018530 - SWITCH

Sustainable Water Management in the City of the Future

Integrated Project

Global Change and Ecosystems

Deliverable D 1.2.8 (WP 1.2)
PhD Thesis Dissertation
Agent Based Models for integrated urban water management.

Due date of deliverable: M60

Actual submission date: M60

Start date of project: 1 February 2006

Duration: 60 months

Revision [Final]

MAIN AUTHOR: Eng. M.Sc. Arlex Sanchez Torres

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission	
CO	Confidential, only for members of the consortium (including the Commission Services)	

SWITCH Deliverable Briefing Note Template

SWITCH Document **Deliverable D1.2.8 PhD Dissertation** **Agent Based models for integrated urban water management**
Audience The document was prepared for an audience both inside and outside the SWITCH consortium. For consortium members it gives an overview on how the agent based and cellular automata technology has been applied to model urban development and growth. It also highlights the potential to use this simulation technique to be integrated with traditional engineering design tools to asses' future scenarios of growth in urban areas. External audience consists of mainly academic fellows that are currently working on similar subjects.
Purpose The purpose of the document is to review the progress in the implementation of the agent-based simulation concepts into urban water management and modeling framework.
Background This document contributes to the SWITCH approach proposed during the project. The document is a step towards the development of a set tools to asses city's future scenarios of development.
Potential Impact The document presents the results of the on-going research work that aim to contribute to the development of a new integrated approach for urban water infrastructure planning which help water companies and municipalities to have a dynamic planning tool to improve the effectiveness of their investments and to be more environmentally efficient and contribute to the sustainability of the systems.
Issues Not applicable
Recommendations The document consists of the PhD Research Proposal, the list of papers published in international conferences and the summary of the activities towards the finalization of the PhD thesis.

Table of Content

	Pag
1. PhD Research Proposal	**5**
2. List of Conference Papers	**63**
3. Planning for finalization of thesis	**64**

Annex

PAPER 1: OPTIMISING SEWER SYSTEM REHABILITATION STRATEGIES BETWEEN FLOODING, OVERFLOW EMISSIONS AND INVESTMENT COSTS

PAPER 2:PLANNING URBAN WATER SYSTEMS: MODELING USING CELLULAR AUTOMATA AND NUMERICAL MODELS

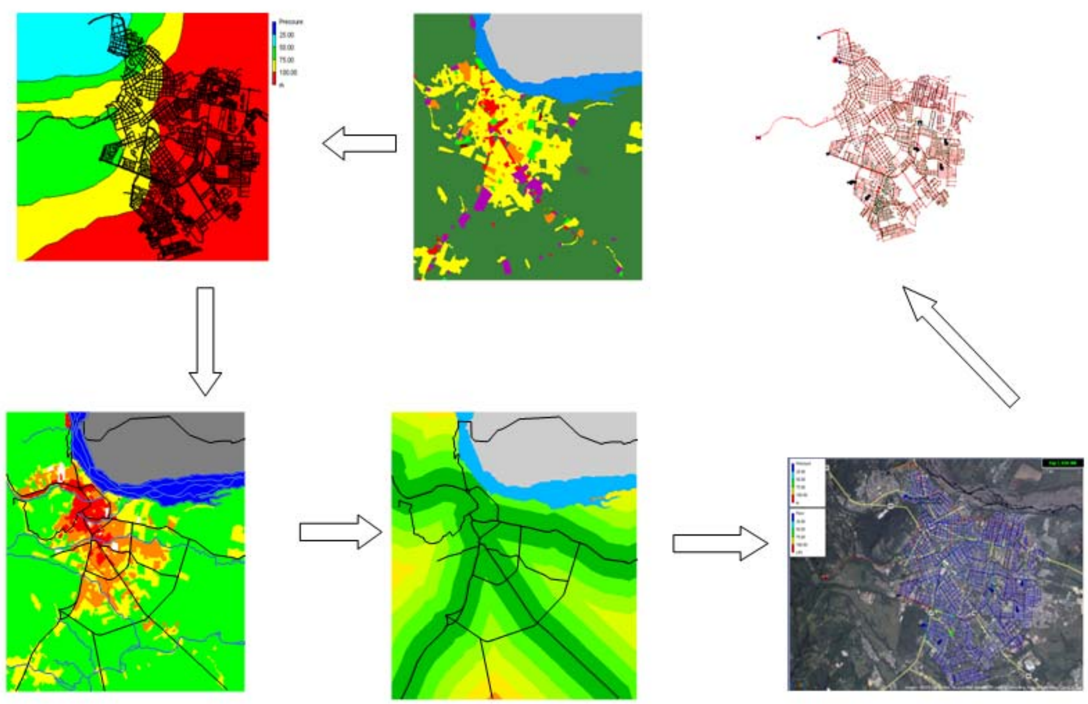
PAPER 3: TOWARDS AN APPROACH TO THE EVOLUTION OF URBAN DRAINAGE NETWORKS USING AGENT-BASED MODELS.

PAPER 4: SUBMITTED ABSTRACT: DETERMINING THE ROUTE FOR A WATER MAIN IN A NEW URBANISING AREA.

The use of Agent-Based Models for integrated urban water management

PhD Research Proposal

Arlex Sanchez Torres



Delft – The Netherlands

January– 2011

The use of Agent-Based Models for integrated urban water management

PhD Research Proposal

Arlex Sanchez Torres

Promotor:	**Prof. Dr. Arthur E. Mynett**
Co-Promotor	**Dr. Zoran Vojinovic**
Supervisor:	**Prof. Dr. Roland Price**

Delft – The Netherlands

January– 2011

Abstract

Cities and urban areas around the world are currently facing considerable pressure to cope with urban development and economic growth. On the one hand urban infrastructure is aging and there is a rapid growth of population while economic resources are in short supply. Under such circumstances urban planning is very important to improve the effectiveness of the investments and interventions that take place in the urban system.

It is acknowledged that the interaction between the different subsystems that make up the city is complex. Often the relationship between one system and another is not obvious. Also the result of certain actions in one part of the system can produce unforseen consequences in another part of the system or even in a different sub-system, and the relationships between these are not yet well described and understood. This is one of the main arguments for the integration of tools that can help our understanding of the complex phenomena of urban dynamics.

Cities are considered as complex systems taking into account their characteristics of emergence, self-similarity, self-organization and non-linear behavior of land use changes. In the world, large scale patterns are usually the result of the interactions of large numbers of smaller pieces that somehow are combined in surprising ways to create the large-scale pattern. The use of tools that can help in the understanding of the above–mentioned characteristics are important to gain knowledge about the patterns and mechanisms behind urban dynamics. Agent based models are interesting to be explored for the characteristics that offer the technique such as the representation of the environment (can be done in two or three dimensions), the integration with GIS and temporal – space variables and the interaction between agents and the environment.

The work proposed here considers the integration agent-based concepts with physically based hydraulic models of the networks to determine the water infrastructure and performance in delivering adequate water services in the future and how this can shape the urban development process. The objective is to design the water systems (water distribution and dranage network) in the urbanising areas of a city based on the characteristics of the existing networks, and to rehabilitate the system so that it is sustainable. New tools will be developing to test this new approach to derive the future networks layout. The expected result is a new approach for urban water infrastructure planning which help water companies and municipalities to have a dynamic planning tool to improve the effectiveness of their investments and to be more environmentally efficient.

Table of Contents

1. Introduction 9
2. Background 11
2.1 The Urban challenge 11
2.2 Urban water systems 12
2.2.1 Issues related to urban water systems and urbanization 12
• Climate change 14
• Deterioration of infrastructure systems 15
2.3 Integrated urban water management 15
2.4 Integrated and strategic planning 17
2.5 Models and integrated urban water modeling 18
3. Agent based models 24
3.1 Cellular Automaton 25
3.2 Elements of AB and CA Models 26
4. Agent based models for water management 28
4.1 Agent-Based Models for Water demand and supply management 30
4.1.1 The Firma Thames Case 30
4.1.2 The FIRMABAR Case 31
4.2 Agent Based Models for Urban and Peri-Urban Water Management 32
4.2.1 The Sao Paulo Model 33
4.2.2 WULUM 34
4.2.3 Tijuana's Border Town Model 35
4.2.4 The Cities Model 36
4.2.5 The SLEUTH model 38
4.2.6 Moland Model 39
4.2.7 The MedAction PSS model 40

4.3 Discussion 41
5. Problem Definition 43
6. Objectives 44
7. Methodology 45
7.1 Illustrative Example 48
8. Organization 51
8.1 research committee 51
8.2 Planning 51
8.3 Budget 53
9. References 54

1. Introduction

Traditionally urban planning and development have been based on the formulation and execution of master plans for a fixed period of time. These plans normally include projections of population growth, demand for future services, land use changes, etc. Master plans normally end up on the bookshelf; they are increasingly ineffective as very often these plans are not fulfilled. As a result the goals are lost, and some areas and sectors inside the cities are developed without any control. This is particularly interesting in urban areas in developing countries for several reasons including unexpected events such as migration, natural disasters, economic factors, etc.

Cities can be considered as complex systems based on their characteristics of emergence, self-similarity, self-organization and non-linear behaviour of land use changes with time; see Batty and Langley, (1994). The use of tools that can help in understanding these characteristics are important to gain knowledge about the patterns and mechanisms behind urban dynamics. Agent-based models are built and used to represent the same phenomena or characteristics in several disciplines of sciences. For modeling land use changes and urban planning, some interesting aspects used in this technique are the representation of the environment which can be done in two or three dimensions, the integration with GIS and temporal – space variables, and the interaction between the agents and the agents with the surrounding environment.

Integrated urban water management is a challenging issue that aims at the sustainable use of the water resources so that the demands can be met now and in the future in terms of quality and quantity. The current practices in the sector are leading towards a crisis that is calling for innovative thinking and the adoption of new strategies including integrated thinking and planning. This sounds nice, but the truth in many situations is that the institutional arrangements are so rigid and fragmented that this is not possible. There is also a need to develop tools that allow such integration. The idea of this work is to contribute to such tools; that can help planners and decision-makers at the city level to understand the main drivers affecting the urban water cycle, to analyze future scenarios of city expansion and foresee bottlenecks and possible solutions. The tool can be used for rehabilitation, testing and planning strategies.

This document is a proposal to develop a new approach to model urban growth and future infrastructure development. The approach will be tested with a prototype of a spatial decision support system for integrated urban water management making use of agent-based modeling techniques that allow for the evaluation of future scenarios and different policy strategies. The proposed system will enable engineers and urban planners to understand the processes driving the urbanization, to evaluate the importance of water related services in the process of city expansion, and to test rehabilitation strategies according to future scenarios of development. It will make use of geographic information systems, agent-based modeling techniques, numerical models to evaluate the performance of the water systems and optimization techniques. The results will be presented in form of maps and indicators.

This proposal is structured in the following manner: chapters 2, 3 and 4 present the main literature review of the themes and experiences that are related to this research, such as: the urban water cycle and integrated urban water management, agent-based modeling techniques and agent based models for water management. Chapter 5 presents the research problem and ways to approach it. Chapter 6 presents the objectives of the research. Chapter 7 presents the methodology and approach to undertake the research. Finally chapter 8 describes the organization of the work, the time frame and the budget.

2. Background

2.1 The Urban challenge

The urban population of the world is growing and it is expected that by 2007 the world's population will be predominantly urban for the first time in human history. UN projections suggest that over the next 30 years, virtually all of the world's population growth will occur in the urban areas of low- and middle-income countries mainly in the South (Garau et all, 2005).

The informal city is one of the outcomes of the urbanization process. Although in developing countries urbanization is associated with increases in a nation's wealth, it is also associated with increases in squatters and slums which lack the minimum living conditions. In many cases the informal city or city dwellers are considered illegal settlements and as such are not recognized by governments. Therefore, the provision of basic services to informal settlements is poor; it usually does not include suitable –or indeed any- provision for services such as water supply, sanitation, garbage disposal, roads, storm water drainage, electricity, public transport, schools and health centers.

Huge investments are needed to improve the situation of many urban areas around the world whilst at the same time ensuring environmental sustainabilit. With increasing population and the uncertainties of climate change in mind, many cities are already planning or executing public works to upgrade the provision of basic services and maintain the levels of service.

The biggest capital investment and expenditure in a municipality is maintaining and upgrading their water-related networks. Due to the high amount of resources and planning needed, this is an investment and an intervention you may want to do once in a certain number of years, and needs to be well planned and executed.

The main challenges that cities are facing now and in the near future are the following:

1. Population growth and urbanization
2. Climate change
3. Deterioration of infrastructure systems
4. Governance and policies
5. New technologies
6. Energy costs

2.2 Urban water systems

An urban water system consists of several components and structures that deal with collection, storage and transportation of water within the cities. The main components are *the natural system* or water bodies, which can be rivers, lakes, wetlands, aquifers, the ocean, etc. The natural freshwater system is the source for the drinking water supply system and possible together with the ocean is also the final recipient for all the discharges of water that have been used within the urban environment.

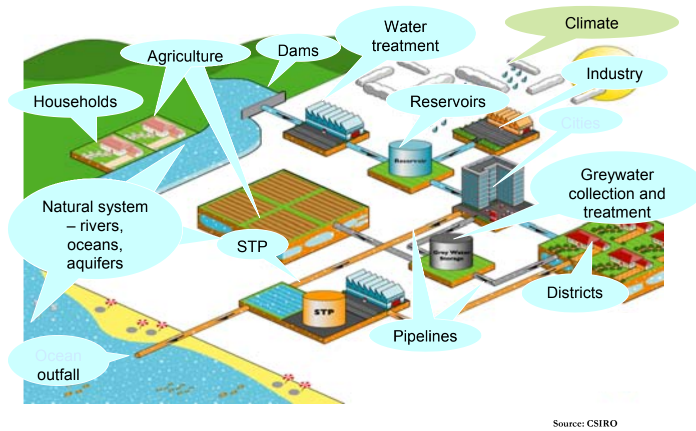


Figure 1. Urban water system

These discharges consist of mainly wastewater from households, industry, commerce and all other users, and the storm-water systems to collect, store and transport the rainfall in the urban areas and prevent flooding. The water quality of all these discharges can affect negatively the recipient water body ecosystem, depending on the concentration of pollutants contained in the water. This also depends on the level of treatment applied to the liquid waste.

All freshwater bodies can assimilate some degradable wastes, which are stabilized by natural self-purification processes. The problems arise when the discharge loads exceed the self-purification capacity of the receiving water body, thus harming aquatic life and restricting the uses of water for several activities (water supply, recreation, irrigation, etc) (Price, 2004).

The water distribution system consists of the catchment where the source of water is located, the source itself (river, aquifer, lake, etc), the water treatment plant, storage tanks, pumping stations, pipes, valves, etc. The water demand depends on living standards, weather, habits, culture, etc.

The drainage and sanitation system of urban areas includes the generation and transport of solid waste, excreta and grey water, and storm water drainage. In general the production of waste depends mainly on standards of living, population densities, habits and the characteristics of the water supply services. Storm water depends on climate, meteorology and geology. Urban drainage is a vital component of urban infrastructure and requires huge investment for planning, design, construction, operation and maintenance throughout the design period. Safe and efficient drainage systems are important to maintain public health and safety, due to the potential impact of flooding on life and property and to protect the receiving water environment. (Vojinovic, 2005).

2.2.1 Issues related to urban water systems and urbanization

The development of any urban area within a catchment generates several impacts on the environment and the natural water cycle such as:

- *Growing demand for water*

An unprecedented growth of the urban population is a major driver for urban water management, especially in the developing world. Growth rates of up to 4% per year face cities in developing countries with almost impossible challenges. Planning the city's expansion, providing shelter, energy, water, food, sanitation, health, etc is needed every year for large numbers of people that are the equivalent of the population of large towns. Increased urban water demand may lead to large infrastructural works to transport water over longer and longer distances.

- *Generation of wastewater*

The amount of water that is supplied to the households and other users within the city is converted into wastewater. The more water is supplied, the larger the wastewater flows. The characteristics of the pollution, both in terms of load and quality, depends on the uses, e.g. the (type of) industry, irrigation, domestic, commercial. Within the city, wastewater is transported away from houses and buildings via pipe networks to minimize human contact with excreta and pathogens. There are hundreds of substances and toxins that are dumped into sewers during normal operation. The wastewater treatment plants are used to reduce the load of pollutants that are finally discharged to the receiving water body and ecosystem.

- *Alteration of the natural hydrodynamic pattern in the water sources, depletion of groundwater levels.*

By extracting water, the normal dynamics of water flow in the ecosystem nearby the city area is affected, including the water table in the aquifer beneath the city. Quite often the rivers and aquifers are polluted by the wastewater affecting downstream users. Groundwater table lowering due to over abstraction is already a reality in many cities.

- *Increase in impervious and hard surfaces: changing the runoff velocity and collection of dust and solid waste.*

These include the pavement of roads and streets, rooftops, etc. Such impervious surfaces cut off the amount of water that infiltrates. This has a direct effect on the recharge of aquifers and affects base flows in the streams. The increase of hard surfaces increases the surface runoff, and peak flows are larger and water moves faster over these surfaces; therefore the peak arrives earlier and the magnitude of urban floods is increased.

The impervious areas collect and accumulate dust, all kinds of solids and wastes, pollutants such as those leaked from vehicles, and particles from tires etc. All these substances and particles get diluted and washed off during rainfall, creating a flush flood (like a toilet) that literally washes the streets generating potentially a highly polluted discharge to the receiving water bodies. This urban runoff from storm water is rarely treated and recognized as a problem in developing countries. Sweeping and street cleaning is a major factor to help limit pollution from urban runoff, as well as safe disposal of batteries and containers of toxics and chemical

substances such as oil, liquids for car cleaning and maintenance; and insecticides and pesticides commonly used at home and for gardening.

- *Impact on the receiving water bodies.*

The effect of wastewater discharges from urban areas into a receiving water body is difficult to quantify and regulate because of their intermittent and varied nature. Although the immediate impact can be measured while a big spill event is happening, the long term effects are often difficult to isolate from other sources of pollution. Drainage discharges that affect water quality come from domestic discharges and normal sanitary sewer transport, industrial discharges, urban wash-off transporting all kind of components and solids (here there is a direct link with solid waste services and cleaning), etc.

The effects on water quality can be classified in four groups (Price 2004):

- Discharges with high concentration of substance that consume oxygen, either organic such as faecal matter or inorganic (heated discharges reduce the saturated concentration of dissolved oxygen; this effect has been reported in some urban was-off discharges especially in tropical storms happening in summer when the paved areas are hot);
- Discharges that contain substances that inhibit re-oxygenation at the water surface, such as oils;
- Discharges containing toxic compounds, including ammonia, pesticides, heavy metals, and some industrial effluents;
- Discharges with high concentration of suspended solids which inhibit biological activity by blocking sunlight or by blanketing the riverbed.

Urban storm water runoff always contains various pollutants. Depending on the pollutant's characteristics, different types of damage can result to either aquatic life or people. Many of these pollutant loadings are watershed specific, and vary as the watershed characteristics changes (i.e. street cleaning frequency, traffic load, etc.). The accuracy of drainage water quality modeling is highly dependent on the availability of local monitoring data and the effectiveness in transferring literature values for parameters to a local area (Zhang et al, 2006, Ahlman, 2006). Very often the collection of data on pollutant urban runoff are not included in water quality monitoring campaigns, and data on pollutant buildup on catchments surfaces are extremely lacking in the tropics (Rahmat et al, 2006).

- *Climate change*

Climate change is becoming a critical issue everywhere in the world, and it poses a challenge to humanity to better use the scarce resources that are still available. Some places need to plan and be prepared to re-use water and deal with droughts, and others need to be prepared for flooding and excess. In general, there is a need to use water wisely and to be more efficient. The combination of social growth and urban drainage services provision poses a challenge of optimization. Climate change is an important driver that affects the pressure on the state of the urban water system. Changes in precipitation patterns towards more intense storms lead to an

increased risk of flooding. Cities located in urbanized river basins may need to compete with agriculture for water allocations during dry periods.

- *Deterioration of infrastructure systems*

In those cities where a major water infrastructure was put in place during the previous century, urban water managers will increasingly be confronted with deterioration of infrastructure, especially pipe networks. In many parts of Europe, pipes are over 100 years old and the cost of rehabilitation of water infrastructure system is increasing substantially. European cities are spending the order of 5-billion Euros per year for wastewater network rehabilitation (Vahala, 2004). The amount spent on asset rehabilitation programmes will further increase over the coming decades due to the synergetic effects of infrastructure ageing, urbanization and climate change. Infrastructure deterioration will impact on public health, the environment, and institutions in various ways. Higher rates of water leakage mean higher water losses and higher chances of in-filtration and ex-filtration of water. This will create higher chances of drinking water contamination and the outbreak of water-borne disease.

Although the effects of urbanization can be severe, there are several options that can help us to minimize these impacts. Here is where we have the opportunity for change and innovative ideas. For example source control: minimizing the use of water (quantity) by being more efficient (on site sanitation, dry toilets and urinals), good cleaning services (solid waste disposals) and recognizing the importance and the links with water, re-use of treated wastewater, storm water management, storage, infiltration, retention, interception and use of rainwater, etc.

2.3 Integrated urban water management

Traditionally the components of the urban water cycle such as water supply, wastewater transportation and treatment, stormwater collection and disposal, have been considered separately for their operation and institutional management. This approach has lead to an ineffective planning and delivery of the water related services with limited reference to one and other. This has caused an increasing impact on the surrounding environment and water bodies, with the subsequent socio-economic and ecological conflicts. Integrated Urban Water Management (IUWM) on the other hand is an emerging concept that refers to the process of managing freshwater bodies, water supply, wastewater and stormwater as links within the same resources management structure, considering the urban areas as the unit of analysis.

The IUWM approach has emerged from the recognition that an integrated approach in the urban water management offers good opportunities for decision making and concrete action. Besides that, it offers a framework to recognize and analyze the effects downstream or upstream of certain actions in other components of the water system (Mitchell, 2004). The main principles for IUWM are summarized as follows:

1. Consider all parts of the water cycle, natural and constructed, surface and sub-surface, recognizing them as an integrated system

2. Consider all requirements for water, both anthropogenic and ecological

3. Consider the local context, accounting for environmental, social, cultural and economic perspectives

4. Include all stakeholders in the process

5. Strive for sustainability, balancing environmental, social and economic needs in the short, medium and long term

In line with the principles described above there are a broad of tools and practices that are employed to make IUWM a reality. Some of them are: water conservation and efficiency; water sensitive planning and design, including urban layout and landscaping; utilization of non-conventional water sources including roof runoff, stormwater, greywater and wastewater; the application of fit-for-purpose principles; stormwater and wastewater source control and pollution prevention; stormwater flow and quality management; the use of mixtures of soft (ecological) and hard (infrastructure) technologies; and non-structural tools such as education, pricing incentives, regulations and restriction regimes (Mitchell, 2004).

