changes in water supply systems e.g. for example to introduce dual supply systems, one for less polluting water uses and second for heavily polluted uses such as sanitation where reused water is used. Effluents from less polluting uses could be directly used in peri-urban agriculture while wastewater from sanitation would be used only for irrigation of non-consumptive crops. Due to high costs of such solution, another approach that is discussed would manipulate on direct agricultural use of raw wastewater. In agricultural production of non-consumption crops wastewater could be use without or after primary treatment only, and for consumption crops wastewater would be treated to carefully calculated standards depending on risks for crop uptake of chemical and bacterial pollution (Bahri 1998). Innovations in inexpensive wastewater purification systems that extensively use aquatic plants to purify wastewater are very promising in this context. One example of such system is so called Phytodepurational Activated Sludge Systems (Bifotem @aol.com, 1999).

Another exciting area of new development is within so called urban or peri-urban agriculture. Urban agriculture is as old as human settlements and cities. People have always tried to improve their living conditions by cultivation of crops in the vicinity of their houses. Parallel with growth of cities, urban agriculture is growing for better or worse, in many cities without research, approval and control by central organizations. In several places urban agriculture has long tradition and no adverse effects on health of population were noticed. For example in Calcutta, wetlands are traditionally used for low-cost waste-water treatment. Simultaneously, these wetlands constitute highly productive multilevel aquaculture system used for solid waste recycling and food production with vegetables, fruit trees and fish as outputs. In 1992 this system was first recognized by central authorities as an ecological treatment and bio-mass production plant, i.e. object worth protection and further development. After that, new wetland developments in Calcutta were initiated for the same purpose. Recently aid agencies (UNDP for example) and governments have begun to realize the potential of urban agriculture.

New development towards small-scale urban agriculture, possible to arrange on very limited area of a densely populated city, begun in Botswana where so called "Sanitas wall" has been developed. The invention is based on application of gray water from households for growing crops for consumption. In condition of lacking space in urban environment, a wall made of concrete (or sun-burned clay) two-compartment stones are constructed. One compartment is filled with sand and the other with compost where plants can grow. These bricks are put on each other to height of about three meters. Plants are irrigated with household's gray water. Three meters high and about

3 meters long wall is enough to absorb average volume of gray water from one household. Figure 1 shows construction of Sanitas wall (Gunther, 1998, Winblad, 1998). Another new solution to apply in small-scale agriculture is so called permanent growing strips (Jarlöv 1998) see Figure 2. Instead of ploughing, soil is ripped in permanent strips to which rainwater is concentrated to take the crops through drought periods. The amount of water for irrigation is significantly lower than in normal agriculture. The method can give astonishing 10 to 25 times more grain per hectare than from traditional agriculture.

Yet another solution is to grow vegetables in concrete Bow Benches, i.e. concrete pots with bow shaped bottom. Scientific community of water researchers has an important role to play in further development of methods used in urban agriculture including aquaculture, pond systems, irrigation with wastewater, and newer types of small-scale gray water-feed agriculture in peri-urban areas. Scientists should see the benefits of such developments and contribute with their knowledge in order to find safe and efficient technical solutions. It is important to make local studies leading to establishment of safety rules with respect to construction, water quality standards and consumption restrictions. Also important is opening of new research leading to substitution of fossil fertilizers with nutrients that are presently discarded as wastewater sludge or organic solid wastes.

Real goal is then not only to recycle water and nutrients but also all matter and, especially, organic matter that constitutes ca 85 % of all "wastes" produced in human settlements. At the moment only about 5 % of solid wastes that households generate in the industrialized world is biologically digested to recover nutrients. Theoretically it is possible to use up to 85% of solid wastes as recyclable resource (Gajdos 1995). That brings us to think much further than just about composting or urine separating toilets. We begin to talk about bio-reactors that are able to decompose not only household wastes but also all organic refuses from all human activities. Microbiological processes in specially designed bio-reactors can digest all organic residuals and the end products will be biogas and bio-fertilizers. In the same way as for wastewater, the task of "solid waste management" is no longer limited to collection and safe disposal but more a question how to organize collection, transportation and recycling. In stead of problems and pollution the end products may feed the growing population and be a source of really clean energy. Thus, we are beginning to talk not only about some new isolated technologies but instead about new total system solutions.