There are many experiences around the world showing adverse economic, social and environmental impacts associated with the traditional approach to water service provision, including aspects such as: reduction of environmental flows affecting aquatics habitats and natural ecosystems, increased waste disposal in natural environments, inadequate handling of contaminants and nutrients, high rates of usage of chemicals (chlorine) and energy, high cost of rehabilitation measures and replacement of ageing water related infrastructure.

Wastewater discharge standards are also becoming increasingly stringent due to environmental and public health protection requirements, while stormwater management has moved beyond purely a flood protection issue to encompass both quality and quantity management during wet and dry periods. Concerns about the consequences of the traditional water servicing approach have led to what is often referred to as a paradigm shift in the urban water industry. Table 1 describes the main characteristics of the “old” versus the “new” paradigm in water services.

Table 1. Characteristics of “old” and “new” paradigms of urban water systems

Old Paradigm	New Paradigm
Human waste is a nuisance. It should be disposed after treatment.	Human waste is a resource. It should be captured and processed effectively.
Stormwater is a nuisance. Convey stormwater away from urban area as rapidly as possible.	Stormwater is a resource. Harvest stormwater as a water supply, and infiltrate or retain it to support aquifers, waterways and vegetation.
Demand is a matter of quantity. Treat all supply side water to potable quality, and collect all wastewater for treatment.	Demand is multi-faceted. Infrastructure choice should match the varying characteristics of water required or produced for different end-users in terms of quantity, quality, level of reliability, etc.
Water follows one-way path from supply, to a single use, to treatment and disposal to the environment.	Reuse and reclamation. Water can be used multiple times, by cascading from higher to lower quality needs.
Gray infrastructure. Infrastructure is made of concrete, metal or plastic.	Green infrastructure. Infrastructure includes not only pipes and treatment plants, made of concrete, metal and plastic, but also soils and vegetation.
Bigger/centralised is better for collection system and treatment plants.	Small/decentralised is possible, often desirable for collection system and treatment plants.
Limit complexity and employ standard solutions. Small number of technologies by urban water professionals defines water infrastructure.	Allow diverse solutions. Decision makers are multidisciplinary. Allow new management strategies and technologies.
Integration by accident. Water supply, wastewater and stormwater may be managed by the same agency Physically, however, three systems are separated.	Physical and institutional integration by design. Linkages must be made between water supply, wastewater and stormwater, which requires highly coordinated management.
Collaboration=public relations. Approach other agencies and public when approval or pre-chosen solution is required.	Collaboration=engagement. Enlist other agencies and public in search for effective solutions.

2.4 Integrated and strategic planning

The urban challenge dictates a much broader and more ambitious approach than the reduction of poverty and environmental sustainability. It also calls for improved urban planning and design, and the provision of adequate alternatives, innovative thinking and decision making, which respond to the informal urban context. To achieve the combined goals of improved efficiency and effectiveness, there is a need to perform integrated analyses. Computer models are generally accepted tools in such optimization processes.

Normally, strategic plans for the urban water system need to take a long term perspective (15-40 years) because the life cycle of part of the infrastructure is 40 years or longer and because the changes and pressures also develop over this period of time. Some changes occur gradually, but some other changes may have the character of step-changes. The plan needs to

take into account the uncertainty around the changes, and therefore needs to be build on a flexible strategy, using technologies and methods that are flexible and that can be applied under different future scenarios.

Projecting and simulating the land use changes in space and time is crucial for the understanding and assessment of consequent environmental impacts. The simulation of human-influenced landscapes changes following different scenarios is helpful to reveal strategy policies that can be modified to improve environmental issues in the future.

2.5 Models and integrated urban water modeling

A model is a representation or abstraction of the world we observed. In general terms models can be considered as a device or mechanism that represents a theory that generates information (outputs) from a set of inputs and assumptions. The output of the model helps in the understanding and the adequacy of the theory embedded in the model. In the real world almost every system is complex, and this complexity and dynamics make them hard to understand and analyze. Therefore, it is a common practice to explore those systems using simplified representations, symbols, laws, rules and processes. In this way systems can be explained, analyzed and managed.

The application of models in scientific research fields is very important. Not only do they provide a framework to express and formulate theories, they enable hypothesis and theories embedded in models to be tested and proved. Models play an important role in day to day engineering practice as tools to simulate and predict the behavior of many systems (transport networks, drainage and water distribution networks, aircraft design, etc); also for social systems that are of concern for environmentalist, urban analyst, planners and decision makers. Due to scale, cost and practical reasons is very difficult to manipulate or experiment with full scale systems, therefore researchers construct models to represent the real situation that allow them to explore, understand and predict the behavior of the systems. So, models provide an artificial environment to carry out experiments that otherwise will not be possible. One of the main drivers to construct models is to answer “What if” type of questions to support planners and decision makers.

Models can be classified in different ways; in general there are three groups or categories: 1. Scale models where the reality has been altered by the scale, such as building models used by architects or coastal models to simulate hydraulics and sediment transport at laboratories. 2. Conceptual models which focus in the description of the relations between the different components of reality, for example the integrated urban water management cycle, which describes the links between the different uses and users of water in urban areas. 3. Mathematical models are in the highest level of abstraction, they describe reality by using mathematics, equation, physics laws, etc. For example the formulation of the fluid dynamics equations and methods to solve them are the basis of widely applied models.

Models applied for urban water management are mostly mathematical models. Traditionally, in the urban water sector every component of the water system is modeled individually; even more, the management and institutional arrangement is often fragmented as well. This fragmentation has caused a form of water crisis, since this arrangement makes it difficult for every group of modelers or practitioners to experiment or evaluate the effect of their actions and decision on the different components of the water system either upstream or downstream.

Urban water management needs to be understood as a highly integrated physical and social system. While a lot of effort has been put in understanding the physical part of the system (assets, pipes, etc), little has been done in understanding the social part. Cities are complex systems that are not at equilibrium; their dynamics is related to chaos theory, the principle of emergence and self-similarity as well as fractal geometry. Recently, there has been progress in the understanding of cities by applying agent based models and cellular automata for land use changes modeling (Engelen et al 2007, Batty et al, 1994, Barredo et al, 2003, van Delden, 2007).

The intention of this research is to combine the use of agent-based models or cellular automata for urban development, which has been successfully applied in several cities around Europe in the framework of the Moland project, with traditional urban water models, integrate them and evaluate the impact of the availability of water related services into urban development and the impact of urban development into the surrounding environment and the water related infrastructure. The expected result is a new approach for urban water infrastructure planning which helps water companies to be ahead with their investment plans and to have a say in the real urban planning exercises, and to stop being seeing as service providers only.

2.6 Urban development modeling

There are several approaches for urban development modeling. One of the first models that are described in the literature is Von Thunen model for agricultural allocation. Von Thunnen considered the inter-relation of three factors: the distance of the farmers to the market, the price received for the farmers for of their goods and the land rent cost. The hypothesis was that the intensity of land use was inversely proportional to the distance from the market or the transportation cost. Considering one city as the central market and a flat topography around it, the Von Thunnen model generates a concentric land use pattern with the less intensive land use farthest away from the city center.

With the development of the digital computer a new era in modeling started, due to the ability to handle complex mathematical formulations. The new computational capacity enabled the construction of several models mostly, transportation models, economic, land use allocation, etc. The developments of these models used a wide number of techniques like linear analysis, mathematical programming, simulations etc.

The development of geographical information systems (GIS) and the integration of GIS with urban models have enrich urban development modeling by providing more data sources and

new techniques to handle data and present outcomes. These developments have contributed to understand cities as evolutionary and complex systems.

2.6.1 Ecological approach

This approach is based on the belief that human behavior is determined by ecological principles, such as competition, selection, succession, and dominance. This was started at the Chicago School of Human Ecology in the 1920s, and the most notable models of this approach were Burgess's (1925) concentric zone model, Hoyt's (1939) sector model, and Harris and Ullman's (1945) multiple nuclei model (Liu, 2009).

Burgess's model of urban growth was based on the notion that various elements of a heterogeneous and economically complex urban society actively compete for favourable locations within the city.

Hoyt (1939) developed the sector model in which he identified that homogeneous areas of residence tended to grow outward from the centre toward the periphery in wedge-shaped sectors. In his sector model, in addition to the obvious emphasis on transportation routes where urban growth was often focused on, Hoyt also considered the effects of topographic variations and the adjacent and nearby land use on urban development.

In the Harris and Ullman (1945) model, the patterns of urban growth and change still followed the general ecological principles identified by Burgess. For example, some activities always tend to be located in the vicinity of each other, and others repel each other, whereas some cannot afford the high rents demanded for the best sites. However, this growth was not centered around one single central business district but on certain growing points or "nuclei."

2.6.2 Socio-physical approach

The social physical approach was based on the concept of human interaction in space. It uses an analogy to physics. That is, it uses Newton's Law of Gravitation as an analogue for social interaction between places. It proposed that the movement of human activities such as changes in residence and employment between places were directly proportional to the mass of the activity at the origin and destination, and inversely proportional to the cost (in terms of distance or time) separating them. The model developed from this analogy was referred to as the gravity model, which was widely applied in studies of migrations, settlement network, and the intra-urban structure in the 1960s.

Following the extensive applications of the gravity models in urban spatial interaction studies, Wilson (1970) developed the social physical approach by introducing the second law of thermodynamics—the maximum entropy law—into this approach. Based on the principles of the maximum entropy law, Wilson formulated his entropy-maximizing spatial interaction model. In this model, the movements of people and goods in cities were treated in the manner that particles in gases were treated in statistical mechanics using grand canonical ensembles and

distinguishing them by origin and destination as “types” and by origin–destination pairs as “states”.

In a typical gravity model, factors such as basic employment, economic structure, and population were usually distributed using particular allocation functions. Models developed under this approach were aggregates; they stressed group behavior rather than individual behaviour.

2.6.3 Neo-classical approach

The neoclassical approach was built on the belief that the process of urban development is essentially an economic phenomenon, being driven by market mechanisms and the natural forces of competition among economic activities and social groups in an urban area. According to the economic theory of equilibrium, the allocation of urban land to various users in both quantitative and locational aspects is controlled by supply-and-demand relationships obeying the general rule of least costs and maximum benefits (Liu, 2009).

2.6.4 Behavioral approach

The central concern of this framework was the behaviour patterns that were the representations of human actions. Urban development was viewed as an end result of human actions, and the value system of urban society as the primary source of the impulse for actions. The objective of this framework was to seek explanations of urban development in terms of human behaviour, with the behavior patterns being a function of people’s values. The fourth element of this framework, the control process, concerns how influence could alter or affect behavior patterns and thereby modify urban development toward certain predetermined goals. This element is often referred to as urban development strategies and plans. Under this framework, urban development was first viewed as the consequence of certain strategic decisions that structure the pattern of growth and development, and then as the consequence of the myriad of household, business and government decisions that followed from the first key decisions (Liu, 2009).

2.6.5 Systems approach

All the elements in the system are linked and interrelated and are also linked to the system’s environment. For instance, an urban system consists of a set of elements or subsystems, such as population, land, employment, services and transport, to mention a few. All elements within the system are interacting with each other through social, economic, and spatial mechanisms while they are also interacting with elements in the environment (Liu, 2009).

The significance of any one element does not depend on itself but on its relationships with others. It is the links between the different elements of the system that determine its evolution and so permit the process of change in the system. Thus, the focus of the systems approach is not on any single element but the connections and processes that link all the elements.

In order to illustrate the structure and behaviour of systems, a diverse range of mathematical methods has been employed. This includes factor analysis, principal component analysis, multicriteria analysis, linear and nonlinear programming, as well as dynamic systems simulation.

2.6.6 Cities as self organizing systems

Based on the understanding of the open system theory, the process of urban development is being looked at in new ways. A city can be viewed as an open and complex self-organising system that is far from being in equilibrium, and it exists in a constant exchange of goods and energy with other cities and its hinterland. The structure of this system emerges from local actions where uncoordinated local decision making may give rise to coordinated global patterns. Urban development is thus a spatially dynamic process, exhibiting some fundamental features of a self-organising system (Liu, 2009).

This understanding suggests that a ground-up approach under the self-organising paradigm to address the local behaviour of the system is more realistic in modelling urban development, which has resulted in the emergence of a new class of simulation models (Benenson and Torrens 2004; Batty 1997, White and Engelen 1994) geosimulation based on automata, and the agent-based model.

Urban models based on the automata technique have also emerged under the paradigm of a self-organising system, with cellular automata being the simplest but most popular in action. An automaton is an entity that has its own spatial and non-spatial characteristics but also has the mechanism for processing information based on its own characteristics, rules, and external input (Benenson and Torrens 2004).

The multi-agent systems are designed as a collection of interacting autonomous agents, each having its own capacities and goals, but together they relate to a common environment. This type of model operates on the same principles as the cellular automata model, with each agent being considered as individual autonomous agent-automata (Torrens 2003), and their states generally represent some agent-based characteristics. However, distinctions between cellular automata and multi-agent systems exist in a number of ways. One distinction is that in the multi-agent system, the basic unit of activity is the collection of agents representing individuals, developers, planners, or government decision-makers. The agents are autonomous in that they are capable of making independent actions, their activities are directed toward achieving defined tasks or goals, and their influence on the environment can be at different scales.

Another distinction between the cellular automata and the multi-agent systems is that cellular automata are fixed cells in the CA lattice, whereas the agents in the multi-agent systems are dynamic and mobile entities that can move within the spaces that they “inhabit” (Torrens 2003).

These agents also can process and transmit information while they move along the spaces and pass the information from one agent and environment to another in their neighbourhood. Consequently, the neighbourhood relationships in agent automata are also dynamic: when individual agents alter their locations in space, their neighbourhood relationships also change.

3. Agent based models

The history of the agent-based model can be traced back to the Von Neumann machine, a theoretical machine capable of reproduction. The device Von Neumann proposed would follow precisely detailed instructions to fashion a copy of itself. The concept was then improved by von Neumann's friend Stanislaw Ulam, also a mathematician; Ulam suggested that the machine be built on paper, as a collection of cells on a grid. The idea intrigued von Neumann, who drew it up—creating the first of the devices later termed cellular automata. von Neumann, 1949.

John Conway formulated the well-known game of life; which unlike von Neumann's machine operated by tremendously simple rules in a virtual world in the form of a 2-dimensional board.

The creation of agent-based models of social systems is often credited to the computer scientist Craig Reynolds. He tried to model the reality of lively biological agents, known as artificial life, a term coined by Christopher Langton.

An agent-based model (ABM) is a computational model for simulating the actions and interactions of a set of individuals (Agents) in a network to asset their effects in the global system behavior. It combines elements of game theory, complex systems, emergence, computational sociology, multi agent systems and evolutionary programming.

The models simulate the simultaneous operations of multiple agents, in an attempt to re-create and predict the actions of complex phenomena. The process is one of emergence from the lower (micro) level of systems to a higher (macro) level. The individual agents are presumed to be acting in what they perceive as their own interests, such as reproduction, economic benefit, or social status (Axtell et all, 2003).

An agent is described as an object with certain characteristics (Tzima et all, 2006):

- *autonomous* – it operates without the direct intervention of others and has some kind of control over its actions and internal state.
- *social* – it interacts with other agents using an agent-communication language;
- *reactive* – it perceives its environment and responds to changes that occur in it;
- *proactive* – it is able to exhibit goal-directed behavior.

The three ideas central to agent-based models are social agents as objects, emergence and complexity.

Agent-based models are situated in networks and in lattice-like neighborhoods. The location of the agents and their responsive and purposeful behavior are encoded in algorithmic form in computer programs. The modeling process is best described as inductive. The modeler makes those assumptions thought most relevant to the situation at hand and then watches phenomena

emerge from the agents' interactions. Sometimes that result is an equilibrium. Sometimes it is an emergent pattern. Sometimes, however, it is an unintelligible mangle.

In some ways, agent-based models complement traditional analytic methods. Where analytic methods enable humans to characterize the equilibrium of a system, agent-based models allow the possibility of generating that equilibrium. This generative contribution may be the most mainstream of the potential benefits of agent-based modeling. Agent-based models can explain the emergence of higher order patterns -network structures of terrorist organizations and the internet, power law distributions in the sizes of traffic jams, wars, and stock market crashes, and social segregation that persists despite populations of tolerant people, etc.

3.1 Cellular Automaton

Cellular Automaton (CA), can be considered as a particular case of agent based model where the agents are fixed and contiguous surface elements. Ulam and Von Neumann (1961) state that a CA is a cellular entity that independently varies its states based on its previous state and that of its immediate neighbors according to specific rules. It is a spaced dynamic system where the variables (ex. land cover), time and space are discrete (Houet et al, 2006).

The state of a cell in the future time step can be defined mathematically as a function of the present state of that cell and its neighbors and a set of rules that express the dynamics or process between them. Let's S^t_{xy} be the state of a cell at time t and position xy, where S belongs to a finite number of cell states in the cellular space. Now, Let's S^{t+1}_{xy} be the state of the cell at time t+1. Then:

$$S^{t+1}_{xy} = f(S^t_{xy}, S^t_{\Omega xy})$$

Where Ω represents the set of cells that are part of the computational neighborhood for the cell S^t_{xy} and f represents a function of the set of transitional rules to be applied.

A CA is defined by:

• Space: represented as an infinite and regular tessellation of cells of discrete states (generally a matrix).

• Set of states: is the set of possible values associated to the cells.

• Neighborhood: corresponds to a set of adjacent cells.

• Transition rules: specified as a rule table that defines the next state of the cell for each possible neighborhood configuration. They are uniformly applied to all cells at fixed time intervals.

CA models have been increasingly used to simulate land-use and land-cover changes due to their computational simplicity and their explicit representation of space and time. Typically, these models use the raster model, as defined in Geographic Information Systems, to represent geographic space (Moreno, et al 2007).

3.2 Elements of AB and CA Models

There are common elements and definitions for agent based and cellular automata models as has been described earlier, such as:

The Cell: defines the basic spatial unit of the system being modeled. The typical arrangement is a two dimensional grid, like a raster map, for urban modeling environments. But it is possible that the modeling environment is 1D like in models of traffic or 3D for some models of molecular gases interaction. The size of the cell is important since this represent the scale of the process that wants to be modeled. For urban environments the cell size can be 200*200 meters or less depending on the amount of information available to set up the conditions in the model. A common source of information for setting up such a model comes from remote sensors like satellites and aerial photographs to classify land uses and coverage. The selection of a smaller scale makes the system more complex and computational demanding. Although is possible to build a model at a house scale it must be kept in mind that urban expansion rarely as a result of an individual decision but as block of houses or housing plans from the municipalities. In the ABM technology the agents can access information regarding the environment condition in each cell.

The cell state: defines the attributes in the system. Each cell can take only one state at every time step. In urban modeling states can represent a property or urban land category such as residential, commercial, industrial etc. Every time the system is updated as a result of the analysis of the transition rules in the interactive neighborhood, the state of each cell will be updated either change or stay in the same state. For Agent based models the state is equivalent to define the role that each agent is playing in the simulation.

The Neighborhood is the set of cells that are considered to play a role or influence the state of the cell that is analyzed. In 1D model the adjacent cells are considered in the analysis. In two dimensional space several configuration of neighborhoods have been evaluated, the more typical set up is the Von Newman and Moore neighborhood. The Von Newman neighborhood includes 5 cells in the analysis, see figure 2-A, the Moore neighborhood considers the 8 cells around the central cell of analysis in a 3*3 array. There is an extended Moore neighborhood which consists of a 5*5 array. See figure 2-B and C.

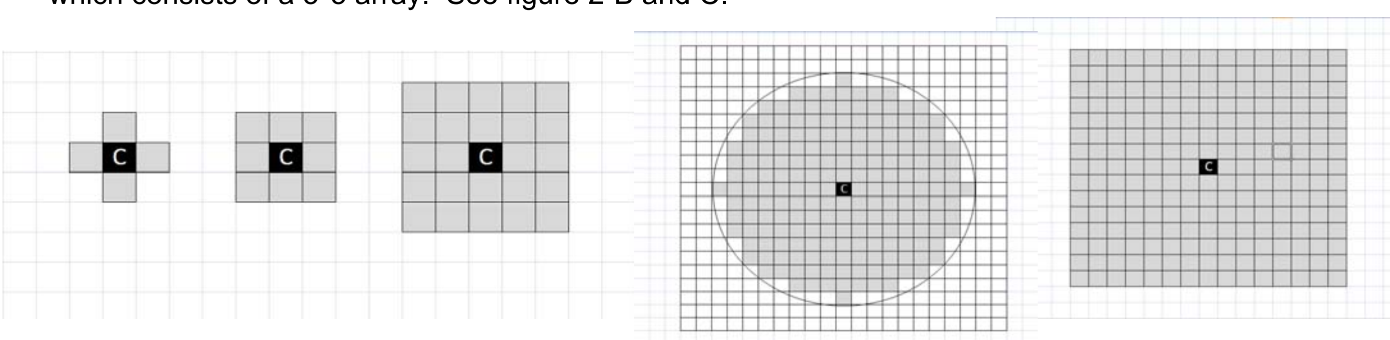


Figure 2. A. Von Newman Neighborhood, B. Moore 3x3 Neighborhood, C. Extended Moore 5x5 Neighborhood, D. Circular Neighborhood 8 Cells diameter, E. Rectangular Neighborhood proposed by Wu (1996).

In the ABM the neighborhood is define in the interaction of each agent with the other agents it encounters in his path, since the agents are dynamically moving in the cell space or environment.

The transition rules directly represent the process that is being modeled and as such are the key elements in CA and ABM. The rules define how each cell or each agent is going to change its state in response to the current conditions in the neighborhood or surrounding agents. Thus the rules represent the dynamics of the system.

In cellular automata these rules normally are a set of IF-THEN statements, such as:

"If something happens in the neighborhood of a cell, then a change will happen to that cell in the next step".

For example in the "Game of Life" the natural behavior of live and death can be modeled using a set of three rules:

If there are 2 or 3 live cells in the Moore neighborhood of a live cell, Then that cell stays alive in the next generation.

If there are less than 2 or more than 3 live cells in the Moore neighborhood of a live cell, Then that cell dies in the next generation.