### **Urban Water System Modeling**

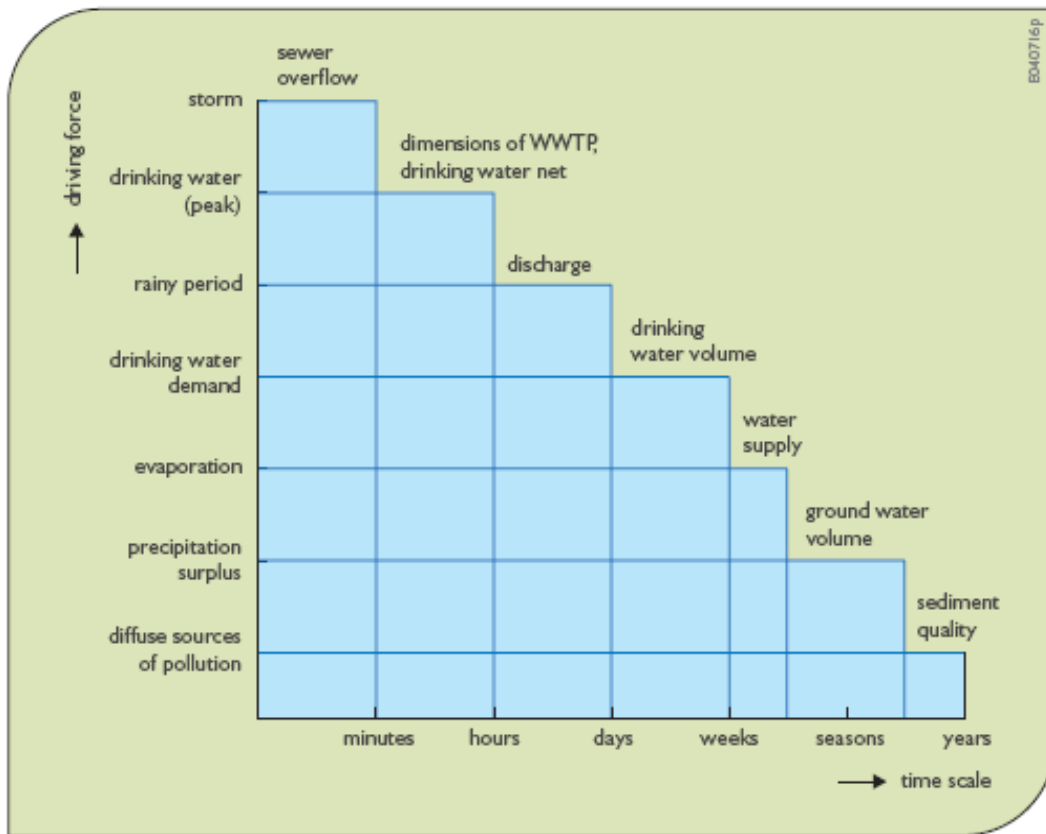
Optimization and simulation models are becoming increasingly available and are used to analyze a variety of design and operation problems involving urban water systems. Many are incorporated within graphic-user interfaces that facilitate the use of the models and the understanding and further analysis of their results.

## Model Selection

A wide range of models is available for the simulation of hydrodynamics and water quality in urban systems. The selection of a particular model and the setup of a model schematization depends on the research question at hand, the behavior of the system, the available time and budget, and future use of the model. The research question and the behavior of the water system determine the level of detail of the model schematization. The time scale of the dominating processes and the spatial distribution of the problem are key elements in the selection of a model, as is illustrated in Figure and Table.

Figure shows the time scales of the driving forces and their impact in urban water systems. It may be wise to consider the processes with largely different time scales separately, rather than joining them together in one model. For instance, the water quality of urban surface waters is affected by combined sewer overflows and by many diffusive sources of pollution. A combined sewer overflow lasts several hours and the impact of the discharge on the oxygen concentration in the surface water lasts for a couple of days. The accumulation of heavy metals and organic micro-pollutants in the sediment takes many years and the influx of the diffusive sources of pollution is more or less constant in time. The impact of combined sewer overflows on the oxygen concentration can be studied with a detailed, deterministic simulation model for the hydrodynamics and the water quality processes in the surface water system. A typical time step in such a model is minutes; a typical length segment is within the range from 10 to 100 metres. The accumulation of pollutants in the sediment can be modeled by means of a simple mass balance. Another example is shown in Table 13.10. In this example the wastewater collection and treatment system in an urban area is modeled in three different ways. In the first approach, only the river is modeled. The discharge of effluent from a wastewater treatment plant is taken into account as a boundary condition. This is a useful approach for studying the impact of the discharge of effluent on water quality.

In the second approach, a detailed water and mass balance is made for an urban area. The main routes of water and pollution are considered. Generic measures, such as the disconnection of impervious areas from the sewage system, can be evaluated with this type of model schematization. In the third, most detailed, approach, a model schematization is made for the entire sewage system and, eventually, the wastewater treatment plant.



**Figure.** Time scales of driving forces and impacts in urban water systems.

type of schematisation	implementation in code	examples
measured data of effluent quantity and quality	boundary conditions	end-of-pipe measures at the treatment plants
water balance and mass balance	rainfall runoff module, emissions module	analysis of main routes of rainfall discharge
detailed model schematisation	sewer flow module, water quality module	reduction of emissions via combined sewer overflows

Three methods of making a model schematization for an urban water system.

## Optimization

The use of the storage, transport and treatment capacity of existing urban infrastructure can be optimized in many cases. Optimization of urban water systems aims at finding the technical, environmental and financial best solution, considering and balancing measures in the sewage system, the wastewater treatment plant and the surface water system at the same time. For instance, the optimum use of the storage capacity in a sewage system by means of real-time control of the pumps may eliminate the need for a more expensive increase in treatment capacity at the wastewater treatment plant.

Storage of runoff from streets and roofs in surface water may be better for river water quality than transporting the runoff to the wastewater treatment plant and subsequent discharging it as effluent. Table 13.11 shows a matrix with the key variables of storage, transport capacity and treatment capacity in the sewage system, the wastewater treatment plant and the surface water. Methods for finding optimal solutions are becoming increasingly effective in the design and planning of urban infrastructure. Yet they are challenged by the complexity and non-linearity of water distribution networks, especially urban ones.

Numerous calibration procedures for water distribution system models have been developed since the 1970s. Trial and error approaches (Rahal et al., 1980; Walski, 1983) were replaced with explicit type models (Boulos and Wood, 1990; Ormsbee and Wood, 1986). More recently, calibration problems have been formulated and solved as optimization problems. Most of the approaches used so far are either local or global search methods. Local search gradient methods have been used by Shamir (1974), Lansley and Basnet (1991), Datta and Sridharan (1994), Reddy et al. (1996), Puma and Liggett (1992), and Liggett and Chen (1994) to solve various steady-state and transient model calibration problems (Datta and Sridharan, 1994; Savic and Walters, 1995; Greco and Del Giudice, 1999; Vitkovsky et al., 2000).

Evolutionary search algorithms are now commonly used for the design and calibration of various highly non-linear hydraulic models of urban systems.

They are particularly suited for search in large and complex decision spaces, e.g. in water treatment, storage and distribution networks. They do not need complex mathematical matrix inversion methods and they permit easy incorporation of additional calibration parameters and constraints into the optimization process (Savic and Walters, 1995; Vitkovsky and Simpson, 1997; Tucciarelli et al., 1999; Vitkovsky et al., 2000).

In addition to calibration, these evolutionary search methods have been used extensively to find least-cost designs of water distribution systems (Simpson et al., 1994; Dandy et al., 1996; Savic and Walters, 1997). Other applications include the development of optimal replacement strategies for water mains (Dandy and Engelhardt, 2001), finding the least expensive locations of water quality monitoring stations (Al-Zahrani and Moied, 2001), minimizing the cost of operating water distribution systems (Simpson et al., 1999), and identifying the least-cost development sequence of new water sources (Dandy and Connarty, 1995).