If there are exactly 3 live cells in the Moore Neighborhood of a death cell, Then that death cell becomes alive in the next generation.

The time defines the temporal dimension were the CA system exist. From the definition of CA all the cells states are updated at every time step, which depend on the state of the cell itself and the state of the cells in the neighborhood of analysis in the previous time step. Some models are configured by starting the model from known spatial data sets that is available, and then letting the model run for a number of iterations until the simulated results "fit" with another set of data at the ending time. These kind models were not configured temporally. There are other examples such as constrained cellular automata where there is an external model that constrained the number of cells per state in time (Engelen and White, 1996).

4. Agent based models for water management

Managing water systems is a complex task, having to cope with various water-related activities and conflicting user perspectives within a specified geographical area – basin, catchment, watershed etc. Typically, there are several stakeholders involved, and their different, typically contradictory goals must be seriously taken into consideration. Water supply for domestic uses, agricultural or industrial use, environmental issues and recreation or amenity provision are only some of the activities the different stakeholders may be involved in (Tzima et al, 2006).

Urbanization and overexploitation of the water resource often leads to water scarcity by quantity and/or quality, aggravating the situation to a socio-economic power struggle. In such complex and multidimensional cases, management strategies not only have to balance water demand and supply, but also find solutions that meet the approval of all users. Issues like the prioritization of users, the construction of water tariffs, the protection of ecological reserves, the compliance with the economic objectives and the legislative context, needs to be equally considered.

This process of conflict resolution has to be done within a system of strongly coupled biophysical, social and economic entities, where the impact of certain strategies cannot be assessed by long-term studies or experimental manipulations alone, making it complex.

Simulation models, and particularly agent-based simulation models, are tools that can facilitate overcoming these limitations. Such tools can be used to evaluate the possible effects of different management plans. It is important to highlight that ABMS tools are not developed to forecast the exact state of the modeled system, but to explore how the system will evolve in view of a possible future. Some of the models that have been study and reported in the literature are presented in figure 2, (Tzima et al, 2006) and shortly described in table 1.

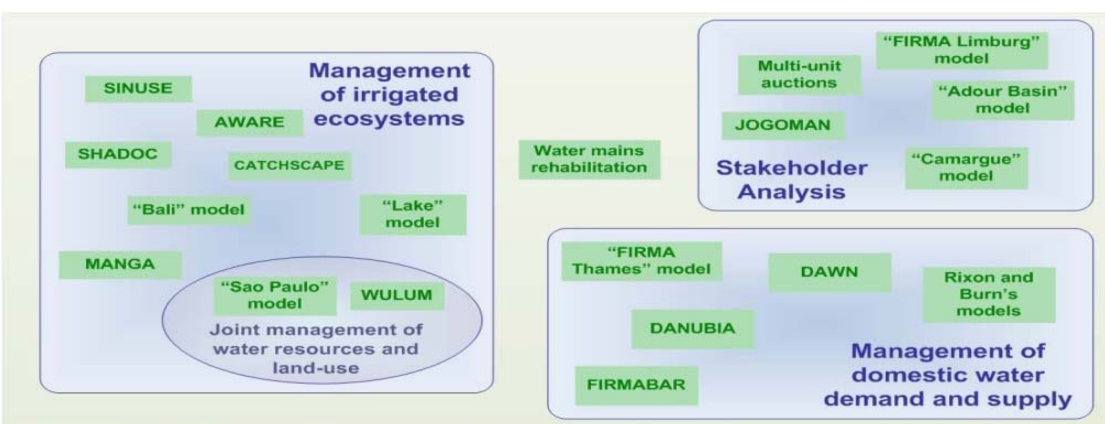


Figure 2. Examples of agent based models for water management, from Tzima et al, 2006.

Table1. Agent based models for water management

Model	Description
SHADOC	SHADOC developed by Barretou et al, 2000, is a MAS seeking to examine the viability of, currently underutilized, irrigated systems in the Senegal River Valley. Based on the assumption that the interaction of the different system components has a large impact on its viability, the model focuses on rules used for credit assignment, water allocation and cropping season assessment, as well as on organization and coordination of farmers.
SINUSE	SINUSE, addresses the problem of integrated management of the Kairouan water table, located in Tunisia, which has been continuously decreasing for more than 20 years. It is an attempt to model the observed system dynamics and explore the effects of different kinds of intervention. Feuilliette et al, 2003.
CATCHSCAPE	Becu et al. 2003 have developed CATCHSCAPE, an agent-based model for the management of Mae Uam, a small catchment in Northern Thailand. The model intends to explore the impact of upstream irrigation management on downstream agricultural viability in an environment where biophysical and social factors are a source of conflict. Thus, in an attempt to foster the achievement of negotiated settlements to such conflicts, it simulates the whole catchment features as well as farmer's individual decisions.
AWARE	Action-research and Watershed Analyses for Resource and Economic sustainability (AWARE) is a simulation tool that models the dynamics of catchment level water management in South Africa, . The water management approach promoted by the National Water Act of South Africa relies on a licensing process, through which water use authorizations are allocated to various competing groups of users. In this context, AWARE is meant to be a support tool to evaluate alternative scenarios representing potential water management strategies.
MANGA	MANGA is a tool aiming to assist decision-makers in the difficult task of collective management of water resources it was developed by Le Bars et al, 2005. It provides a simulation environment for testing the consequences of various water allocation rules, in order to identify an acceptable compromise. Rule consequences depend on agricultural constraints, actors' behaviours, and confrontation of their decision rules with other actors.
The Bali Model	The Lansing-Kremer model (Lansing et al, 1993) simulates the irrigation system of the Oos- Petanu watershed in Bali. It involves the representation of the various water flows, the topology of rice terraces, as well as the coordination procedure used by local farmers for water allocation and control pests. The aim of the model is to prove that among the various levels of coordination for water sharing, the temple level, traditionally used, maximizes the production of rice.
The Lake Model	Eutrophication is a widespread and growing problem of hydro-systems that is caused by an excess input of nutrients, like phosphorus. The model presented in Janssen, 2001; specifically focuses on the management of lake eutrophication and explores the lake dynamics in relation to the behaviour of agents using phosphorus for agricultural purposes in the area.

4.1 Agent-Based Models for Water demand and supply management

Water management in urban areas is a challenging procedure during which, environmental, economic, social and political parameters have to be considered. Population growth, technological development, urbanization trends and climate change form a landscape of water scarcity, where water demand needs to be controlled and reshaped. Examples of water demand control mechanisms include variable water tariff schemes, exhortations, public campaigns and promotion of water-saving technologies.

The common objective of all these demand management strategies is water conservation, or in other words, the encouragement of customers to make more efficient use of the resource. Their evaluation process aims on calculating future water demand changes and must therefore take into account all the factors affecting water demand behaviour. In this context, social behaviour is a critical aspect, as most demand-side strategies focus directly - or indirectly - on human behavior.

Water demand management is inevitably influenced by both environmental and socio-economic factors. Thus, the need for tools that can model the water management dynamics in an integrated way is evident. Unlike traditional statistical or econometric approaches, these tools should take into account social interaction and human behavior, and achieve the difficult task of promoting public participation.

In achieving this bilateral goal, agent-based modelling is a promising approach. The following sections briefly present some of the agent-based models for water management in urban areas found in the literature.

4.1.1 The Firma Thames Case

The "Thames" model was developed as part of the FIRMA project, and particularly the case study concerning the south of England, and aims at balancing supply and demand, in order to ensure effective water use during periods of climate change. The modelling procedure involved the development of two versions of the system, the second being more specific and realistic, based on the feedback received from stakeholders.

Modelling approach

The first version of the system, implements a hydrological model that determines the amount of water in the soil and a society of agents representing domestic users with various monthly water consumptions. A policy agent represents the policy authorities and determines restrictive exhortations when drought conditions prevail.

As far as user agents are concerned, a social model defines a set of acquaintances for each household –that is the agents whose public consumption activities are visible to it. There are also, private consumption events, not visible to any agent but the consumer himself.

Each household agent determines its frequency of water consumption events and the quantity per event. To do so, agents employ a decision-making process based on endorsement schemes and chose among alternative behaviors according to evidence, social pressure and public authority exhortations. The latter, are recommendations by the policy agent, concerning the frequency of each activity as well as consumption per use event. These recommendations become stricter when drought conditions persist and cease when the soil water levels recover.

In the *second stage* of water demand modelling the random frequencies and volumes of water per consumption activity, were replaced by actual statistical data**.** The model was also extended to specify ownership of appliances related to specific water consumption activities, thus making it possible to investigate the effects of technological change.

4.1.2 The FIRMABAR Case

FIRMABAR is an agent-based simulator developed as part of a second case study of the FIRMA project, in the Metropolitan Region of Barcelona (MRB). It is an integrated tool for the evaluation of alternative supply and demand policies under different climatic and technological scenarios, taking into account the important changes in the territorial model of the region. Similar to the "Thames" model, its design and validation were based on participatory processes with a platform of representative stakeholders.

Modeling approach

The modeling of the system is based on the assumption that urban dynamics play a central role in water consumption behavior. Thus, space is represented explicitly as a grid and follows cellular automata rules. The agent model involves the following actors:

i) The families that incorporate social attitudes and lifestyles and compute their maximum expected water demand and real consumption.

ii) The real estate companies that build new housing around the municipalities and act as intermediates in the second-hand market. This modeling choice reflects the trend "driving the territorial model from the compact city to diffused patterns of urbanism".

iii) The municipalities that correspond to the different districts in the studied area - each of the latter having an initial urban development plan.

iv) Regional government that decides about water prices and infrastructure investments calculates the water stock and enforces various supply-and-demand policies in the area.

Figure 3. Interface of the Firmabar model.

Families have to make decisions on house movement and water consumption. House movement depends on several parameters such as the size of the house versus size of the family, social class in the neighborhood and the evolution of prices for new houses versus the second-hand market. Based on these factors, families may decide to migrate, thus producing a new territorial model.

The second decision a family has to make concerns its water consumption and partly depends on individual level rules and preferences (water price and gross income, maximum demanded water, housing type and appliance technology, social class and size of the family). Another factor affecting this decision is the social attitude towards emergency situations of drought or scarcity. Finally, water consumption is adapted to the local habits by a local mechanism of imitation.

4.2 Agent Based Models for Urban and Peri-Urban Water Management

Peri-urban areas around rapidly growing cities are, most of the times, characterized by a ‘‘patch structure’’ in terms of land use, that ranges from urban infrastructure to strictly rural and agricultural use. On the other hand, illegal settlements in these areas are a very common case and suffer from a lack of basic infrastructure and public facilities, thus constituting major non-point pollution flow sources. These dynamics directly affect the hydrological processes of the

whole area, by changing the permeability of the soil, the runoff coefficients, the distribution of peak flows in the natural streams, the degradation of the water quality in drinking water reservoirs and aquifers. In many cases, this situation is already leading to water use restrictions and open conflicts.

The management of such complex and dynamic systems must take a more integrative approach and jointly consider all the hydrological and social processes involved. Agent-based models have been tested in this kind of participatory approach for ecosystem management and proved to be interesting and effective tools in the modeling and implementation phases. In the case of peri-urban areas, they can provide a way to structure and study the interactions between conflicting land uses and the competition for water availability among urban demand, agriculture irrigation, industry and recreational activities.

4.2.1 The Sao Paulo Model

The model reported by Ducrot et al, 2004 is MAS attempting to represent the relationships between urbanization dynamics and land and water management in peri-urban catchment areas. It was inspired from the spring areas of Sao Paulo city, which is the main drinking water reservoir of a great metropolitan area, suffering from high urban pressure and problems of pollution connected to land use and rain. The model takes a combinatorial approach, using cellular automata, spatial passive entities and communicating agents.

Modelling approach

The model's architecture involves a Cellular Automata (CA) layer to spatially represent the hydrological model and its dynamics. The agents are used to represent the behaviors of stakeholders and the decision-making processes, affecting water management in the area. Land-use changes and urbanization are specifically taken into account.

In order for the model to be spatially explicit, the catchment area is represented as a grid, with each cell having a unique value of land cover: reservoir, river, favelas, residential building, industry, tourism infrastructure, irrigated crop (horticulture), or non-irrigated crop (cereals). Cells are also aggregated into three municipalities and one reservoir, the latter having a specific water level and pollution rate.

There are two types of land-user agents, farmers (or producers) and urban owners (or speculators), all initially attributed with a plot, a cashbox and family needs.

Farmers all grow crops in their plots, choosing among horticultural crops that need to be irrigated, cereal crops (not irrigated), and fallow. In the other hand, urban owners employ one of the following strategies: i) using the plot for recreational purposes, ii) using the plot for speculation purposes, waiting for a higher price, or iii) developing a profitable activity on their plot, such as tourism or industry.

Any plot may be left in “fallow” state and changes in land use are possible, depending on owner’s parameters and on the local configuration around a plot. Land-use dynamics are central in the model and rely on two different driving forces: transition rules between cells, and agents’ decision-making. Examples of changing land-use include: (i) unoccupied cells in the immediate surroundings of a favela becoming urbanized, (ii) the rural land-use model changing according to the farmers’ cropping choices and (iii) investments changing plots into touristic or industrial settlements.

The model’s migratory dynamics are summarized in two processes. An immigration process involves new land-user agents being added to either the farmers or the speculators population. On the other hand, land-users owning no plots are removed from the model, in a process representing emigration.

Finally, a land market is organized every year, where indebted farmers have to sell their plots. The model adopts “priority sale to neighboring farmers to account for social links between farmers as well as for a preference to avoid land dispersal”.

4.2.2 WULUM

Water Use and Land Use Model (WULUM) (Zellner, 2007) is an agent-based model investigating the relationship between land use, water use and groundwater dynamics in the Monroe County in Michigan. The main objective is to link these processes in an integrated model and evaluate their effect on groundwater levels.

Modelling approach

The physical model in WULUM is spatially explicit. A grid is used, where each cell contains information including groundwater, forest, soil quality, roads, zoning restrictions and municipal water coverage. Cellular automata transitions rules are used to create the regional west-east groundwater gradients with points of recharge and discharge. Under the same principle, farm cells may become populated by residents or quarries, depending on residential preferences for location, existing development and zoning.

The agent model involves three water-extracting actors: residents, stone quarries and farmers. Agents are located on the grid and perform several water extracting activities, thus changing the landscape and the levels of groundwater.

These changing conditions then provide feedback to the decisions space of the agents.

As far as the water resource dynamics are concerned, the water aquifer’s level depends on the natural renewal rates and the degree of development. Moreover, the climatic (precipitation), hydrological (groundwater flow) and demographic data (annual rates of residential growth) used in the model are based on literature and expert knowledge about the area.

4.2.3 Tijuana's Border Town Model

This model developed by De Leon , 2007, simulates various socio-economic realities of low-income residents of the City of Tijuana for the purpose of creating propositional design interventions.

The Tijuana Bordertowns model allows input of migration rates and border crossing rates relative to employment and service centers in order to define population types (i.e. migrants or full-time residents). Population densities relative to block sizes are adjustable via the interface in order to steer the simulation toward specific land-uses such as urban centers or peripheral (rural) development. The rate of residential building is adjustable based upon relative community size, land value (approximate), required (per-capita) capital and the carrying capacity of (potentially) existing infrastructure.

Modelling Approach

A CITYSCAPE is generated, spreading out from a city center. Each patch is assigned a land-value, and a level of electrical, water and transportation service. A road network is drawn, and maquiladoras or industrial areas are placed at the edge of the city. See figure 4.

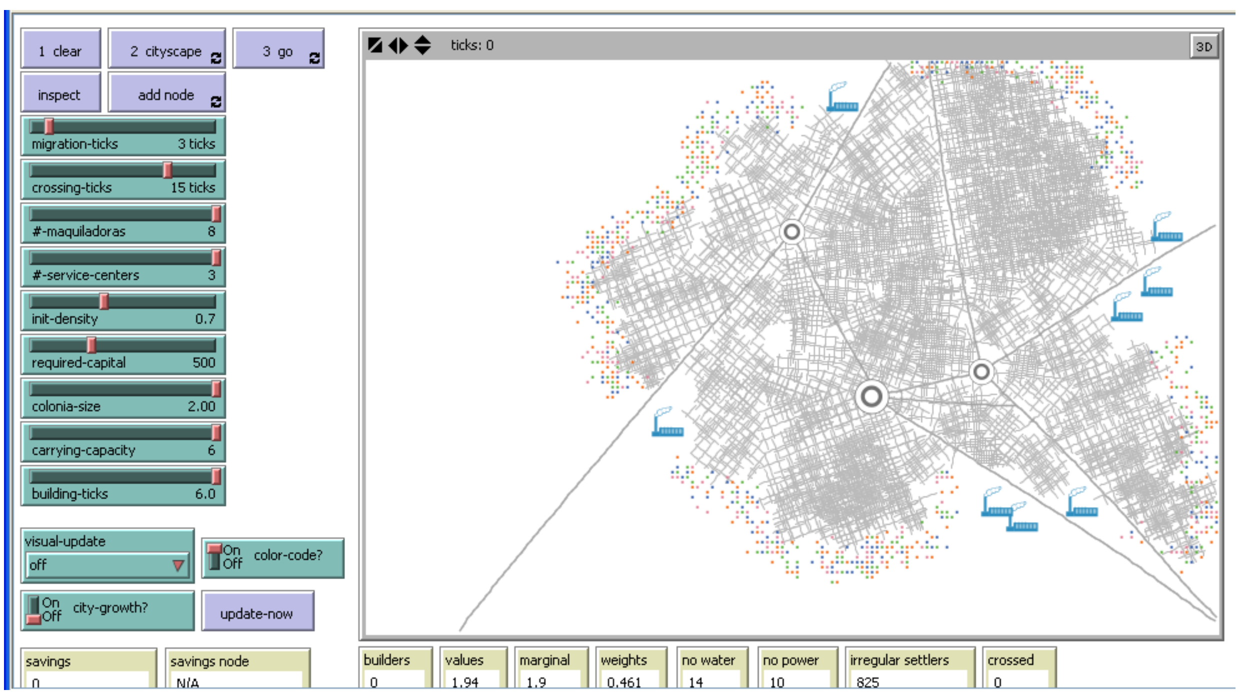


Figure 4. Interface of Tijuana's border town model

An initial set of migrants are created at the edge of the city on "irregular" patches, meaning those patches with a low land-value, near water and away from maquiladoras. A second set of migrants is created in the neighboring patches. This establishes the base population of the irregular settlements. The migrants also keep their citizenship, such as Jaliso or Oaxaca.

Then each migrant is assigned a living-expanses values, which is determined by the value of the land they occupy, food and other utility costs, as well as the electrical, water, and transportation. Food and other utility costs are constant for all agents. The electrical and water costs are determined by the patches values. Transportation is determined by their distance to service centers (like shopping centers), the distance to the maquiladoras they work at, and the access to transportation services.

With each model tick, new migrants move into patches next to existing migrants, some migrants cross the border, some migrants move into nicer locations once they have sufficient savings, and all of them participate in the economy, earning and spending money, as well as saving if possible.

New migrants will enter in unoccupied spaces adjacent to migrants who came from their home state.

Migrants that move will look for a patch in their area with electrical and water services, which is affordable to them.

Groups of migrants form colonias. The size of these colonias is determined by the COLONIA-SIZE slider. The larger the value, the larger the colonia. Colonias with sufficient density will be targeted for regularization. New electrical, water and transportation services will be developed for them.

This model explores the migration of population and the development and growth of the economy in the city. This is a preliminary version of the model and there are some capabilities that are not yet fully developed or implemented, such as the extension of the city infrastructure for the regularization of the colonias with high potential.

4.2.4 The Cities Model

The Cities model has been developed in the framework of the project “Procedural modeling of cities” at the Center for Connected Learning (CCL) and Computer Based Modeling, Lechner et al , 2004. This model allows a user to create a terrain and environment in which a set of builders will create a city. Users can interrupt the city build and change the environment and then continue the city creation simulation. The city consists of roads, parcels (sets of patches which are developed as a single unit), and buildings. Parcels are zoned for specific types of usage, commercial, industrial, residential, or park.

Modelling Approach

The user paints parameters onto the terrain, such as elevation, road grid constraints, and "honey" which are hot spots that attracts specific type of developers. The user may also create multiple city seeds, or move the existing one. The user may also draw primary roads and link them to the edge of the terrain, to simulate the city's major routes.

In addition the user can also set some of these parameters at a global level, affecting all patches. There are also global variables constraining the number of developers, the ratio of land-use between the development types, minimum parcel sizes for different land uses, and many other factors.

There are agents sets with role of builders for each type of development, such as residential, commercial, industrial, and park. These agents move through the terrain, grouping patches into parcels and then attempting to "develop" them by putting a new building upon the parcel, or increasing the size of the current building. Road builders move through the terrain building roads between areas, thus increasing their value.

At any time, the user can stop the model, paint new parameters onto the terrain, free up terrain that has been developed, draw primary roads, or change the land use ratios. When the model is restarted, builders will respond to these changes.

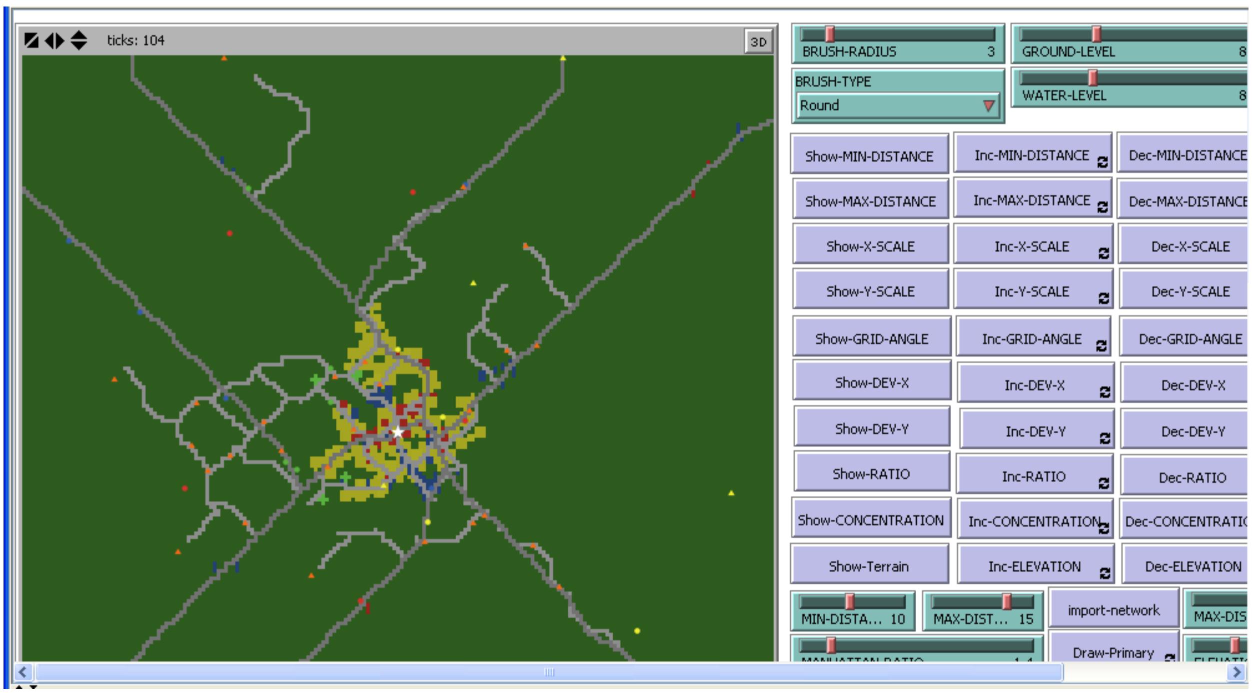


Figure 5. Interface of the cities model

In this model there is a set of agents that has the role to search the modeling space for patches that are not connected or far away from the road network, thus extending and adding new roads to the model according with the parameters that affect the accessibility and that are user specified.