These search methods are also finding a role in developing master or capital improvement plans for water authorities (Murphy et al., 1996; Savic et al., 2000). In this role they have shown their ability to identify low-cost solutions for highly complex water distribution systems subject to a number of loading conditions and a large number of constraints. Constraints on the system include maximum and minimum pressures, maximum velocities in pipes, tank refill conditions and maximum and minimum tank levels.

As part of any planning process, water authorities need to schedule the capital improvements to their system over a specified planning period. These capital improvements could include water treatment plant upgrades or new water sources as well as new, duplicate or replacement pipes, tanks, pumps and valves. This scheduling process sewer WWTP surface water storage moderate none limited – high transport capacity limited – high treatment capacity none high limited

Urban Water Systems requires estimates of how water demands are likely to grow over time in various parts of the system. The output of a scheduling exercise is a plan that identifies what facilities should be built, installed or replaced, to what capacity and when, over the planning horizon. This plan of how much to do and when to do it should be updated periodically long before the end of the planning horizon. The application of optimization to master planning for complex urban water infrastructure presents a significant challenge. Using optimization methods to find the minimum-cost design of a system of several thousand pipes for a single demand at a single point in time is difficult enough on its own. The development of least cost system designs over a number of time periods that experience multiple increasing demands can be much more challenging.

Consider, for example, developing a master plan for the next twenty years divided into four five-year construction periods. The obvious way to model this problem is to include the system design variables for each of the next four five-year periods, given the expected demands at those times. The objective function for this optimization model might be to minimize the present value of all construction, operation and maintenance costs. As mentioned previously, this is a very large problem that is probably unmanageable with the current state of technology for real water distribution systems.

Dandy et al. (2002) have developed and applied two alternative modeling approaches. One approach is to find the optimal solution for the system for only the final or 'target' year. The solution to this first optimization problem identifies those facilities that will need to be constructed sometime during the twenty-year planning period. A series of sub-problems are then optimized, one for each intermediate planning stage, to identify when each necessary facility should be built. For these sub-problems, the decisions are either to build or not to build to a predetermined capacity. If a component is to be built, its capacity has already been determined in the target year optimization.

For the second planning stage, all options selected in the first planning stage are locked in place and a choice is made from among the remaining options. Therefore, the search space is smaller for this case. A similar situation applies for the third planning stage. An alternative approach is to solve the first optimization problem for just the first planning stage. All options and all sizes are available. The decisions

chosen at this time are then fixed, and all options are considered in the next planning stage. These options include duplication of previously selected facilities. This pattern is repeated until the final 'target' year is reached.

Each method has its advantages and disadvantages. For the first, 'build-to-target' method, the optimum solution is found for the 'target year'. This is not necessarily the case for the 'build-up' method. On the other hand, the build-up method finds the optimal solution for the first planning stage, which the build-to-target method does not necessarily do. As the demands in the first planning stage are known more precisely than those for the 'target' year, this may be an advantage.

The build-up method allows small pipes to be placed at some locations in the first time planning stage, if warranted, and these can be duplicated at a later time; the build-to-target method does not. This allows greater flexibility, but may produce a solution that has a higher cost in present value terms.

The results obtained by these or any other optimization methods will depend on the assumed growth rate in demand, the durations of the planning intervals, the economic discount rate if present value of costs is being minimized, and the physical configuration of the system under consideration. Therefore, the use of both methods is recommended. Their outputs, together with engineering judgment, can be the basis for developing an adaptive master development plan. Remember, it is only the current construction period's solution that should be of interest. Prior to the end of that period, the planning exercise can be performed again with updated information to obtain a better estimate of what the next period's decisions should be.

## **ACUTALIZATION**

### **Case Study 1: Storm Water Management**

Ringdansen is a residential development in the south-eastern part of the City of Norrköping, which is located approximately 140km to the southwest of Stockholm.

Two identical sets curved apartment blocks arranged in circles - Guldringen (Gold Ring) and Silverringen (Silver Ring) - constitute Ringdansen. Each block has an inner and outer circle of buildings which are of varying heights (2 to 8-storeys).