This model presents a good example of an agent base system to generate urban dynamics and complexity. It is a tool the gain inside in the process that drives urban development rather than a prediction tool. Nevertheless the authors reported that this model can generate land use distribution that realistically represents the urban landscape of cities like Chicago in the USA. There is not report of the model being applied to a real case dataset.

4.2.5 The SLEUTH model

The SLEUTH model is a cellular automaton model, developed with predefined growth rules applied spatially to gridded maps of the cities in a set of nested loops, and was designed to be both scalable and universally applicable. Urban expansion is modeled in a modified two-dimensional regular grid. Maps of topographic slope, land use, exclusions, urban extents, road transportation, and a graphic hill shade layer form the model input. The model was first developed and applied in the San Francisco Bay area in the United States (Clarke, Hoppen, and Gaydos 1997). The name of the model came from the six input data layers, namely Slope, Land cover, Exclusion, Urbanization, Transportation, and Hillshade.

The model applies four types of urban land-use change: spontaneous growth, new spreading centre growth, edge growth, and road-influenced growth. A spontaneous growth occurs when a randomly chosen cell falls close enough to an urbanized cell, simulating the influence of urban areas on their surrounding land; a new spreading centre growth spreads outward from existing urban centres, representing the tendency of cities to expand; an edge growth urbanizes cells that are flat enough to be desirable locations for development even if they do not lie near an already established urban area; and a road-influenced growth encourages urbanized cells to develop along the road network.

The four types of urban growth are applied sequentially during each growth cycle and are controlled through the interactions of five growth coefficients: diffusion, breed, spread, road gravity, and slope (Clarke, Hoppen, and Gaydos 1997; Clarke and Gaydos 1998). The first four coefficients describe the growth pressure in the urban system. For instance, the diffusion coefficient determines the overall outward dispersive nature of the distribution; the breed coefficient specifies how likely a newly generated detached settlement is to begin its own growth cycle; the spread coefficient controls how much diffusion expansion occurs from existing settlements; and the road-gravity factor denotes the attraction of new settlements toward and along roads.

Resistance to growth is incorporated through the slope coefficient, which captures the effect of steep slopes on restricting development. In addition, resistance is also applied through an excluded data layer that identifies areas that are wholly (e.g.,water or parks) or partially (e.g., restrictive zoning) excluded from development. All five coefficients are calibrated to control the growth rate so that growth will not become unusually high or low. The overall rate of urban growth is the sum of the four types of growth.

The SLEUTH model is implemented in two general phases: a calibration phase, in which the model is trained to replicate historic development trends and patterns, and a prediction phase, in which historic trends are projected into the future. The model can be used to simulate the non-urban to urban conversion; it can also model the process of multiple land-use change.

This model has been applied and calibrated in real cases, for example Silva and Clarke, 2002 developed a SLEUTH model for Lisbon and Porto in Portugal. The model was successfully calibrated and validated, capturing the dynamics of the cities and was proposed to be used for planning and evaluation of future scenarios of development.

4.2.6 Moland Model

The aim of MoLAND is to provide a spatial planning tool that can be used for assessing, monitoring and modeling the development of urban and regional environments. Moland was a project that was initiated in 1998 (under the name of MURBANDY - Monitoring Urban Dynamics) with the objective to monitor the developments of urban areas and identify trends at the European scale. The work includes the computation of indicators and the assessment of the impact of anthropogenic stress factors (with a focus on expanding settlements, transport and tourism) in and around urban areas, and along development corridors. JRC, 2009 (accessed via web)

Since 2004, MoLAND is contributing to the evaluation and analysis of impact of extreme weather events, in the frame of research on adaptation strategies to cope with climate change. The MoLAND methodology has been applied to an extensive network of cities and regions for an approximate total coverage in Europe of 70,000 km2.

The MOLAND urban growth modeling tool was developed by the company RIKS (Research Institute for Knowledge Systems, Ltd) The model is part of RIKS's Metronamica modeling framework, which is based on dynamic spatial systems called cellular automata. www.riks.nl. The model takes as input different types of spatially referenced digital data:

Land use maps, showing the distribution of land use types in the area of interest.

Suitability maps, showing the inherent suitability of the area of interest for different land use types. These maps are created using an overlay analysis of maps of various physical, environmental and institutional factors.

Zoning maps, showing the zoning status (i.e. legal constraints) for various land uses of the area of interest. These maps are dervived from existing planning maps (e.g. master plans, zoning plans, designated areas, protected areas, historic sites, natural reserves, land ownership).

Accessibility maps, showing the accessibility to transportation networks for the area of interest, and they are based on the importance of access to transport networks for the various land uses.

Socio-economic data for the main administrative regions of the area of interest, comprising demographic statistics (i.e. population and income), and data on production and employment for the four main economic sectors (i.e. agriculture, industry, commerce, and services).

The main components of the model are:

- A two-dimensional grid or cell space, each grid-cell having its own unique set of attributes (i.e. land use, suitability, zoning, accessibility, socio-economic);
- A cell neighborhood, consisting of a circular area of radius eight pixels around each cell;

- A set of discrete cell states (i.e. 24 MOLAND land use classes or the Corine land use classification);

- Transition rules (describe the effect of neighboring cells on central cell).

The socio-economic information is used to build a regional model that accounts for the demand of the different land uses in the future or modeled time frame. Thus, the regional model constrains the local model or cellular automata by assigning a number of cells according with the demand. Once all the cells for a particular land use are assigned no other cell can change to that land use even if it has the highest potential, instead it will get the immediate land use class in the highest potential list.

Moland has been applied in several European cities to study the urban dynamics and patterns, for spatial planning and hazard mitigation, strategic environmental assessment, the application of sectoral policies and their spatial impact. Figure 6 shows the application of Moland in Dublin urban area.

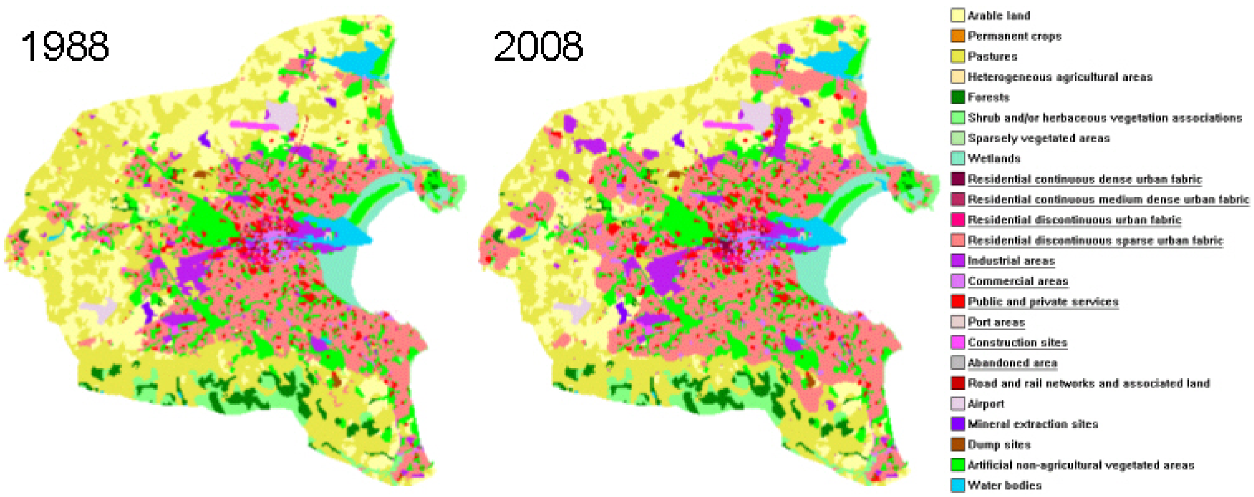


Figure 6. Urban growth in Dublin present and predicted land use change.

The output from the MOLAND urban model are maps showing the predicted evolution of land use in the area of interest, over the time. By varying the inputs into the MOLAND urban model (e.g. zoning status, transport networks), the model can be used as a powerful planning tool to explore in a realistic way the future urban and regional development of the area of interest.

4.2.7 The MedAction PSS model

The MedAction system was developed as part of an EU project "Policies to combat desertification in Northern Mediterranean Region". It is a dynamic spatial integrated model, which integrates 15 individual models with different modeling paradigms and temporal resolutions varying from minutes (for the rainfall and erosion models) to a year (for the land use and crop choice models). It has a finest spatial resolution of 1 ha grid cells and can therefore incorporate detailed spatial characteristics. The model is implemented in the GEONAMICA framework developed by RIKS in the Netherlands, similarly of the Moland model describe in the previous section.

The MedAction PSS reuses to a large extent models incorporated in its predecessor, MODULUS. The latter, in turn, is based on past research carried out in a number of EC-funded projects. The models that were included in the Core of MedAction are: Climate and Weather, hydrology, sedimentation, salinisation, water demand and usage, water resources, land use, profit and crop choice, dynamic suitability, plant growth, natural vegetation, land management. Figure 7 shows the system diagram. Van Delden et al, 2007 and Kok et al, 2007.

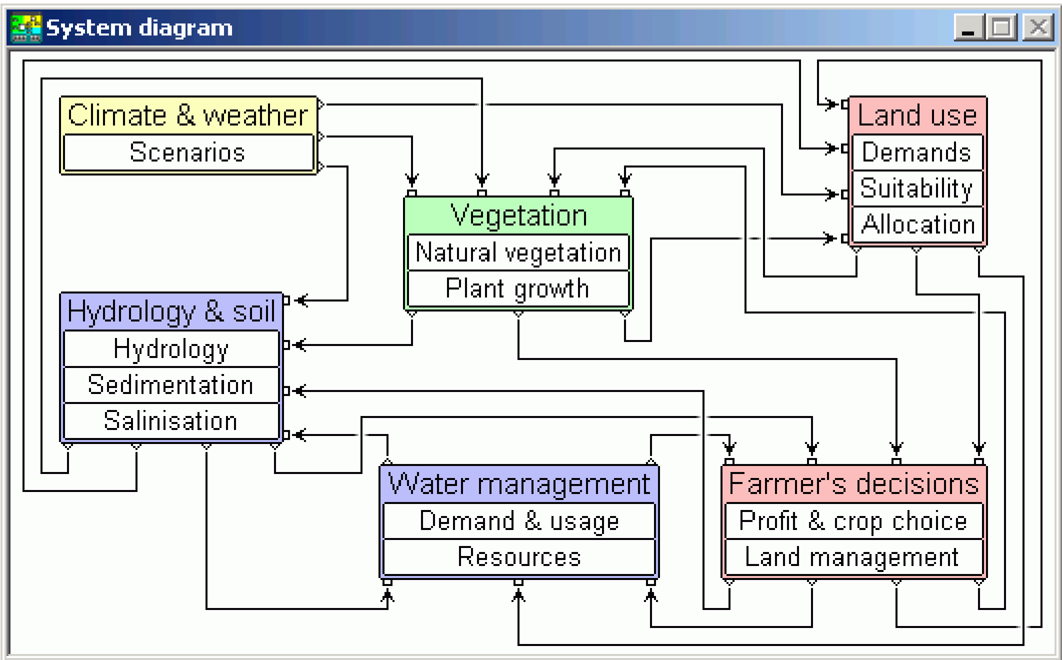


Figure 7. System diagram of Mediaction PSS. Van Delden et al, 2007

The integration of the processes and models provides a tool to uncover the behaviour of the system analyzed as the result of its autonomous dynamics largely determined by the human agents active in the system, subsidies and other policy measures imposed on the agents, and the exogenous drivers, climate change, technological change, demographic growth, and market forces. While the autonomous dynamics are very much core elements of the processes represented, policy measures and exogenous drivers impact on one or more model in the system. Impacts are passed on from one to the other models as a result of the many feedback loops. A high degree of integration was achieved in this model by providing more feedback loops between the models and by incorporating the dynamically suitability model that directly affects the change of land use patterns.

This model is in a demonstration version and the authors indicate the there is further work to be done to validate the model and released a version as an end user application.

4.3 Discussion

This chapter presented the basic concepts of cellular automata and agent base models; moreover there is a description of several experiences reported in the literature regarding the application of agent base modeling to urban growth and water management.

The revision of the experiences show that this modeling paradigm is rather new and the application have been developed in the last 15 years. Nevertheless, the experiences show that agent based models can replicate the complexity and dynamics of urban growth in real cases. The different experiences also shows that there has been advances in the technique and approach, there are several authors testing different neighborhood sizes and shapes and evaluating different techniques to formulate the transition rules.

The amount of land use classes considered in the models is limited to main drivers or stakeholders. The classes at the urban level can be considered as urban or non urban activities. This is understandable since we know very little about the main forces and drivers that shape our modern cities.

Almost all the experiences considered land use classes or categories that are assigned to every grid in the model. But there is little information about population dynamics and building classification at the urban level, these characteristics are important for urban water management since water use and patterns are associated with building types, population density, population income, etc.

The selection of the neighborhood is pragmatic. There is very little information or recommendations from the theoretical or experienced point of view, in the experiences reviewed. We know that the size of the neighborhood will affect the shape of the clusters in the final simulation. And that the size depends very much of the processes involved in the phenomena being modeled. For urban scale the approach used by Riks has shown good results in practice.

Most of the models are not set temporally. This means that the simulation is run for a consecutive number of iteration until the results match a dataset that is used for calibration. The only model that considers time is Moland or the Geonamica framework developed by Riks. Their approach used socio-economic information to set-up a regional or national model that imposes constraint in the growth per land use, according with the plans and expectations at a macro level.

The integration of urban growth models with urban water management has been explored in some the experiences presented here.The experiences report that the integration is hard to achieve and the models become even more complex. Most of the integration is done by incorporating the outputs of numerical models as inputs in the agent based models in the form of suitability maps with certain weight in the decision making process. The MedAction experience report a full integration with several physically based models, the integration was achieved by developing a dynamically suitability model that handles the changes caused by certain actions in the output of the individual models, then creating more feedback loops to other models that can be affected and finally building a new set of suitability map per time step in the simulation.

5. Problem Definition

Cities are complex systems that are not in equilibrium, they are changing all the time and we still know very little about the dynamics and processes that govern the growth of the urban areas. Cities show characteristics of emergence, self-similarity, self-organization and non-linear behavior of land use changes. In the world, large scale patterns are usually the result of the interactions of large numbers of smaller pieces that somehow are combined in surprising ways to create the large-scale pattern. Such large-scale (macro-) patterns that arise out of the interactions of numerous interacting (micro-) "agents" are called "emergent phenomena" — that is, phenomena that emerge from interactions at a lower level or bottom – up approach.

Cities need to achieve a level of sustainability in their water systems to cope with urbanization and the external treats. To do that, there is a need to implement integrated approaches and improve urban planning and decision making. Since the 90's the concept of integrate water resources management has been promoted. The complexity of the water systems and the highly interlinks between the water sub-systems cause that the actions taken in one part of the system are reflected elsewhere, most of the time difficult to foresee those impacts in a very fragmented managed sector.

Frequently the modelers are asked to predict the complex interactions and links between the management actions or projects developments with the response of the systems. Most of the time to understand the complexity of the multi-casual network of interactions several model tools (physically base and/or data driven) are used. One of the biggest challenges is to integrate the outputs of the different models to understand the system dynamics, the effect of the actions, improve the decision process and clearly communicate with the public.

The use of tools that can help in the understanding of the above–mentioned characteristics are important to gain knowledge about the patterns and mechanisms behind urban dynamics. Agent based models are a good modeling paradigm that helps exploring the characteristics of urban growth.

The work proposed here will explore the application of agent-based models to urban water problems in combination with GIS and standard engineering numerical models to show the impact of the urban dynamics in the evolution of the water systems (pipe networks) but also how the planning of the water services and water services availability drives urban growth.

6. Objectives

This PhD research is done in the framework of the SWITCH (**Sustainable water management improves tomorrow's cities health)** project financed by the European Commission. The results of this investigation can contribute to the visioning and strategic planning exercises for the cities involved in the project. For the cities to achieve and keep a level of sustainability in their water systems officials need to improve urban planning and design, innovative thinking and decision making. To achieve the combined goals of improved efficiency and effectiveness, there is a need to perform integrated analyses.

The proposed research aims to look at the evolution of water services according with urban development with time. Given a proposed future scenario can we identified the way that water distribution and drainage services should be extended from existing urban areas to new development areas?.

The main hypotheses of this research are:

Hypothesis 1: By relating water distribution in existing areas to land use the revised and extended network serving the existing and new developed areas can be estimated.

Hypothesis 2: By relating drainage to topography (stream network) and land use (including major roads) the revised and extended network serving the existing and new developed areas can be estimated.

The objectives of the research

- to explore the application of agent-based models on urban water problems.
- to apply the concepts and principles of emergence in the development of urban areas.
- to show the impact of the urban dynamics in the evolution of the water systems (pipe networks) and vice versa.
- To demonstrate the functioning and effectiveness of agent-base models for IUWM on two selected SWITCH demo cities.

7. Methodology

Agent based models, including cellular automata has been used and tested in several cases for land use changes modeling, including urban dynamics. Some cases have been briefly presented in the literature overview above. The majority of the cases work at the catchment scale, involving regional factors in the simulation of land use changes and urban development. The results of those models have successfully probe that the application of ABM and CA for land use changes modeling is possible and that the outcome of the models are similar of what is observed in reality. Moreover, the Metronamica framework has been successfully applied and calibrated to real life cases, as presented by Barredo et al, (2003), Engelen et al, (2007), van Vliet and van Delden, (2008), among others.

This research will be focused in the study of water services networks evolution and performance (water distribution and drainage networks) to evaluate proposed future scenarios that can lead to a better understanding of the actions that need to be taken to achieve goals of sustainability.

The hypothesis here is that the incorporation of variables related to the water services will have an impact in the direction of growth of the new developments in the urban areas produced by the cellular automata model. These results can then be compared with simulations where no water related services are considered. In some cases the inclusion of the water services may become a major driver for the land use changes in the urban areas, in others it may be a secondary order driver overtaken by other factors such socio-economic, demography, etc. The results can also be used to describe the impact of the provision of water services as a trigger to stimulate urban development.

Figure 3 presents the flowchart of the methodology of this research, which is in line with the hypothesis and objectives stated previously.

Following the main components of cellular automata framework the model can have the following components:

A regional model: for the distribution and allocation of the demand per land use category according with plans, regulations and estimations of growth and wealth.

Land use maps: are the bases to establish the initial conditions of the model.

A set of numerical models: that describes the performance of the water systems (water distribution and urban drainage).

A reverse engineering model: that takes the predicted new developments land uses to asses the layout of the water services networks in such a way that the water services accessibility maps can be updated and create dynamic conditions that are incorporated in the simulation loop.

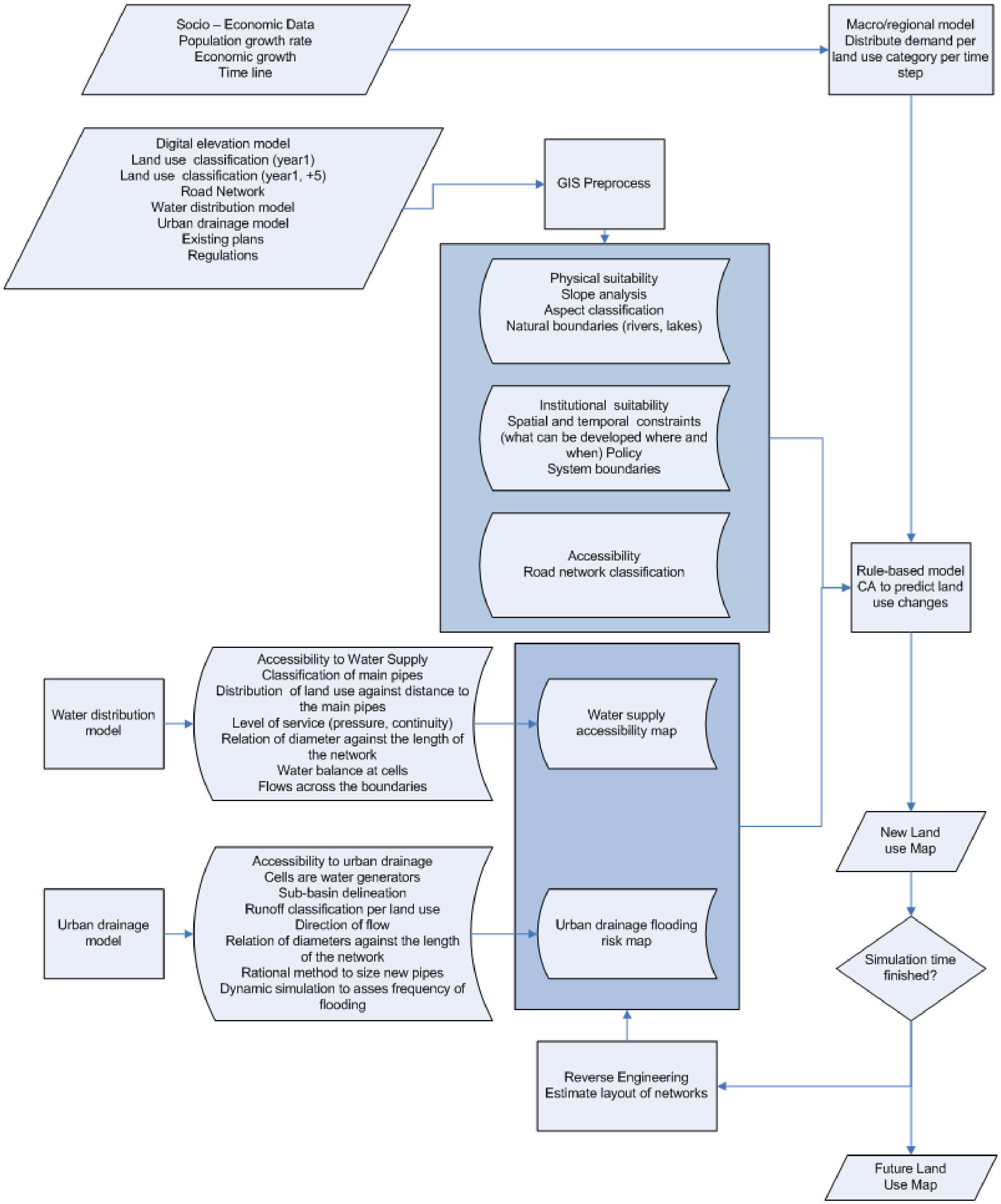


Figure3. General flowchart of the research methodology

Within the cellular automata model there are six elements that determine if a cell changes its land use state in a particular time step.