The blocks were constructed between 1970 and 1972 and belong to Hyresbostäder i Norrköping AB, a municipally owned housing company. In 1994, the municipality started a development programme to renovate the area. The Ringdansen project began in 1997 with the aim to create an ecologically sustainable residential area with low household consumption of energy and various recycling plans, including rainwater. A computer model was developed to explore the water saving potential of the rainwater collection scheme. This was evaluated in terms of its water saving efficiency (WSE), which is a measure of how much potable water has been saved in comparison to the overall demand.



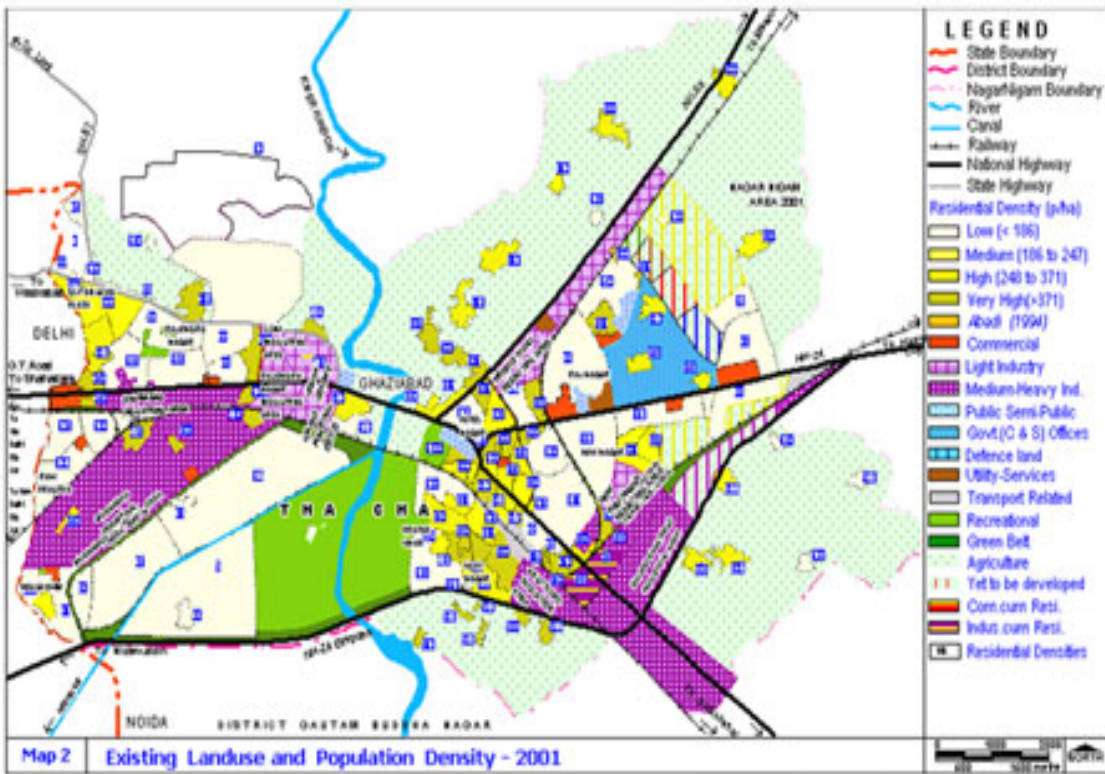
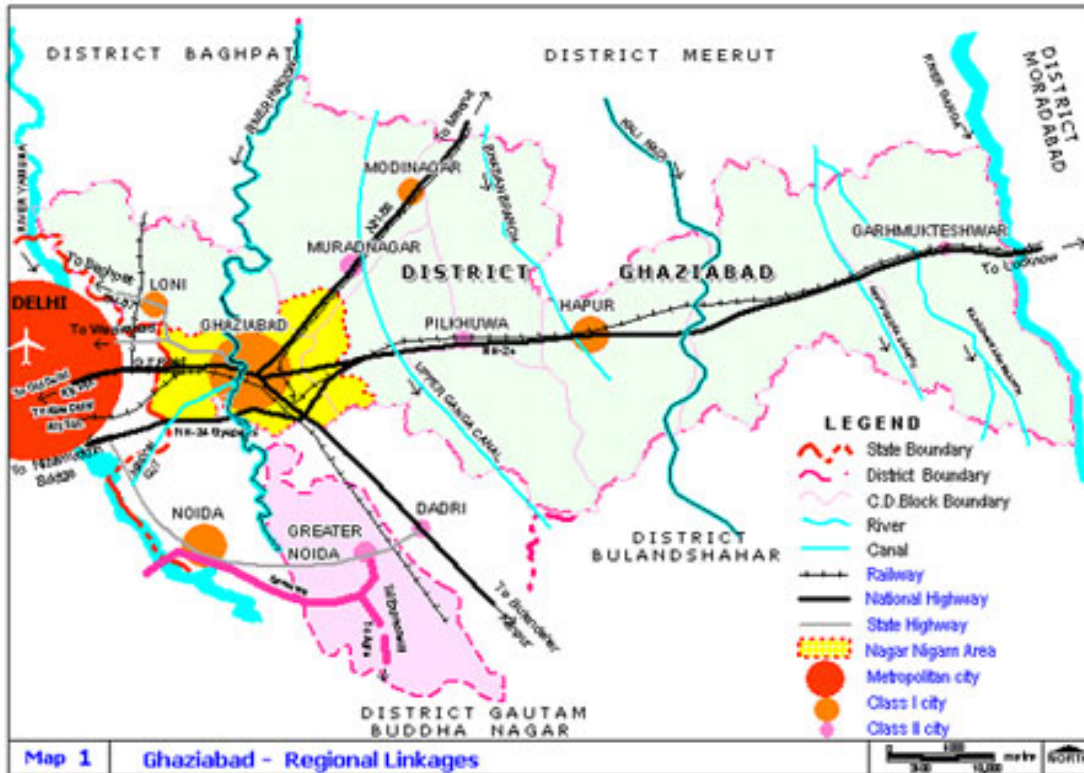
Significant water saving efficiencies at Ringdansen are possible if rainwater tanks are included as part of a dual water supply solution, especially if low water consumption appliances are installed. Assuming that the whole roof area at Ringdansen is used to collect rainwater and rainwater is used only for toilet flushing, a 40m<sup>3</sup> tank would give a saving of more than 60% of the main water supply. For a low flush washing machine, a 40m<sup>3</sup> rainwater tank can save almost 40% of the water demand. The same tank capacity would result in a 30% saving if both toilets and laundries are supplied with rainwater. For each ring, it is estimated that an 80m<sup>3</sup> rainwater tank with a collection area of 20,000m<sup>2</sup> would supply almost 60% of the water needed for irrigation of the central area during the summer months. Preliminary results reveal that if half the households have a car, about 60% of the water demand for car washing can be met using water from a dedicated rainwater system of 20m<sup>3</sup> with a collection area of 20,000m<sup>2</sup>. This assumes 50 litres per wash and that each car is washed once a month. Results from the irrigation scenario show that about 60% of the water needed for irrigation during the summer months could be supplied with an 80m<sup>3</sup> tank and a collection area of 20,000m<sup>2</sup>. In general, it was found that for a certain roof area/storage combination the highest WSE is reached for the smallest population density, while those for the default and large population densities are practically the same. It was also found that WSE at Ringdansen is little affected by increases in effective surface area for all the storage capacities. Significant water savings can be made with a 20m<sup>3</sup> rainwater tank and a collection area of 20,000m<sup>2</sup> if low flush-volumes appliances are installed. If, for example, only a small portion of the whole

roof area is available for collecting rainwater and local conditions only allow the installation of the small rainwater tank, almost half of the drinking water used for flushing toilets and at least one fifth of the water used for laundry can be saved on an annual basis. If existing toilets and washing machines are retained at Ringdansen (standard appliances), about one third of the water needed for flushing toilets can be provided by rainwater, but only if a 90m<sup>3</sup> rainwater tank is installed. The sensitivity of the model output to changes in individual parameters has been determined for four main scenarios of rainwater use: only for toilet flushing, only for laundry, a combination of toilet and laundry, and for irrigation. In addition, preliminary results were obtained for car washing. For each scenario, several combinations of collection area and storage capacity were modeled. A virtual Ringdansen population was built-up from a number of different occupancy scenarios (one to five people for each flat) relating to three different population densities: default, small and large.

## **Case Study 2: Urban Water Supply: Ghaziabad City, India**

National Capital Region (NCR), a unique region, is the fastest growing region. It has the best economic base for growth of industries and new economy as well (software, Export Promotion Zone (EPZ) and Special Economic Zones (SEZ)). Within NCR, Ghaziabad is one of the fast developing Delhi metropolitan area city. Ghaziabad district, carved out of Meerut district in 1976, had Ghaziabad as class I city. During partition of India, it was a class III town. With onset of industrialization of the surrounding areas, it became class II town in 1961 and with growth rate of 82.10% in 1961-1971, it acquired the status of class I city in 1971. After Kanpur, Ghaziabad is the biggest industrial city in Uttar Pradesh (U.P.) state. The city has grown at very fast pace during the last three decades to emerge as a Metro and strengthen its economic base. The city has one of the best road and rail connections among cities in U.P. State (Map 1).

The urban development of the city has been achieved through Master Plan 1981 and Master Plan 2001 from a population base of 70000 (1961) to 2.72 (1981) lakh and 9.68 lakh (2001), an emerging metro as per census (Map 2). River Hindon flows through the city dividing it into east of Hindon (Cis Hindon Area i.e. CHA) and west of Hindon (Trans Hindon Area i.e. THA). CHA constitutes 2/3rd in area and population while THA constitutes 1/3rd area and population. The proportion of the slum population to total population is one third.



The status of Ghaziabad was upgraded from Municipal Board to Municipal Corporation, known as Ghaziabad Nagar Nigam (GNN) on 31 August 1994 following 74th Constitution Amendment Act 1992 and conformity legislation by state government. GNN area has been divided into four administrative zones namely City zone, Kavi Nagar Zone, Vijay Nagar Zone and THA Zone. The area is further divided into 60 wards.

The economy of the town has been bi-functional – industries-cum-services since 1971. The industrial development of the city is visible on both sides of Hindon River. Chemical and allied distillery (33%) dominates its industrial scene. It is also an important centre for trade and commerce in western U.P. sub-region. The workforce participation ratio and percentage workers in secondary sector are marginally declining but the size of work force in the city has maintained its increasing trend.

### **Water Supply System**

Hydro-geologically, U.P. sub-region of NCR, comprising of Ghaziabad, Meerut and Bulandshahr districts, is a part of vast central Ganga plain, a monotonous stretch of a low relief plain. Ghaziabad district is very fertile and it lies in the doab of Ganga and Yamuna rivers. The district is bestowed with shallow and deep aquifers and the city has been exploiting the ground water source since last four decades. Apart from utilizing ground water for providing water through hand pumps in rural and unauthorized areas, ground water has been utilized for piped water supply since 1955, when piped water supply scheme was introduced.

The water supply facility, in developments carried out by Nagar Palika and thereafter Ghaziabad Improvement Trust, was on colony basis. From 1977, onwards Ghaziabad Development Authority started developing the Master Plan sectors and with U.P.Jal Nigam services, water supply facility continued to be provided on sector basis without any water supply master plan. To prepare the status and pre-feasibility report of water supply in Ghaziabad city, U.P.Jal Nigam, in 1995, delineated the water supply zones for equitable, economical and efficient distribution of water. Ghaziabad city, under the jurisdiction of GNN and Development Authority has been divided into CHA having 23 Master Plan sectors which are reorganized into 19 water supply zones (WS Zns) and 10 Master Plan sectors of THA reorganized into 10 water supply zones. Residential areas of the Railways, Central Government and Police Department are considered in separate water supply zones having their own independent water supply system (Map 3).



## CONCLUSION

Urban water systems must include not only the reservoirs, groundwater wells and aqueducts that are the sources of water supplies needed to meet the varied demands in an urban area, but also the water treatment plants, the water distribution systems that transport that water, together with the pressures required, to where the demands are located. Once used, the now wastewater needs to be collected and transported to where it can be treated and discharged back into the environment. Underlying all of this hydraulic infrastructure and plumbing is the urban storm water drainage system.