Physical suitability map: This is a map per land use being modeled. It is a composite map base on ecological and environmental maps, including factor such as elevation, slope, soil quality and stability, agricultural capacity, etc.

Zoning or institutional suitability: this is also a map per land use category, it is a composite map based on master plans and planning documents. Incorporate buffer zones, valuable protected zones, etc.

Accessibility map: it is calculated based on the easy access to the transportation network.

Water supply accessibility map: It's a map that considers the relative to the easy access to the pipe networks and the level of service. This map is updated at certain time steps when the feedback model or reverse engineering model is run.

Urban drainage flooding risk map: It's a map that considers the easy access to the pipe networks and the risk of flooding. This map is updated at certain time steps when the feedback model or reverse engineering model is run.

Transition rules: determines the dynamics and interaction of every cell within its neighborhood. For each land-use function, a set of rules determines the attraction or repulsion of each cell and land use function present in the neighborhood. If the attractiveness is high enough, the function will try to occupy the location; if not, it will look for more attractive places.

Figure 4 shows an example of a simulation time step.

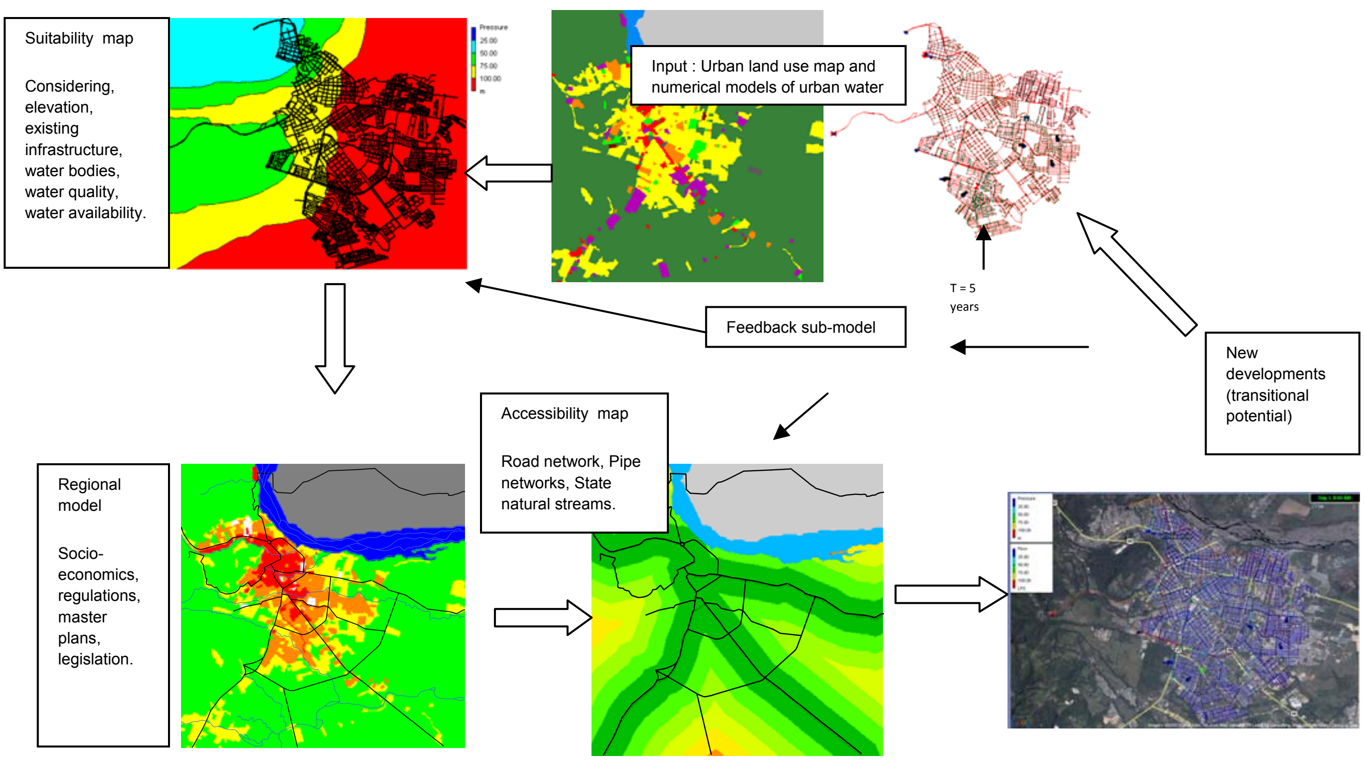


Figure 4. Example of a simulation time step with the proposed research methodology.

The reverse engineering model will considered the information from the new generated transition potential land use map necessary to estimated the layout of the water services networks and update the correspondent accessibility maps for the new simulation time step. Figure 5 presents an idea of how this can be done for the distribution network model.

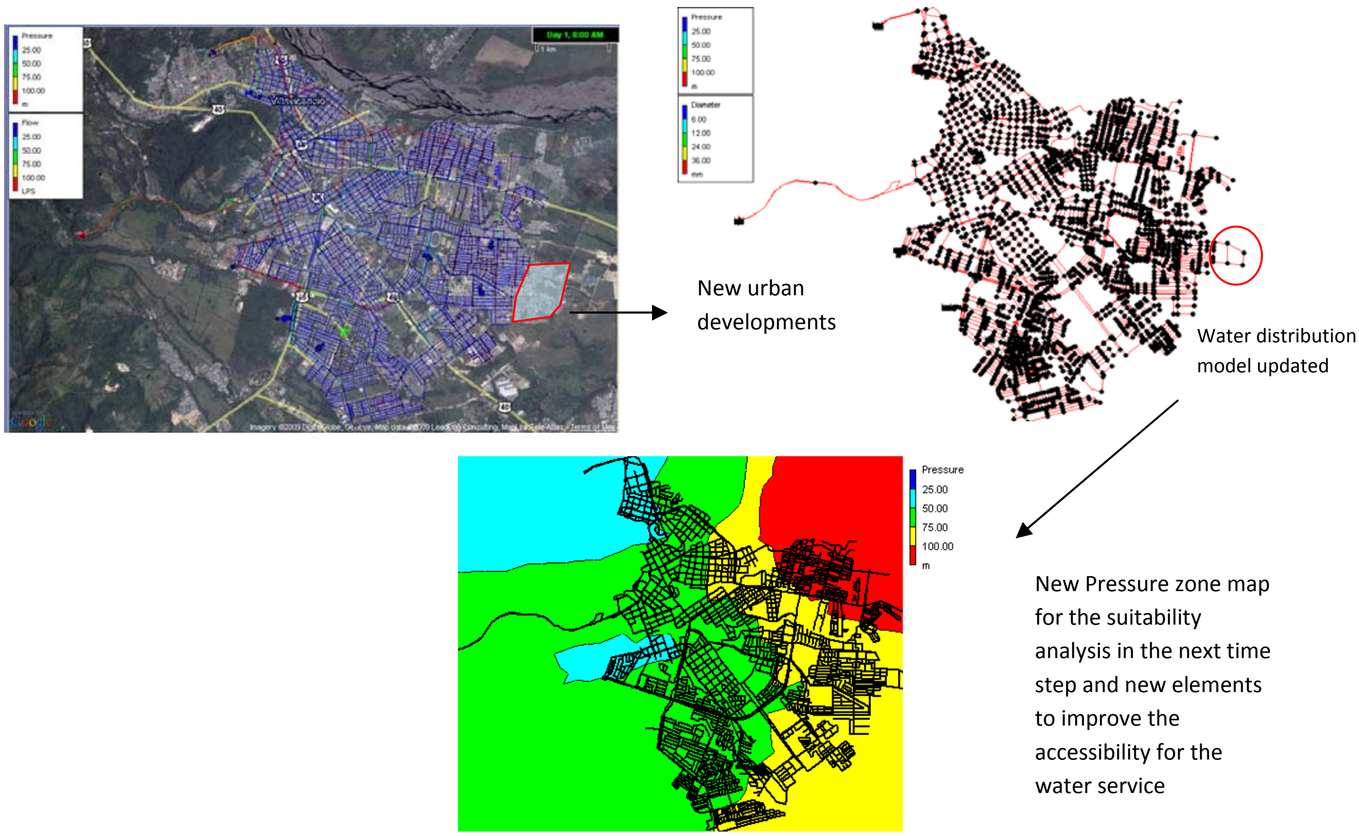


Figure 5. Reverse engineering model

As figure 5 shows the land use model will produce a new land use map that gives the growth directions of new developments. We can use that direction to get an idea of the environmental impact of the new developments, the risk and hazards and the impact to the existing water infrastructure. That direction serves also to spatially position the new layouts of the water services networks.

7.1 Illustrative Example

The example shown in figure 4 corresponds to a small municipality located in Colombia. For that case there was a water distribution model of the system available. An analysis of the existing network was carried out. First the distribution of diameter or pipe sizes against the length of the pipes gives an idea on the pipe size according with the total length of the system. This relation is shown in figure 6.

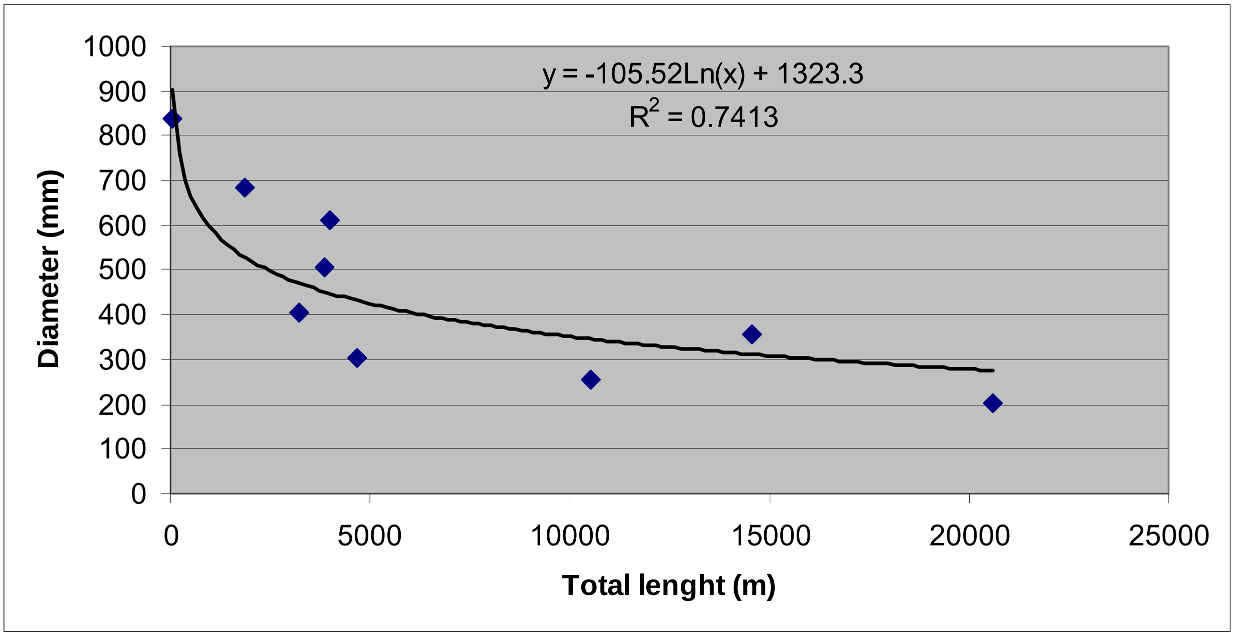


Figure 6. Distribution of pipe diameter against the length of the pipes.

From all the pipes that are part of the system, a selection was made in order to get the main trunks of the distribution system. Those main rings or pipes were used to build corridors or buffers at every 100 meters from the pipe until 1000 meters. This was done within ARCGIS 9.2.

The built corridors were then intercepted with the land use map to get a distribution of the land use area per category that fells into each corridor. Figure 7 shows the result of the analysis for residential land use category. Figure 8 shows the results for the land uses commercial, industrial, institutional and recreational.

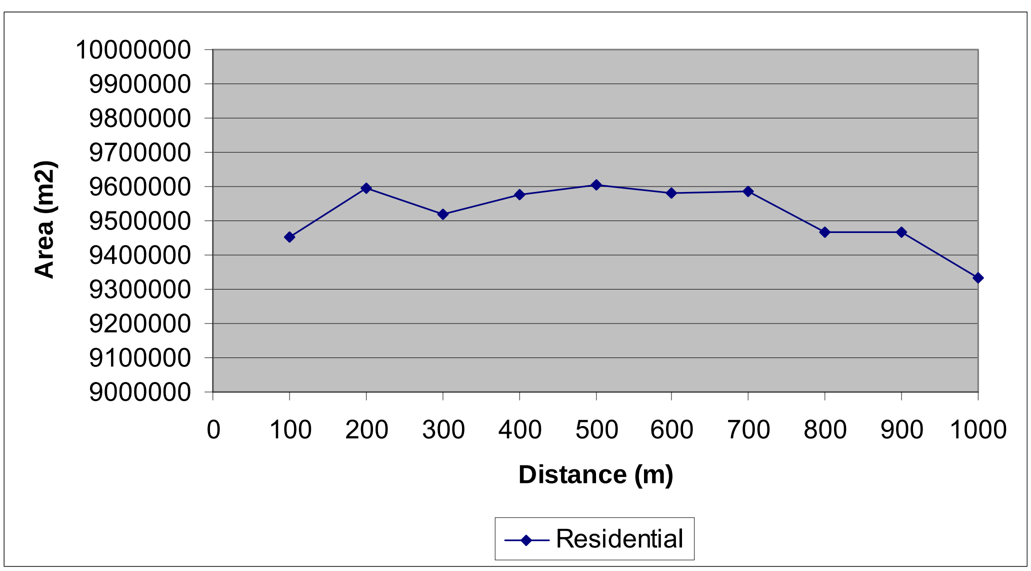


Figure 7. Residential land use area distribution with distance from the main pipes

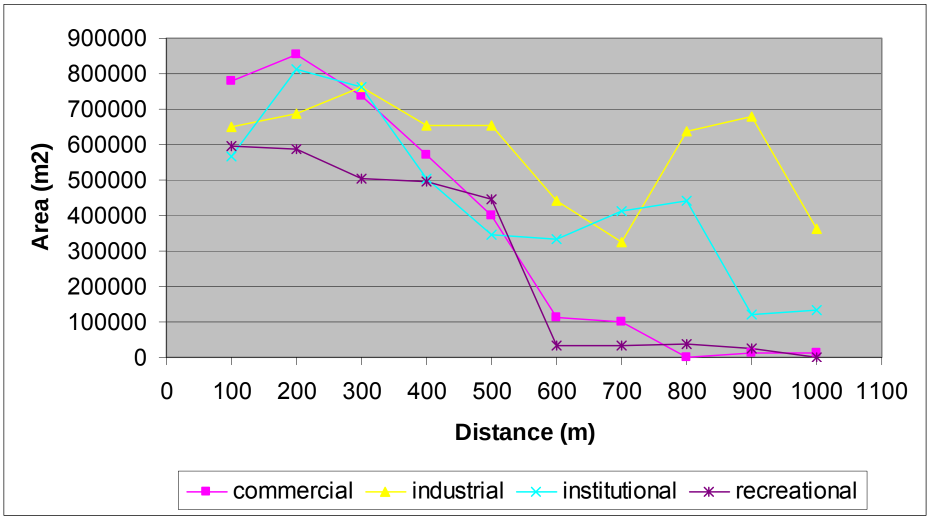


Figure 8. Land use area distribution with distance from the main pipes

Figure 7 shows that there is very little variation of the intercepted area of residential land use along the distance from the main pipes. This means that the distribution of residential land use tells very little about the possible position of water distribution pipes. In the other hand figure 8 shows that commercial and recreational land use can give information about the layout or positioning of the water distribution pipes. That information can be used to predict based on the estimated land use the positioning of new pipes in the futures scenarios. Industrial and institutional are more sensible to the distance and to which pipes are selected to perform the analysis.

This analysis was performed for different selections of pipe trunks increasing the interval of the pipe size to incorporate more pipes and the results are similar.

The same analysis using the same pipes and corridors was done for different cell sizes and the results are similar for residential land use no matter the scale of the cells. For commercial the behavior is also similar. There were some changes for institutional and recreational specially the initial values of the areas covered within the first corridor of 100 meters.

These results give an indication about some rules that can be used within the reverse engineering algorithm to position new pipes in the predicted new developments achieved by the cellular automata model.

For the drainage network the principle is similar, but the idea is to consider the main pipes or collectors of the system. Normally the shape of this network is dendritic and its location not only depends on the roads but also the direction of the flow and the delineation of the sub catchment at urban scale which depend on the elevation or terrain map.

8. Organization

8.1 research committee

Professor Dr. Arthur E. Mynett will be the promoter of this PhD research. Dr. Zoran Vojinovic will act as the co-promoter. The supervision of the research will be done by Professor Dr. Roland Price. Table 8.1 presents the team involved in the supervision of the research and their field of expertise. The Supervision, Training and Education Plan (STEP form) is presented in Annex I. Annex 2 Presents the curriculum vitae of the Author of the research. Results and updated research plans will be reported and submitted every year in February to the Unesco-IHE academic board via the PhD annual progress report and planning. This research is financed by the Unesco-IHE Suistainable Water management Improves Tomorrows Cities Health (SWITCH) Programme under theme 1 (urban water paradigm shift) and sub-theme 1.2 (Modeling of urban water systems and development of a decision support system). Additional funds are secured from Deltares software center and urban water systems.

Table 8.1 Supervision Team

Supervision Team		**Field**
Promoter	Prof. Dr. Arthur E. Mynett	Environmental hydroinformatics Hydraulic Engineering Cellular Automata / Population dynamics
Co-Promoter	Dr. Z. Vojinovic	Modeling and management of urban water systems Geographical information systems (GIS) Decision support systems
Supervisors	Prof. Dr. R.K. Price	Urban water systems Physical based modeling Knowledge management

8.2 Planning

The time frame is estimated to be 4 years, starting in April 2008 to April 2012. Table 8.2 shows the activities that are planned in this research. A summary of activities is listed below:

1st year: i. Research proposal. Review of experiences in the use of agent-based modeling for urban planning and water management.

ii. Agent based for urban water management: requirements and conceptual framework

2nd year i: Detail conceptual design of agent based for urban water management

ii: prototype of ABM for UWM Case study with water distribution network

3rd year i. prototype of ABM for UWM case study with urban drainage network

ii. prototype of integration of ABM for UWM

4th year i. Performance test and validation

ii. Review, comments, analysis and discussion

iii. Dissertation

Table 8.2 Research activities

Activities	2008			2009				2010				2011				2012			
	2/4	3/4	4/4	1/4	2/4	3/4	4/4	1/4	2/4	3/4	4/4	1/4	2/4	3/4	4/4	1/4	2/4	3/4	4/4
Literature review																			
Research Proposal																			
Methodology																			
Cellular automata and agent based models																			
Water distribution																			
Urban Drainage																			
Case 1																			
Data acquisition																			
WD model																			
UD model																			
CA model and Integration																			
Case 2																			
Data acquisition																			
WD model																			
UD model																			
CA model and Integration																			
Dissertation and Defense																			
Publications																			

8.3 Budget

The research is funded by SWITCH programme which is financed by the European Commission under the sixth framework directive.Additional Funds are secure from Deltares Software center development and urban water systems. Table 8.3 presents the cost and finances related to this research.

Table 8.3 PhD Budget

PhD Programme	**Euro**
Tuition Fee (Euro 8400/per year, @ 4 years)	33600
Health Insurance (euro 38 * 12 months* 4.75 years)	2166
Thesis printouts	4538
Public Defense	2723
Renovation MVV	200
Handling fee (Euro 455 * 4.75 years)	2275
Monthly allowance 12 months@1210 euro * 4.75 years	68970
Book allowance (300 euro per year)	1500
Travel cost in the Netherlands (500 euro per year)	2500
Conference/Excursions (750 euro per year)	3750
Miscellaneous (500 Euro per year)	2500
Total Ph.D Programme	**124722**

9. References

Barredo J., Kasanko M., McCormick N., Lavalle C. (2003). “Modeling dynamic spatial processes: simulation of urban future scenarios through cellular automata.” Journal of Landscape and urban planning. Vol 64. pp 145-160. Elsevier Science.

Batty, M. 1997. Cellular automata and urban form: a primer. Journal of the American Planning Association 63: 266–74.

Batty M and Longley P. (1994). Fractal Cities. A geometry of form and function. Academic Press. London, UK.

Benenson, I. and Torrens, P. M. 2004. Geosimulation: automata-based modeling of urban phenomena. London: John Wiley.

Chen Q. and Mynett A. E., "Effects of cell size and configuration in cellular automata based prey-predator modeling," Simulation Modelling Practice and Theory, vol. 11, pp. 609-625, 2003.

De Leon, F.D., Felsen, M. and Wilensky, U. (2007). NetLogo Urban Suite - Tijuana Bordertowns model. http://ccl.northwestern.edu/netlogo/models/UrbanSuite-TijuanaBordertowns. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL

Ducrot, R., Page, C. L., Bommel, P., and Kuperb, M. (2004). Articulating land and water dynamics with urbanization: An attempt to model natural resources management at the urban edge. Computers, Environment and Urban Systems, 28, 85- 106.

Engelen G., C. Lavalle , J.I. Barred, M. va n de r Meulen and R. White. (2007). The Moland modeling framework for urban and regional land-use dynamics. In: Modeling Land Use change: Progress and applications. Edited by Koomen Eric, Stillwell John, Bakema Aldrik, Scholten Henk J. Springer. The Netherlands.

Farolfi, S., and Hassan, R. M. (2003). AWARE: A Decision Support Tool towards decentralized water management in South Africa. International Colloquium in “Water Governance and Sustainable Development”, Sousse (Tunisia), 9 & 10 October 2003.

Feuillette, S., Bousquet, F., and Goulven, P. L.(2003). SINUSE: A multi-agent model to negotiate water demand management on a free access water table. Environmental Modelling & Software 18, 413-427.

Houet T & L Hubert-Moy, 2006. Modelling and projecting land-use and land-cover changes with a Cellular Automaton in considering landscape trajectories: An improvement for simulation of plausible future states. EARSeL eProceedings, 5(1): 63-76.

Kok Kasper and van Delden Hedwig. (2007). Combining two approaches of integrated scecnario development to combat desertification in the Guadalentin watershed, Spain. Environment and Planning B: Planning and Design 2007, vol. 34.

Lechner T., Watson B.A., Tisue S., Wilensky U. & Felsen M. (2004). Procedural modeling of land use in cities. Technical report NWU-CS-04-38.

Moreno N., and Marceau D. (2007). Modeling land use changes using a novel vector-based geographic cellular automata. Proceedings of international conference Modeling and Simulation. IAESTED. Canada.

Price, R. K. (2004). Modelling Urban Drainage Systems: Part I Theoretical Development. Hydro informatics Lecture Notes. UNESCO-IHE. Delft. The Netherlands.

RIKS. (01/2009). Accesed via Web at http://www.riks.nl

Torrens, P. M. 2003. Automata-based models of urban systems. In Advanced Spatial Analysis: the CASA Book of GIS, Eds. P. Longley and M. Batty, 61–81. Redlands, California: ESRI Press.

Tzima F., Athanasiadis I., and Mitkas P. (2006). Report on the development of agent based models for water demand and supply. Nostrum-DSS. EC.

Van Delden H., Luja P., and Engelen W. (2007). Integration of multi-scale dynamic spatial models of socio-economic and physical processes for river basin management. Journal Environmental modeling and software. Vol. 22, pp 223-238.

Van Vliet J., and Van Delden H. (2008). “An activity based cellular automaton model to simulate land use changes”. International Congress on Environmental Modelling and Software. (iEMSs). Barcelona, Spain.

Vojinovic, Z. (2005). “Introduction to Urban Water Modelling.” Lectures notes in Hydro-informatics. UNESCO-IHE. Delft – The Netherlands.

Von Neumann, J. 1949. Theory of self-reproducing automata. University of Illinois Press, Urbana and London. 388 pp.

White, R. and Engelen, G. 1994. Cellular dynamics and GIS: modelling spatial complexity. Geographical Systems 1: 237–53.

Zellner, M., L. (2007). Generating policies for sustainable water use in complex scenarios: an agent-based model of Monroe County, Michigan. Environment and Planning B: Planning and Design 2007, vol. 34, pp 664-686.

Appendix 1. STEP programme

(This form is to be submitted to the academic board together with the PhD Research Proposal for approval. A first draft is to be discussed with the PhD coordinator within one month upon arrival in Delft.)

Date of submission of this report:

1. PERSONAL DATA

Surname : Sanchez Torres

First Name : Arlex

Nationality : Colombian Date of Birth: 17/01/1977 **Male**/Female

Locker Number : HIKM

Email : a.sanchez@unesco-ihe.org / asantorres@hotmail.com

MSc Degree

Year : 2007

Discipline : Hydroinformatics

University or institute : UNESCO-IHE at: Delft

Starting date of PhD (date of enrolment): 1st April 2008

Financing (sponsor) : SWITCH Project and Deltares

2. SUPERVISION

Promoter : Prof. Ph.D Arthur E. Mynett

Co-Promoter : Assoc. Prof. Ph.D Z. Vojinovic

Supervisor : Prof. Ph.D R.K. Price

Other member(s) :

3. RESEARCH PLAN

Title research project:

The use of Agent-Based Models for integrated urban water management

Problem Setting and Objective:

Problem setting

Cities are considered complex systems that show characteristics of emergence, self-similarity, self-organization and non-linear behavior of land use changes with time, Batty and Langley, 1994. Agent-based models are a modeling paradigm used to represent the same phenomena or characteristics in several disciplines of sciences. Integrated urban water management is a challenging issue that aims the sustainable use of the water resources so that the demands can be met now and in the future in terms of quality and quantity. The current practices in the sector are leading towards a crisis that is calling for innovative thinking and the adoption of new strategies including integrated thinking and planning. The idea with this work is to contribute to the development of a tool for integrated analysis and planning that can help planners and decision-makers at the city level to understand the main drivers affecting the urban water cycle, to analyze future scenarios of city expansion and foresee bottlenecks and possible solutions. The tool can be used for rehabilitation testing and planning strategies.

Objective

The objectives of the research are:

- to explore the application of agent-based models on urban water problems.
- to apply the concepts and principles of emergence in the development of urban areas.
- to show the impact of the urban dynamics in the evolution of the water systems (pipe networks) and vice versa.
- To demonstrate the functioning and effectiveness of agent-base models for IUWM on two selected SWITCH demo cities.

Time Schedule (summary)

1st year: i. Research proposal. Review of experiences in the use of agent-based modeling for urban planning and water management.

ii. Agent based for urban water management: requirements and conceptual framework

2nd year i: Detail conceptual design of agent based for urban water management

ii: prototype of ABM for UWM Case study with water distribution network

3rd year i. prototype of ABM for UWM case study with urban drainage network

ii. prototype of integration of ABM for UWM

4th year i. Performance test and validation

ii. Review, comments, analysis and discussion

iii. Dissertation

4. TRAINING

List modules or courses that are of interest for the PhD research. This list may contain elements of all Master Programmes provided by UNESCO-IHE. Listing a module or course doesnot give the obligation of actually taking the course, but it helps to formulate in a later stage a suitable training programme.

Name of module/course	Name MSc programme/Specialisation	Time in year (Block#)	Study Load (ECTS)
Water system modeling	WSE	11	5
Integrated urban water management	WSE	2	5
Data analysis	WSE	6	5

For courses to be taken elsewhere permission has to be obtained from the Promoter and financing has to be secured first.

Course to be taken elsewhere	Name University or institute	Estimated Cost	Study Load (ECTS)
Individual and agent based modeling	Dresden university of technology	Euro 500	
Advanced agent based modeling	University of Surrey	Euro 250	

5. CONTRIBUTION TO THE EDUCATIONAL PROGRAMME OF UNESCO-IHE

The intention to contribute to the educational programme of UNESCO-IHE may be listed here, if appropriate. For those working in a sandwich construction, opportunities to participate in the transfer of knowledge in their own country should be explored.

It is generally recommended not to be involved in teaching activities during the first year after registration.

Type of contribution [1])	Name MSc programme/Specialisation	Time in year (Block#)
GIS Exercise	HI	2009, 3
Modeling system development	HI	2009, 5
Groupwork assitance	WSE	2009, 12
MSc Supervision	HI	2009, 15

1) Lecturing,supeprvision of workshop or laboratory sessions, fieldwork,excursion, role play, MSc supervision, groupwork guidance, etc.

6. COMPULSORY COURSES WITH EVALUATION FOR NON-IHE MSc HOLDERS

PhD student who did not obtain an MSc at UNESCO-IHE have to list the courses and/or modules that are compulsory part of the PhD training programme.

Name of course or module	Month/year	Study load (ECTS)
No compulsory courses are needed.		

Appendix 2. Curriculum Vitae

Personal Detail

Name :	Arlex Sanchez Torres
Profession:	Sanitary Engineer, MSc.
Date of Birth:	January 17 / 1977, Cali - Colombia
Nationality:	Colombian
Home Address:	Zuidpoldersingel 5, 2645 JJ Delfgauw – The Netherlands.
Telephone Contact:	+ 0031 623407206
e-mail:	a.sanchez@unesco-ihe.org / asantorres@hotmail.com

Profile (Key Points)

- PhD research fellow at the hydroinformatics department at Unesco-IHE, Delft - The Netherlands. Research topic on the use of agent-based models for integrated urban water management.
- Experience on evaluation and implementation of water supply systems in developing countries.
- Formulation of plans for integrated water resources management and planning at catchment level.
- Water distribution and sewer network modeling and optimization (Epanet, SWMM, Watercad and others).
- Research experience on drinking water treatment technologies.
- Trainer on operation and maintenance and water quality control in water treatments plants and water distribution network modelling

Education

Master of Science Degree. 2007. Water, Science and Engineering, specialization in Hydroinformatics. Diploma issued by UNESCO-IHE Institute for Water Education. Delft, The Netherlands.

Sanitary Engineer May. 2001. Professional Diploma issued by Universidad del Valle. Cali, Colombia.

Language

Spanish and English

Experience

Instituto Cinara - Universidad del Valle, - Instituto de Investigación y Desarrollo en Agua Potable, Saneamiento Básico y Conservación del Recurso Hídrico. Sanitary Engineer, Since 2001 – October 2005. Participation at the following projects:

Programme: Formulation of 10 plans for land and watershed management in the Valle del Cauca Region. January 2005 – October 2005.

Project : Integrated water resources management plan of the watershed of Tasajo´s River jointly with Corpocaldas. January 2005 – Current position.

Rural Water Supply Programme in the Valle del Cauca Region. Coordinator of the efficient use of water component in three rural communities. August 2003 – November 2004.

Junior Professional Officer at IRC, International Water and Sanitation Centre. International Exchange programme between Cinara and IRC. November 2001 – July 2003. Delft, the Netherlands

- Project: “Municipio del Tambo, Cauca. Zona rural. Convenio Municipio del Tambo, Fundación Cinara”. June-November, 2001. Preparation and execution of a community workshop: Participative evaluation of components of the water supply systems. Sanitary inspection and sanitary risk assessment. Inventory and review of the water distribution network. Participation on the design of the water treatment plants and preparation of final Budget.

- Project: “Corregimiento de Tribunas Córcega, Pereira. Convenio Municipio de Pereira, Aguas y Aguas de Pereira, Asociación de Usuarios del Acueducto de Tribunas Córcega, Fundación Cinara”. February – May, 2001. Design of the water treatment plant by Multi-Stage Filtration technology. Elaboration of hydraulic calculations and budget.

- Short Workshop. March, 2001. “Operación y mantenimiento de plantas de potabilización por filtración en múltiples etapas en el Colegio Ingles de los Andes”. Cali. Valle. Preparation of presentations, execution of operation and maintenance activities at the water treatment plant.

- Short Workshop. June, 2001. “Operación y mantenimiento de plantas convencionales y compactas para la potabilización del agua”. Municipio de Palmira. Valle. Preparation of presentations and the course manual, ejecution of operation and laboratory activities at the water plant.

- Research Project. October 2000 – January, 2001. Use of natural and syntectic fabrics for the protection of the filter media on slow sand filters in tropical environments. Initial test and monitoring the efficiency and hydraulics performance of the pilot plant. Managing and processing information; writing part of the final report and summary report.

Instituto Cinara - Universidad del Valle, - Instituto de Investigación y Desarrollo en Agua Potable, Saneamiento Básico y Conservación del Recurso Hídrico. Student Assistant, Since 1996 - 2000. Participation at the following projects:

- Research: Optimization and development of contact clarification technology using roughing filters in layers:

- Search literature, Database " Biblio" management of bibliografic references.

- Research Student. Thesis "Comparison of two Configurations of filter media in clarificators of gravel in layers, treating water of the Cauca river. Water quality monitoring and hydraulic behaviour of the pilot plant. Processing and analysis of information. Writing the final document.

- Research and development of the MSF, Multi stage Filtration technology:

- Actualisation the database on MSF technology generated during the research projects in the research and technology transfer station in Puerto Mallarino.

- Support of the Ph. D. Program of Prof. Gerardo Galvis. Desk work. Processing and management of water quality information.

- Facilitator of training programs :

- Workshop-seminar "Abastecimiento de Agua y –Sostenibilidad. Agua 98. Preparation of case studies and course moderation.

- Preparation of a short workshop on Drinking water networks modelling for the last year students of the sanitary engineer programme at Univalle.

- Programs to improve the water quality :

- Project: "Selección de Tecnología y Análisis de Costos en Sistemas de Potabilización de Agua" . Inventory about optimization of plants and type of plants in Colombia.

Universidad del Valle. Student assistance for the Laboratory practices on drinking water and wastewater process. 1998. Preparation of laboratory practises for students of the sanitary engineer program.

University student exchange program. Work Experience USA, subdivisión of CampCounselors USA. May - October / 2000. Unit Supervisor at Cedar Point Amusement Park. Sandusky, Ohio. USA.

Additional degrees/certifications:

Professional development course on " Water conservation and demand management". June 2003. offered by the University of Newcastle and the University of Birmingham. New Castle, United Kingdom.

II International Conference “Efficient use and management of urban water supply". April 2003. Organized by IWA, International Water Association. The conference was held in Tenerife, Spain.

Short course "Water transport and distribution".2002. Offered by IHE-UNESCO institute for Water Education, held in Delft, the Netherlands.

Seminar. Water Distribution Network Modelling . September. 2000. Offered by Haestad Methods. Columbus, Ohio. USA.

Publications

Vojinovic Z., and Sánchez Torres A. 2008. Optimising Sewer System Rehabilitation Strategies between Flooding, Overflow Emissions and Investment Costs. Paper presented at 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

Sanchez Arlex. 2007. Towards a demonstrator of an urban drainage decision support system. Master of Science Thesis. UNESCO-IHE. Delft, The Netherlands.

SANCHEZ Arlex, SANCHEZ Luis D. and VARGAS Silena. CD ROM. Multimedia Material on efficient use of water. 2004.

SANCHEZ Arlex, SMITS Stef, SANCHEZ Luis D. ; 2003. Recognizing reality ; multiple use of rural water supply systems. International Conference Agua 2003. Cartagena de Indias, Colombia.

SANCHEZ Arlex and SANCHEZ Luis Dario. 2003. Uso Eficiente de Agua. Thematic Overview Paper, TOP. IRC, International Water and Sanitation Centre; Instituto Cinara. Cali, Colombia.

SANCHEZ, Arlex. 2000. Comparación de Dos Configuraciones de Medio Filtrante en Clarificadores de Filtración Gruesa Ascendente en Capas. Tesis de Grado. Facultad de Ingenieria. Universidad del Valle. Cali, Colombia.

FERNÁNDEZ, Javier, SANCHEZ, Arlex; LATORRE, Jorge; MUÑOZ, Noel; BERÓN, Fabiola; y RESTREPO, Maribel. 2001. Uso de Fibras Naturales y Sintéticas en Filtración Lenta en Colombia. Una Experiencia en Ambientes Tropicales. Universidad del Valle – Cinara – Colciencias. Cali, Colombia.

2. List of conference papers

ACCEPTED AND PUBLISHED

Vojinovic Z. and Sanchez A. (2008). Optimising Sewer System Rehabilitation Strategies between flooding overflow emmisions and investment costs. 11th International conference on urban drainage. Edinburgh, Scotland.

Sanchez A., Vojinovic Z., and Price R. K. (2010). Planning urban water systems: modeling using cellular automata and numerical models. 9th International Conference on Hydroinformatics, HIC 2010. Tianjin, CHINA.

Sanchez A., Vojinovic Z., and Waly M. (2011). Towards an approach to the evolution of urban drainage networks using agent-based models. 12th International Conference on Urban Drainage. Porto Alegre, Brazil. This Paper is accepted, will be published in September 2011.

UNDER REVIEW

Sanchez A., Price R. K. and Vojinovic Z., (2011). Determining the route for a water main in a new urbanising area. Submited to the 11th International conference Computing and Control for the Water Industry: :Urban Water Management: Challenges and Opportunities”. CCWI 2011. Exeter, UK.

3. Planning for Finalizing the Thesis

Overview of Work to be done

The methodology to generate the layout of the water distribution model is almost complete, The new algorithm has been integrated with with an optimization tool (NSGA II) to size the pipes in the existing areas and compare with the real situation. The results are promising since the designed network resembles the existing system spatially. The range of the pipe diameters found is also similar to those in reality. Currently the work is focus in building a set of indicators to evaluate the performance of this approach. A tool to link the demand of water with the land use has to be developed to estimate the demand in the new areas. After this the approach will be applied to new areas of development predicted by the Cellular automata model. Once this approach is completed it will be applied to the case studies. This activity has a delay according with the original planning since the software development and debugging has taken a big effort to be completed. The tools are being developed in the framework of this project since they did no exist previously.

Based on the experience with the development of the code for the water distribution network modeling approach, it is estimated that during 2011 the tools to integrate the urban drainage component will be completed. Some work has been done already in this part since there are already tools that link the urban drainage tool with an optimizer to size the network and estimate the flood damages and costs. The methodology developed has been tested in the case study of the city of Birmingham in the UK. The drainage network for the Upper Rae Main was made available by the learning alliance and Severn Trend. The model was built in the software platform infoworks. The model consisted of nearly 6500 pipes and nodes. For the purpose of using it in this case study, the model was converted to SWMM 5.0 and simplified so that the main skeleton of the network was kept. The simplified model was setup and run for two events of different return periods. The cellular automata model for the city of Birmingham was also developed. There is still work to be done to calibrate the cellular automata model and built a tool to integrate the SWMM model with the CA.

In parallel to the completion of the modeling tools, they will be tested using case studies to debug and evaluate the performance of the algorithms and the whole approach.

Publications in peer review journals are expected for 2011 onwards. The dissertation is expected to be finalized by the end of 2012. The new time schedule is presented in the table below. There is a shift in the planning of approximately 8 months. Since the Switch project finished in January 2011, there is a need to find resource for 2 years of research.

Likely Source of Funding

Funds are secure from Deltares Software center development and urban water systems.

Date of submission: 03/25/11	**Approval by Supervisor** Yes
Assoc. Prof. Dr. Zoran Vojinovic	
Comments by the Supervisor	**The work is in accordance with the objectives set at the beginning of the research. No further comments.**

Table 1 New Time Schedule for Research activities

Activities	2011				2012			
	1/4	2/4	3/4	4/4	1/4	2/4	3/4	4/4
Literature review	■	■	■	■	■	■	■	
Research Proposal	■							
Methodology								
Cellular automata and agent based models	■	■	■	■				
Water distribution	■	■						
Urban Drainage			■	■				
Case 1								
Data acquisition	■	■						
WD model		■	■					
UD model	■	■						
CA model and Integration		■	■					
Case 2			■	■	■	■		
Data acquisition		■	■					
WD model			■	■				
UD model				■	■			
CA model and Integration					■	■		
Dissertation and Defense						■	■	■
Publications		■		■			■	

ANNEX

Optimising Sewer System Rehabilitation Strategies between Flooding, Overflow Emissions and Investment Costs

*Z. VOJINOVIC, AND A. SÁNCHEZ T**.

Department of Hydroinformatics and Knowledge Management, UNESCO-IHE, Institute for Water Education, Westvest 7, 2611 AX Delft, The Netherlands

**Corresponding Author E-mail* z.vojinovic@unesco-ihe.org

*** Institute Cinara, Universidad del Valle, Cali – Colombia.*

ABSTRACT

Sewer systems constitute a very significant portion of all assets in urban areas. Their structural integrity and functional efficiency represent key parameters for the safe transfer and disposal of surface run-off and domestic/trade discharges. The failure of these assets may easily result in uncontrollable discharges and surface flooding, pollution of receiving waters, pollution of ground water and soil, treatment plant impacts and increasing maintenance costs. The lack of an appropriate methodology for remedial works identification may result in expenditure programmes not achieving their given objectives, and therefore, the optimisation of rehabilitation works is of utmost importance. A platform that links the hydrodynamic model of a drainage system with the multi-criteria global evolutionary optimisation engine that takes into account the performance indicators relevant for rehabilitation decisions (including various constraints such as, system capacity, overflow emissions, environmental impacts, and investment costs) related to the system's operation is being developed. The results obtained to date suggest that the proposed approach can be effective in solving some of the difficult problems concerning urban drainage/sewerage infrastructure.

KEYWORDS

Multi-Objective Optimization, Urban drainage system, sewer rehabilitation strategies, NSGA-II, SWMM 5.0

INTRODUCTION

Sewer systems constitute a very significant portion of all assets in urban areas. Their structural integrity and functional efficiency represent key parameters for the safe transfer and disposal of surface run-off and domestic/trade discharges. The failure of these assets, which could be caused by various factors such as ageing, structural collapses, inflow/infiltration, exfiltration (leaking) and insufficient capacity due to increased urbanisation, may easily result in uncontrollable discharges and surface flooding, pollution of receiving waters, pollution of ground water and soil, treatment plant impacts and increasing maintenance costs. Therefore, the sustainability of such assets, which frequently, if not continuously, interact with other components of urban water cycle (i.e., water supply, groundwater and receiving waters), is therefore an important issue for urban drainage system managers. Furthermore, the frequency of high intensity rainfall seems to increase in many regions and climatologists predict climate changes that will increase the problem even further. The lack of an appropriate methodology for remedial works identification may result in expenditure programmes not achieving their given objectives, and therefore, the optimisation of rehabilitation works is of utmost

importance. With the reference to the work published to date, the practitioner's attention to the use of full-fledge multi-criteria global evolutionary optimisation techniques in the dynamic context of sewer systems is found to be very limited.

A platform that links the hydrodynamic model of a drainage system, SWMM 5.0, with the multi-criteria global evolutionary optimisation engine, NSGA II, which takes into account the performance indicators relevant for rehabilitation decisions (including various constraints such as, system capacity, overflow emissions, environmental impacts, and investment costs) related to the system's operation is being developed.

The advantage of this approach over the standard industry applied approaches (which are often limited to the use of a linear optimization scheme or a non-hydrodynamic computation) is that it solves the problem within the entire catchment with the use of sophisticated optimisation techniques and takes into account the dynamic nature of drainage systems during the process of identifying the least cost rehabilitation option. This paper presents the results from an ongoing research work and builds upon the foundation of earlier research efforts (Vojinovic et. al. 2006, Barreto et. al. 2007, Vojinovic et. al. 2007).