Well-designed and operated urban water systems are critically important for maintaining public health as well as for controlling the quality of the waters into which urban runoff are discharged. In most urban areas in developed regions, government regulations require designers and operators of urban water systems to meet three sets of standards. Pressures must be adequate for fire protection, water quality must be adequate to protect public health, and urban drainage of waste and storm waters must meet effluent and receiving water body quality standards. This requires monitoring as well as the use of various models for detecting leaks and predicting the impacts of alternative urban water treatment and distribution, collection system designs and operating, maintenance and repair policies.

Modeling the water and wastewater flows, pressure heads and quality in urban water conveyance, treatment, and distribution and collection systems is a challenging exercise, not only because of its hydraulic complexity, but also because of the stochastic inputs to and demands on the system. This chapter has attempted to provide an overview of some of the basic considerations used by modellers who develop computer-based optimization and simulation models for design and/or operation of parts of such systems. These same considerations should be in the minds of those who use such models as well.

## REFERENCE:

CHAUDRY, M.H. and ISLAM, M.R. 1995. Water quality modeling in pipe networks.

In: E. Cabrera and A.F. Vela (eds.), Improving efficiency and reliability in water distribution systems.

GRAYMAN, W.M.; CLARK, R.M. and MALES, R.M. 1988. Modeling distribution system water quality: dynamic approach. Journal of Water Resources Planning and Management, ASCE, Vol. 114, No. 3,

ISLAM, M.R. and CHAUDRY, M.H. 1998. Modeling of constituent transport in unsteady flows in pipe networks. Journal of Hydraulic Engineering, ASCE, Vol. 124

Lexington, Ky., University of Kentucky. MALES, R.N.; CLARK, R.M.; WEHRMAN, P.J. and GATES, W.E. 1985. Algorithms for mixing problems in water systems. Journal of Hydraulics Engineering, ASCE, Vol. 111, No. 2,

ORMSBEE, L.E. 1989. Implicit network calibration. Journal of Water Resources Planning and Management, ASCE, Vol. 115, No. 2,

ROSSMAN, L.A.; BOULOS, P.F. and ALTMAN, T. 1993. Discrete volume-element method for network water quality models. Journal of Water Resources Planning and Management, ASCE, Vol. 119, No. 5,

ROSSMAN, L.A.; CLARK, R.M. and GRAYMAN, W.M. 1994. Modeling chlorine residuals in drinking-water distribution systems. Journal of Environmental Engineering, ASCE, Vol. 120, No.

SHAMIR, U. and HOWARD, C.D.D. 1968. Water distribution systems analysis. Journal of the Hydraulic Division, ASCE, Vol. 94, No. 1,

TANG, K.; KARNEY, B.; PENDLEBURY, M. and ZHANG, F. 1999. Inverse transient calibration of water distribution systems using genetic algorithms. In: D.A. Savic and G.A. Walters (eds.), Proceedings of water industry systems: modelling and optimization applications, Baldock, UK, Research Studies Press. Vol. 1, .

TODINI, E. 1999. Using a Kalman filter approach for looped water distribution network calibration In:

VIESSMAN, W. Jr. and WELTY, C. 1985. Water management technology and institutions. New York, Harper and Rowould, J.E. 1992. Rainwater Catchment Systems for Household Water Supply, Environmental Sanitation Reviews, No. 32, ENSIC, Asian Institute of Technology, Bangkok.

Gould, J.E. and H.J. McPherson 1987. Bacteriological Quality of Rainwater in Roof and Groundwater Catchment Systems in Botswana, *Water International*, 12:135-138.

Nissen-Petersen, E. (1982). *Rain Catchment and Water Supply in Rural Africa: A Manual*. Hodder and Stoughton, Ltd., London.

Pacey, A. and A. Cullis 1989. *Rainwater Harvesting: The Collection of Rainfall and Runoff in Rural Areas*, WBC Print Ltd., London.

Schiller, E.J. and B. G. Latham 1987. A Comparison of Commonly Used Hydrologic Design Methods for Rainwater Collectors, *Water Resources Development*, 3.

Wall, B.H. and R.L. McCown 1989. *Designing Roof Catchment Water Supply Systems Using Water Budgeting Methods*, *Water Resources Development*,