METHODOLOGY

The present work explores the use of some of the recent multi-objective evolutionary approaches such as NSGA-II (Deb, 2002) for the purpose of finding optimal sewer system rehabilitation strategies by using three objective functions namely, rehabilitation cost, flood damage and overflow caused pollution.

To handle the optimization process the NSGA-II algorithm developed by Deb (2002) was used. The NSGA-II has been tested and probed to develop good Pareto fronts and can manage several objective functions and constraints (i.e Barreto et al 2006, and Muschalla 2006). The Storm Water Management Model (SWMM version 5.0) is used as computation engine to simulate hydrological, hydraulics and water quality routing and processes in the system.

To link the genetic algorithm with the computation engine SWMM 5.0 two intermediate link routines were written. The first one runs the original model in SWMM 5.0 and computes the magnitude of the flooding, the surcharged pipes, and the initial values of the different variables and maximum values of the objective functions. The second routine directly links the NSGA II and SWMM 5.0 by interpreting the randomly generated population of the GA for the variables and computing the value of the three objective functions that are passed to the GAs for evaluation and generation of further populations.

The following steps are used in finding the optimal alternative of rehabilitation works requirements (see Figure 1):

- Initial simulation of the existing drainage network.
- Performance evaluation against given standards (constraints).
- Calculation of objective functions.
- Identification of the new drainage network set up (i.e., new rehabilitation strategy).
- Simulation of the new drainage network.

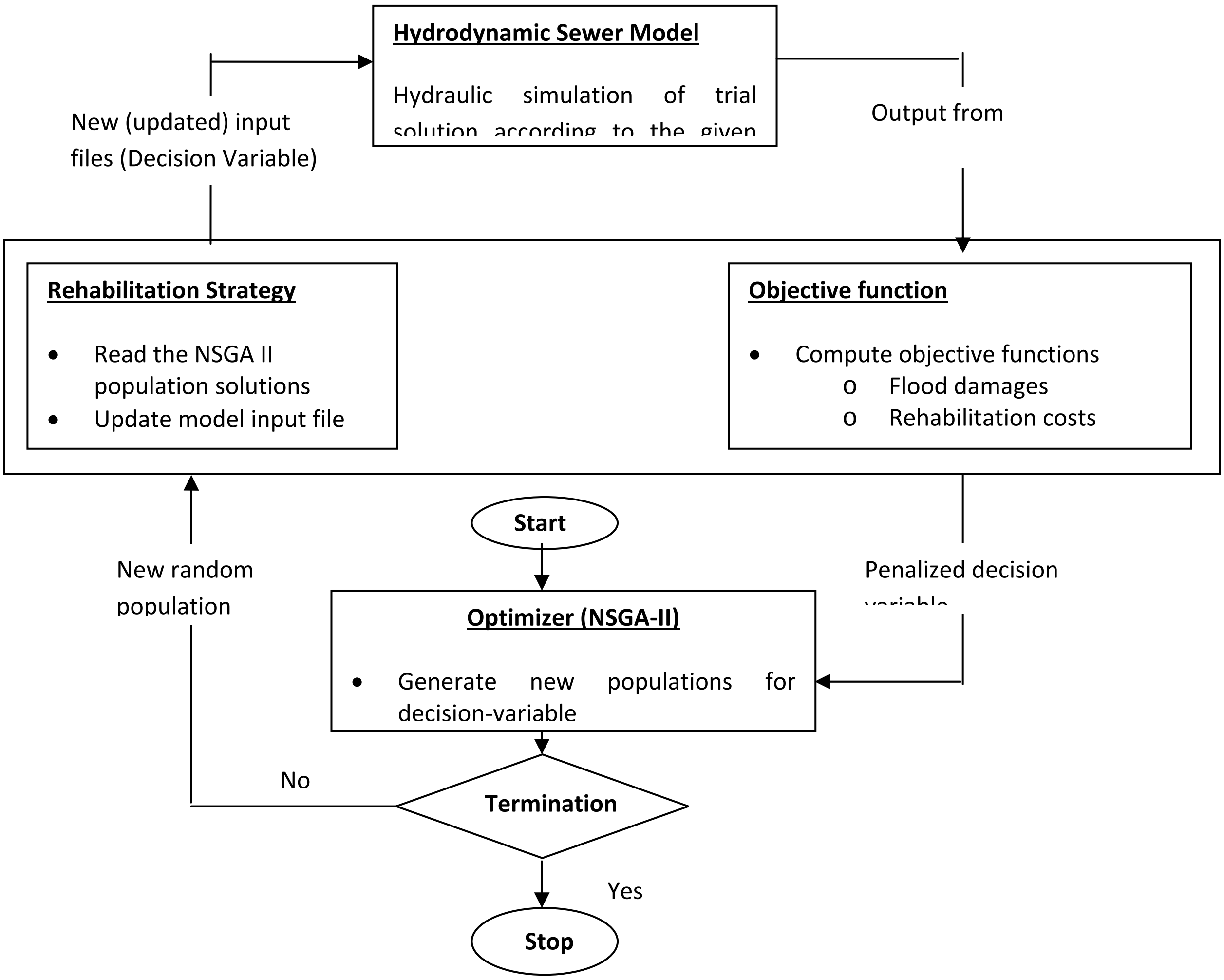


Figure 1. Schematization of the optimization loop.

Objective Functions

Overflow caused pollution

In this study a concentration of total suspended solids is assigned for different nodes as dry weather flow and the event mean concentration method is used for the build up of pollutants in the catchments. Once the model is run in SWMM 5.0 the output reports the total amount (mass) of pollutants that was generated from dry weather flow and wet weather flow.

If sufficient conveyance capacity exist within the network, then the sum of these two amounts will represent the total mass of pollutants that will end up in the recipient water body. In case of flooding, the model accounts for overland surcharge and in the same way it accounts for the total mass of pollutants that is contained within the corresponding mass of flood water.

To represent this situation and take into account possible Best Management Practices (BMPs) for urban drainage, Figure 2 shows a conceptual model that illustrates a mass balance in the system. BMPs are referred to as measures that can improve the water quality and alleviate the discharge that goes to receiving water body. Some of the measures include storage or detention basin with a certain level of treatment, infiltration, biofiltration, etc.

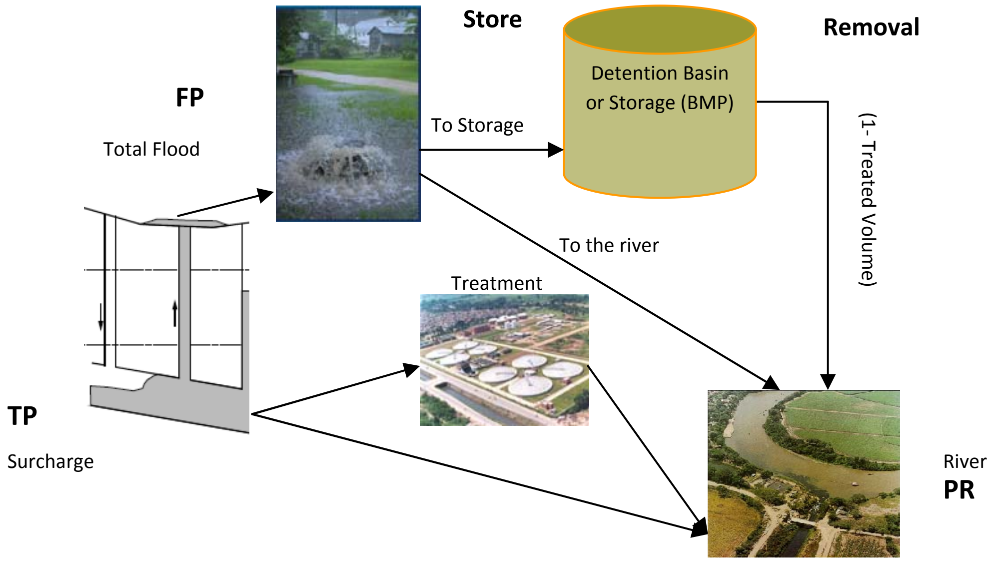


Figure 2. Conceptual model to account for storage and treatment of flooding.

(TP) = Total mass of pollutants (dry weather) + Pollutants (wet weather);

(FP) = Mass of pollutants leaving the system by flooding;

(PR) = Mass of pollutants that reaches the outfall in the river;

Store = Volume of water to store;

Removal = Fraction of pollutants that can be removed (efficiency).

In this model, one fraction of the amount of water and pollutants that leaves the system in the flooding is allowed to be stored. The storage is represented as a fraction of the total flood and it is a variable which is used in the optimization process. To control the storage volume, a percentage of the maximum flood can be assumed as the maximum storage capacity available in the urban area under consideration.

The amount of water that is stored in this way is discounted from the flood damage objective function. Additionally, the stored water can have a certain level of treatment or removal of the pollutants. This is also represented as a fraction of removal and it is yet another variable used in the optimization process of the work presented here.

The objective function is formulated as a penalty function for water pollution. For this study the following amounts are assumed for the penalty function:

Maxallow : 5000 (maximum amount of pollutant that can be discharged to the river without affecting the environment).

C1 : Cost associated to the discharge below Maxallow (assumed as 100)

C2: Cost associated to the discharge above Maxallow (assumed as 10000)

C3: Assumed cost penalty for having polluted water on the streets (10000)

C4: Assumed cost to discharge wastewater from storage with not treatment (100)

The objective function for the overflow caused pollution can be written as:

Water Pollution Objective = (PR -Maxallow)*C2 + Maxallow*C1 + (1-store)*FP*C3 + store*(1-removal)*FP*C4

Flood damage function

The flooding damage is computed based on the flooding magnitude calculated at each node. This follows a similar approach as discussed by Tanaka and Tarano (2000), Vojinovic et al. (2005) and Barreto et al. (2006).

The flood damage function is as follows:

$$FD(h) = (\sum_{i=1}^{n} \beta * (\exp(\frac{S_i - S_{allow}}{1000}) - 1)$$

Where:

FD(h) is the flood damage with the function of volume;

S_i is the flood volume at each node (ha-mm);

S_{allow} is the maximum allowable flood volume (assumed 1ha-mm);

n is the number of nodes analyzed in the network;

β is a penalty factor (100.000 in this case), this value will depend on the value of property for example.

To account for the effect of the allowed storage volume from the total flooding, an equivalent fraction is deducted from the flood damage function during the evaluation of the above objective function in the optimization loop.

Flood damage function can be expressed as:

$$\text{Flood damage } = (1 - vol / \max vol) * FD(h)$$

Where: *vol*: is the storage volume of a particular solution;

Max vol: is the maximum allowable volume of storage

Rehabilitation Cost

The total cost is a combination of actual cost and operational cost when the whole design cost need to be considered. For example the cost of storage and wastewater treatment and operation of pumps will need to be considered. The infrastructural cost objective function includes the cost of pipe replacement, the cost for storage of a fraction of the flood volume and the level of treatment of the stored water.

The rehabilitation cost function can be expressed as:

Rehabilitation cost $= \sum_{i=1}^{n} C(D_i) * L_i + Vol * Cost_{vol} + TreatedVol * Cost_{treat} + Treatment_{WWTP} * Cost_{TreatWWTP}$

Where, n is the number of pipes in the network and $C(D_i)$ is the cost per unit length of the pipe (i) with diameter D_i and length L_i, Vol (storage volume of flood (%)), $Cost_{vol}$ (cost of storage \$/m3), $Treatedvol$ (fraction of store volume that receives treatment) and $Cost_{treat}$ (cost of the treatment system, it will depend on the BMP or treatment technology), $Treatment_{wwtp}$ is the amount of pollutant treated at the treatment plant, $Cost_{treatwwtp}$ is the operational cost to remove the pollutant (assumed as 1.2 \$/Kg)

All results obtained from objective functions calculations are normalized within the interval [0,1]. Normalization typically provides an advantage for the graphical evaluation of the pareto and the solutions.

Case Study

An experimental work based on a case study was carried out in order to test the approach described in previous sections of this paper. The study area comprises of a combined sewer catchment in the city of Cali in southwestern Colombia. The base model was built in SWMM 5.0, the model incorporates a node with wastewater treatment in a simplified way (the concentration of the pollutant is removed by a 60% efficiency). The receiving water river is also incorporated in a simplistic way to integrate the system and to facilitate an integrated analysis. Figure 3 shows the schematization of the network.

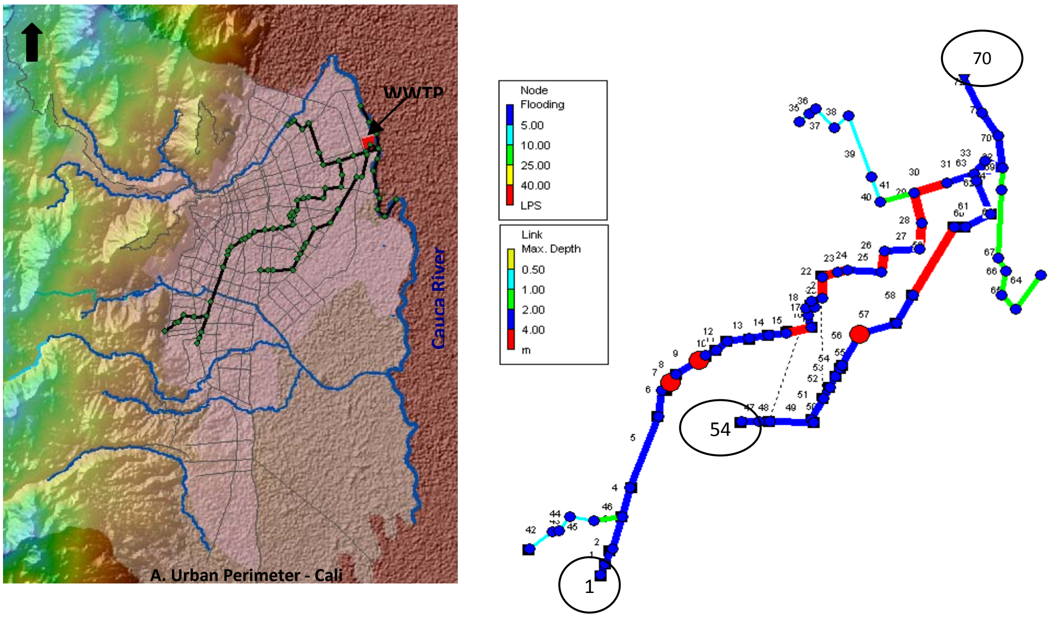


Figure 3. Schematization of the case study and initial run.

A typical design rainfall event for the area was used (i.e., 1:5 year ARI event). The initial run displayed a result with several locations being flooded. These are the locations which were used within the optimization process to adjust diameters of those pipes which are cause for flooding and to minimize flood impacts.

The probability of crossover was set as 0.9 and the probability of mutation was set as 1/nreal, where nreal is the number of real variables. Barreto, 2006.

The total number of variables used in this study was 74. Out of 74 variables, 72 correspond to the number of pipes in the model; the diameter is used as a variable and each pipe has a value in a catalogue with 20 commercially available sizes. The last two variables are kept for storage and removal of the pollutant. The idea with the remaining two variables is that at the end of the optimization process there will be more solutions to solve the problem of flooding and to reduce the concentration of a pollutant in the system which overflows into the river. In this way each specific solution has an estimate of the size of the storage required and the removal of the pollutant gives an indication of the BMP to be used.

Results

Several trial runs were done with different configurations of population, number of generation and random seed; some of these runs took 24 hours on a Pentium 4 centrino duo processor and 2 Gb of RAM . The trial runs indicate that with less number of combinations results are likely to be in the same range. This paper presents the results of two runs that were done to perform the analysis with the same set of parameters. The test was done with a population of 100 individuals and 70 generations, the same value of the seed was used (0.494) and the experiment lasted for 268 minutes. In the first experiment the maximum inflow of the link connected the treatment node is set to zero. In the second experiment the maximum inflow to the treatment node is set to a maximum value of 2.7 m^3/s.

Figure 4 shows the results of the optimization process. Only the dominated points are plotted, the graphs are organized in pairs per objective function so that they can be observed easier. During the optimization process 100 solutions were found in the best population kept by the NSGA-II.

From the results of the optimization process presented in Figure 4 it can be observed that there are solutions that solve the problem of flooding and pollution in the river simultaneously. It can be also observed that there is a certain level of infrastructure cost where the pollution function is at the minimum and which tends to be at the constant value thereafter, while for the same value of infrastructure cost there is still some level of flooding. Therefore, the NSGA-II gets a set of solutions where the water pollution is at the minimum and constant, while extra infrastructure cost is added in solving the flooding problem.

An observation of the solutions of the hydrodynamic model (SWMM 5.0) shows that there are solutions that can solve flooding and minimize the pollutant in the river. The system can achieve this by retaining the solutions where the diameter of the pipe connecting the WWTP is larger and it attempts to pass the maximum possible amount of water to the treatment node.

In reality, most of the time allowing such an overload to the WWTP is not advisable and not allowed in many cases since it has a negative effect on the treatment process and the overall performance of the WWTP.

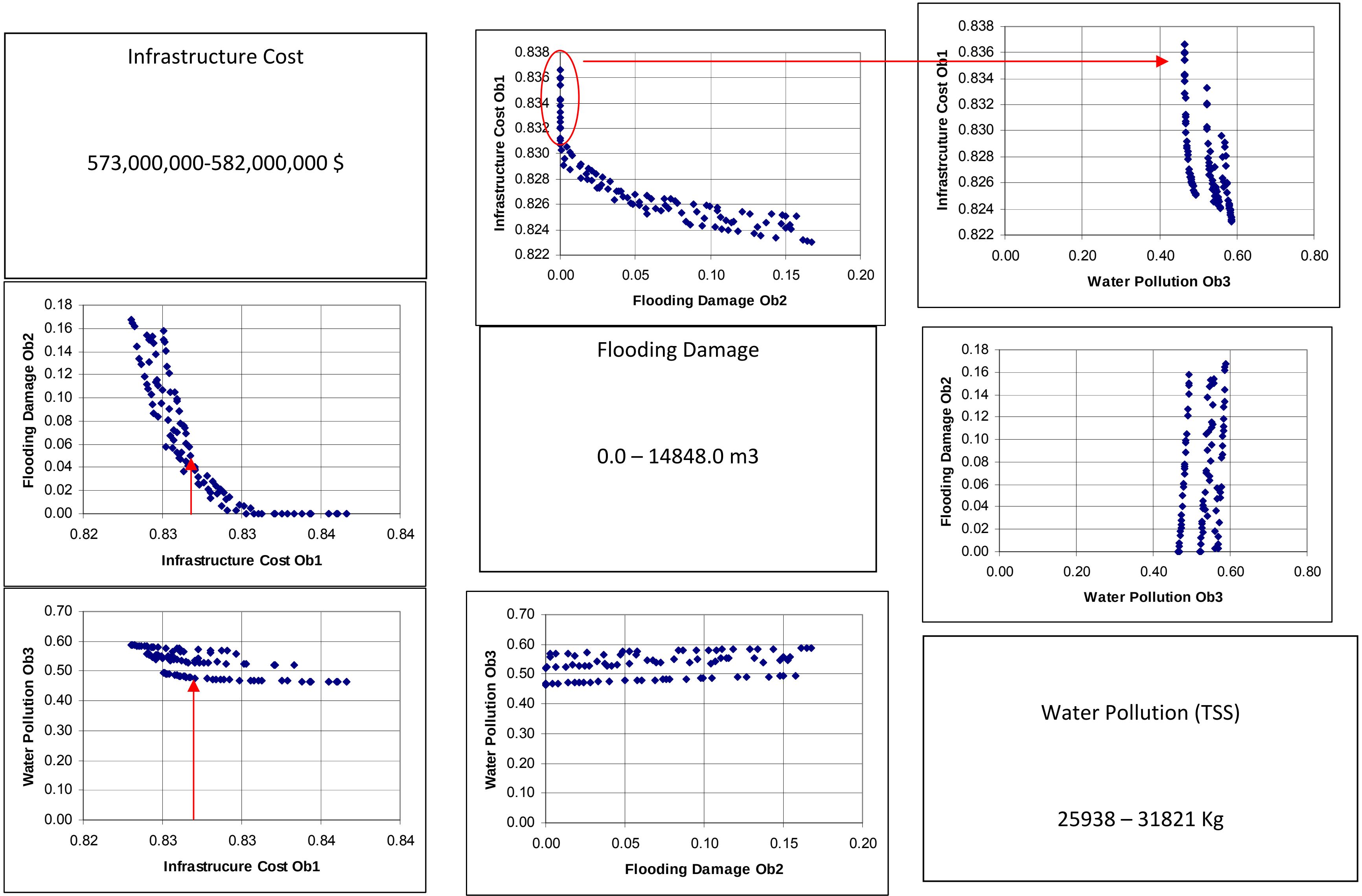


Figure 4. Results of the optimization process without limiting the flow into the WWTP

In a second experiment the maximum inflow to the treatment node was set to a maximum value of 2.7 m^3/s. The parameters to run the NSGA-II were the same as for the previous case. Figure 5 shows the results of the optimization process. Only the dominated points are plotted, the graphs are organized in pairs per objective function so that they can be observed easier. During the optimization process 100 solutions were found and only the best population was retained by the NSGA-II.

Figure 5 should be observed carefully since the tendency of the variables does not follow the same principle as it is the case with two objectives. An important thing to recall is that the objective function for the pollution caused by the overflow contains a certain threshold or value of the maximum flooding that is allowed to be stored and treated outside the system. That is the reason why in the plot corresponding to objective function 2 (X) and objective function 3 (Y) there is an inflexion point that corresponds to the maximum storage capacity of the city that is set up at the beginning of the exercise

Due to the constraint imposed to the pipe that transports wastewater to the treatment node, not only the magnitude of the flood was found to be higher when compare to the previous case but also the amount of pollutant that gets into the river was also found to be higher. in comparison with the previous case. This certain has an effect on the number of solutions that can solve the problem of flooding. For example, there were 12 solutions with zero flood identified in the first experiment, whereas, in the second experiment there were only 2 solutions.

Nevertheless, this experiment also shows that there are a number of combinations of the storage capacity and removal of the pollutant that helps diminishing the flooding and the pollution that reaches the river. A group of 17 solutions were found that combine the principles formulated for the objective function of the pollution caused by the overflow.   This shows that the initial idea of introducing two additional variables for storage and removal of pollutant in the optimization process can be feasible. In fact, if both variables are considered together they could guide the selection of BMPs to improve the urban runoff water quality.

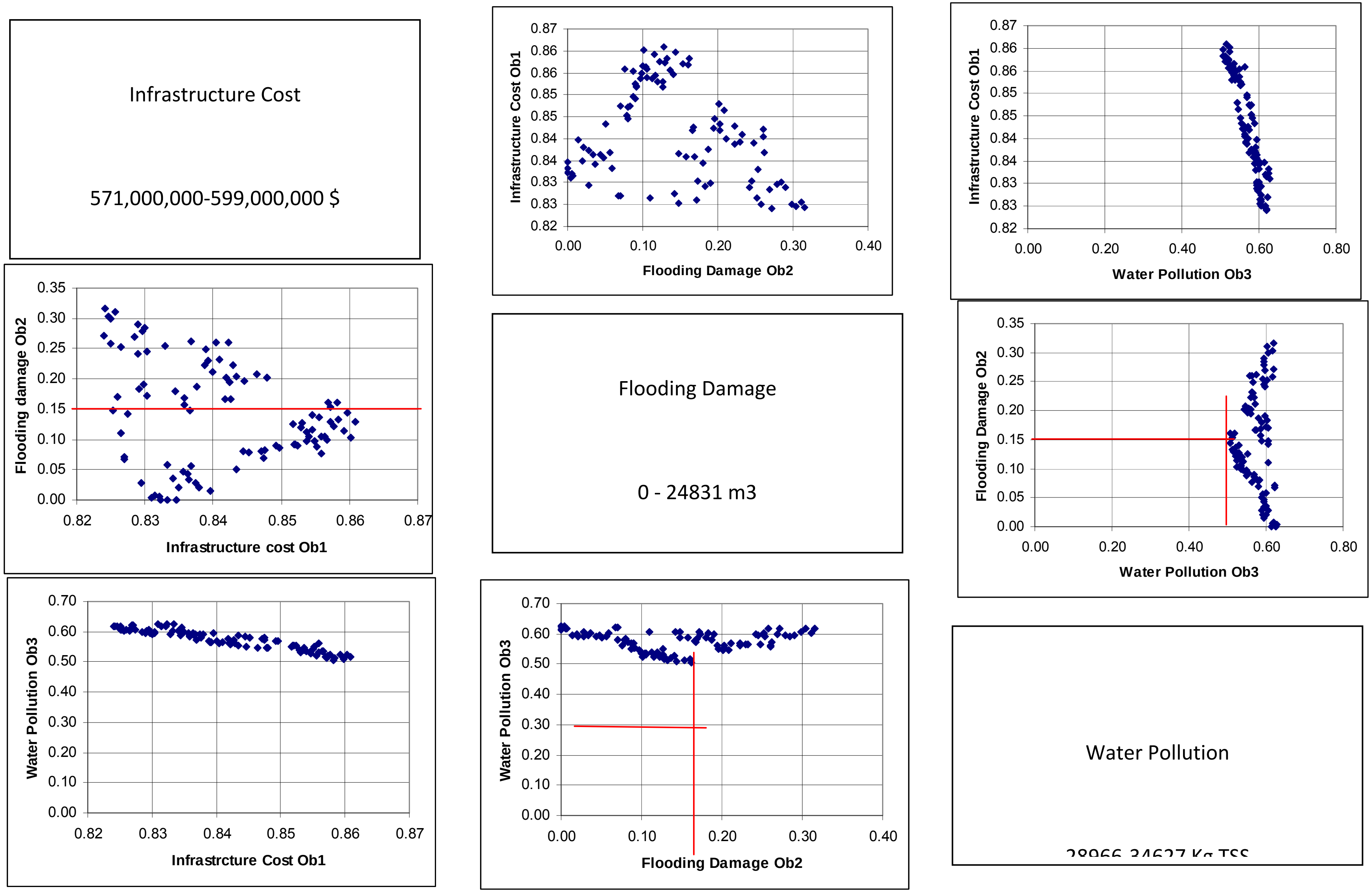


Figure 5. Results of the optimization process limiting the flow capacity to the WWTP

Conclusions

The main objective of the study presented here was to develop an approach to optimize urban drainage systems. Traditionally, optimization of drainage systems is done using a trail and error approach and the challenge was to apply a multi-objective optimization approach and to test some preliminary results.

The optimization process described here involved reduction of a flood risk and reduction of concentration of pollutants. The computational time spent on finding a good set of solutions took nearly 4.5 hours.

Two experiments were carried out using the multi-objective optimization scheme with three objective functions: 1) without limitation of flow to the WWTP and 2) with limitation of flow to the WWTP. The results from both experiments show that the use of multi-objective optimization to solve some of the complex problems of urban drainage/sewerage infrastructure can be effective and relatively easily applied. Certainly, the work presented here has its limitations (e.g. the assumptions used in calculation of storage volumes and WWTP processes. Our intention is to improve the work and presents the results in a new paper.

Acknowledgement

This study has been carried out within the framework of the European research project SWITCH (Sustainable Urban Water Management Improves Tomorrow's City's Health). SWITCH is supported by the European Commission under the 6th Framework Programme and contributes to the thematic priority area of "Global Change and Ecosystems" [1.1.6.3] Contract n° 018530-2

References

Barreto, W.,J., Vojinovic, Z., Price, R., Solomatine, D., 2006, Approaches to multi-objective multi-tier optimisation in Urban Drainage Planning, 7th International Conference on Hydroinformatics, Acropolis - Nice, France, September.

Deb K.; Pratap A.; Agarwall A. and Meyarivan T., 2002, A Fast and Elitist Multiobjective Genetic Algorithm, IEEE Transactions on Evolutionary Computation, Vol. 6, No. 2, pp 182-197.

Muschalla D.; (2006). "Evolutionäre multikriterielle Optimierung komplexer wasserwirtschaftlicher Systeme", Institut für Wasserbau und Wasserwirtschaft, PhD thesis, Technische Universität Darmstadt. Germany.

Tanaka, N. and Tarano, H. (2000).; A Performance Evaluation Methods of Monitoring System For Inner-Basin Drainage Under Imperfect Observation. Hydrological Processes, 14, 621-638.

Vojinovic Z., Solomatine D.P., and Price, R.K., 2006, Dynamic Least-Cost Optimisation of Wastewater System Remedial Works Requirements, Water Science and Technology, Vol 54, No 6-7, pp 467-475, IWA Publishing.

Vojinovic, Z., Barreto, W.J. and Solomatine, D., 2007, Towards an Automatic Optimisation of Urban Drainage Assets, Proceedings of Watermatex 2007 Conference, 7th International IWA Symposium on Systems Analysis and Integrated Assessment in Water Management, 7-9 May, Washington DC.

PLANNING URBAN WATER SYSTEMS: MODELING USING CELLULAR AUTOMATA AND NUMERICAL MODELS

ARLEX SANCHEZ TORRES
Department of Hydroinformatics and Knowledge management, UNESCO-IHE Institute for Water Education, Westvest 7, 2611 AX, Delft – The Netherlands

ZORAN VOJINOVIC
Department of Hydroinformatics and Knowledge management, UNESCO-IHE Institute for Water Education, Westvest 7, 2611 AX, Delft – The Netherlands

ROLAND PRICE
Department of Hydroinformatics and Knowledge management, UNESCO-IHE Institute for Water Education, Westvest 7, 2611 AX, Delft – The Netherlands

ABSTRACT

Cities and metropolitan areas around the world need to achieve a level of sustainability in their water infrastructure to cope with population growth, urbanization and climate change. In order to do that, there is a need to promote and implement integrated approaches to improve urban planning and decision making. The dynamics of urban growth is a complex phenomenon that involves the interaction of many sub-systems (physical elements) with human behavior.

The work described here explores the integration of a cellular automata model of urban growth based on attraction – repulsion rules that define the potential of land use change. This model incorporates information coming from urban water models (water distribution model) to asses the suitability of urbanization. There is a feedback loop between urban development and its impact to the exiting water infrastructure that can affect the availability of water services and therefore the suitability for urbanization. At the same time new infrastructure will be developed as a result of the urbanization process that again affects the suitability for urban land. The integration of these models allows the exploration of several planning scenarios to asses the impact of certain actions, policies, regulations and to explore several urban futures.

The expected result is a new approach for urban water infrastructure planning which help water companies and municipalities to have a dynamic planning tool to improve the effectiveness of their investments and to be more environmentally efficient.

Keywords: *Urban water planning, urban growth modeling, cellular automata, urban water services.*

INTRODUCTION

Cities can be considered as complex systems based on their characteristics of emergence, self-similarity, self-organization and non-linear behaviour of land use changes with time; see [2]. The use of tools that can help in understanding these characteristics are important to gain knowledge about the patterns and mechanisms behind urban dynamics. Cellular automata models are built and used to represent the same phenomena or characteristics in several disciplines of sciences.

Integrated urban water management is a challenging issue that aims at the sustainable use of the water resources so that the demands can be met now and in the future in terms of quality and quantity. The current practices in the

sector are leading towards a crisis that is calling for innovative thinking and the adoption of new strategies including integrated thinking and planning. This sounds nice, but the truth in many situations is that the institutional arrangements are so rigid and fragmented that this is not possible. There is also a need to develop tools that allow such integration. The idea with this work is to contribute to such tools; that can help planners and decision-makers at the city level to understand the main drivers affecting the urban water cycle, to analyze future scenarios of city expansion and foresee bottlenecks and possible solutions. The tool can be used for rehabilitation, testing and planning strategies. This paper presents the results from an ongoing research work that aims to implement such an integrated framework and develop the tools.

METHODOLOGY

Agent based models (ABM) and cellular automata (CA) has been used and tested in several cases for land use changes modeling, including urban dynamics. There are several successfully cases reported in the literature that uses such a framework to predict land use changes at catchment scale. The results of those models have shown that the application of ABM and CA for land use changes modeling is possible and that the outcome of the models are similar of what is observed in reality. The Moland framework is an example of such a model that has been successfully applied and calibrated to real life cases in Europe and different cities around the world, as presented by [1], [3], [4], among others.

The ongoing research is focused in the study of water services networks evolution and performance to evaluate proposed future scenarios that can lead to a better understanding of the actions that need to be taken to achieve goals of sustainability. The hypothesis is that the incorporation of variables related to the water services will have an impact in the direction of growth of the new developments in the urban areas produced by the cellular automata model. These results can then be compared with simulations where no water related services are considered. In some cases the inclusion of the water services may become a major driver for the land use changes in the urban areas, in others it may be a secondary order driver overtaken by other factors such socio-economic, demography, etc. The results can also be used to describe the impact of the provision of water services as a trigger to stimulate urban development. Figure 1 presents the flowchart of the methodology used in this work.

Following the main components of cellular automata framework the model can have the following components:
A regional model: for the distribution and allocation of the demand per land use category according with plans, regulations and estimations of growth and wealth.
Land use maps: are the bases to establish the initial conditions of the model.
A numerical model: that describes the performance of the water systems (water distribution).
A reverse engineering model: that takes the predicted new developments land uses to asses the layout of the water services networks in such a way that the water services accessibility maps can be updated and create dynamic conditions that are incorporated in the simulation loop.

Within the cellular automata model there are six elements that determine if a cell changes its land use state in a particular time step: 1. Physical suitability map: This is a map per land use based on factors such as elevation, slope, soil quality and stability, agricultural capacity, etc. 2. Zoning or institutional suitability: this is also a map per land use category based on master plans and planning documents. Incorporate buffer zones, valuable protected zones, etc. 3. Accessibility: it is a map calculated based on the easy access to the transportation network. 4. Water supply accessibility map: It's a map that considers the relative to the easy access to the pipe networks and the level of service. This map is updated at certain time steps when the reverse engineering model is run. 5. Urban drainage flooding risk map: It's a map that considers the easy access to the pipe networks and the risk of flooding. This map is updated at certain time steps when the reverse engineering model is run. 6. Transition rules: determines the

dynamics and interaction of every cell within its neighborhood. For each land-use function, a set of rules determines the attraction or repulsion of each cell and land use function present in the neighborhood. Figure 2 shows an example of a simulation time step.

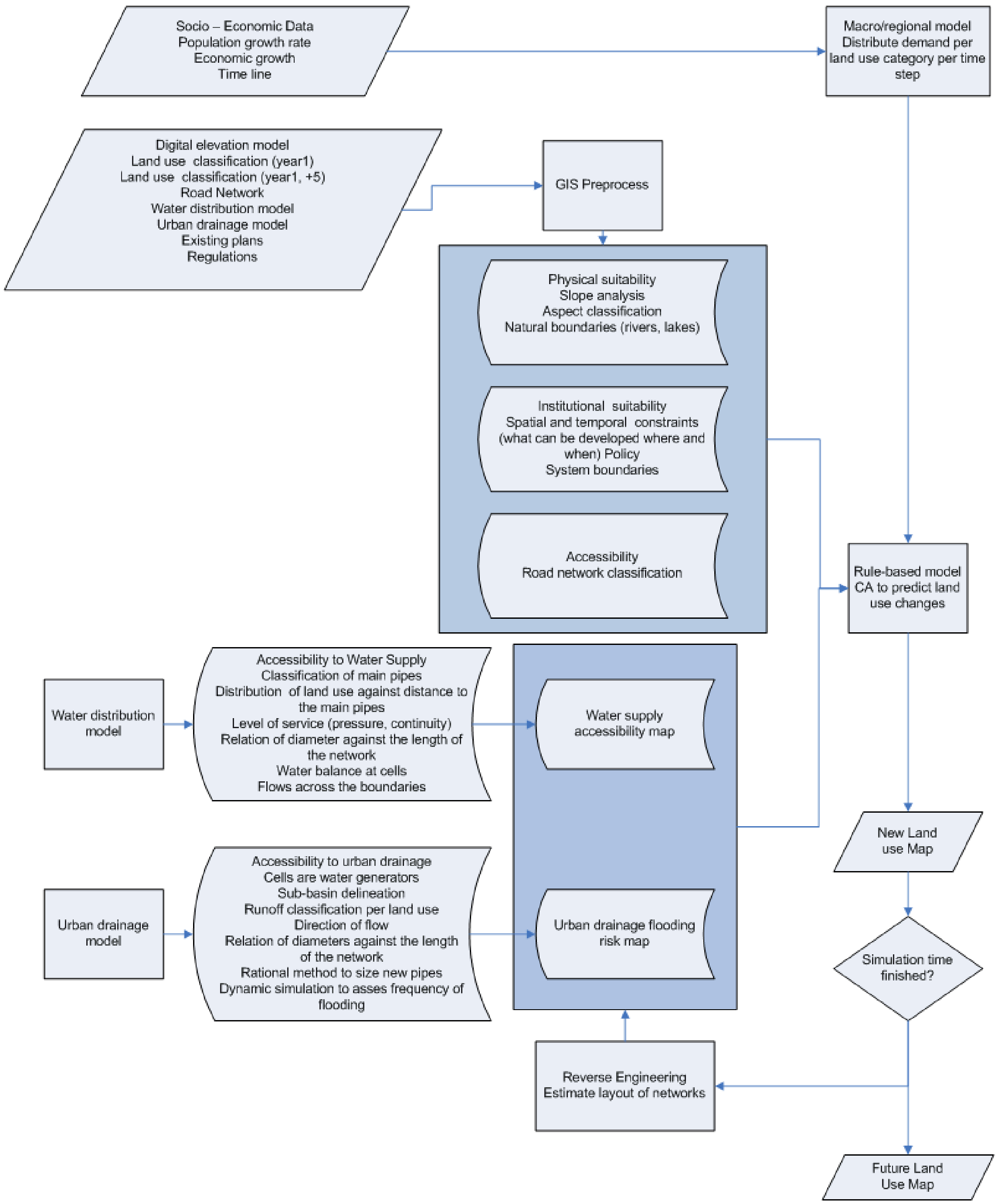


Figure1. General flowchart of the research methodology

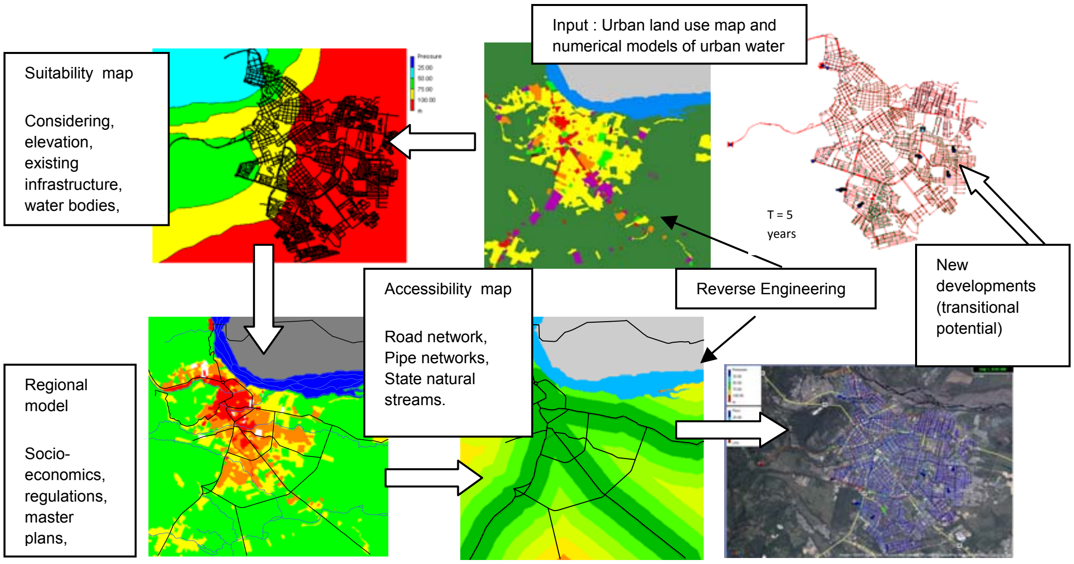


Figure 2. Example of a simulation time step with the proposed research methodology.

Case Study

An experimental work based on a case study was carried out in order to test the approach described in previous sections of this paper. The study area is the city of Villavicencio a medium size municipality located in the south-east part of Colombia with an approximate population of 400.000 inhabitants. Data sets of the land use classification were available for different years. Digital terrain model, main roads and a model for the water distribution system of the city were also available. The basic cellular automata model was build using the Metronamica tool developed by RIKS in the Netherlands to estimate the land use changes. The water distribution model was build in Epanet 2.0 and consisted of 4100 pipes and 2800 nodes. The pre-processing of the data set to build the different required maps was done in ArcGis 9.2.

RESULTS

The cellular automata model was setup in Metronamica to estimate the land use changes for 2 known years to follow a calibration –validation process for the growth and land use changes model. The performance of the cellular automata model seems to be good for the known information on this test case study. The following question is how can the water distribution network be extended to the new cells or urban parcels that need the water service? Figure 3 shows an illustration of such case. This is what can happen with the prediction of the future land use change by the cellular automata model. The question is then to which node in the existing system shall a draw a connection to get the desire level of service? What will be the impact of such a connection to the existing system performance?

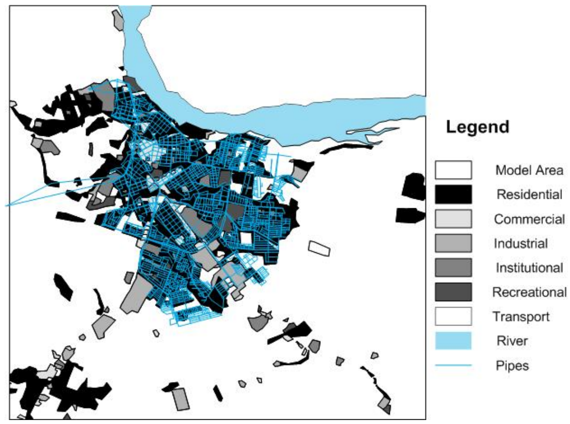


Figure 3. Example of land use growth and network expansion

An analysis of the existing network was carried out. From all the pipes that are part of the system, a selection was made in order to get the main trunks of the distribution system (pipes with a diameter equal or bigger than 356 mm). Those main rings or pipes were used to build corridors or buffers at every 100 meters from the pipe until 1000 meters.

The built corridors were then intercepted with the land use map to get a distribution of the land use area per category that fells into each corridor. Figure 4 shows the result of the analysis for residential land use category. Figure 4 show that there is very little variation of the intercepted area of residential land use along the distance from the main pipes. This means that the distribution of residential land use tells very little about the possible position of water distribution pipes. Figure 5 shows the results for the land uses commercial, industrial, institutional and recreational.

Figure 5 shows that commercial and recreational land use can give information about the layout or positioning of the water distribution pipes.

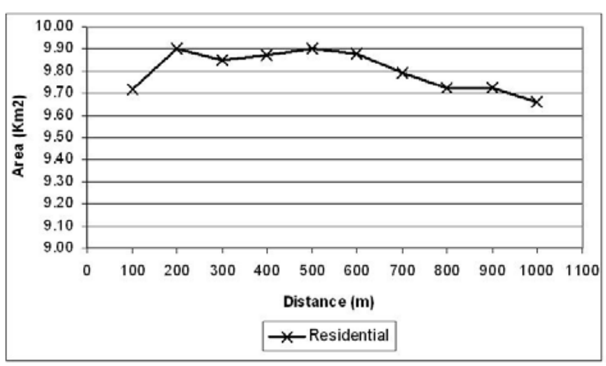


Figure 4. Residential land use area distribution with distance from the main pipes

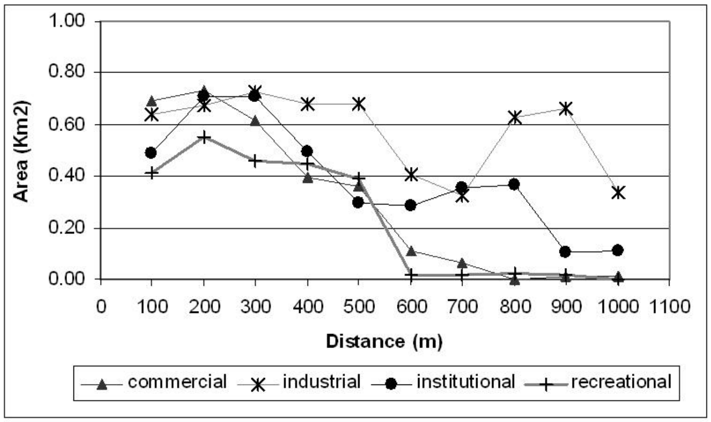


Figure 5. Land use area distribution with distance from the main pipes

The information found with his analysis can be used to predict based on the estimated land use the positioning of new pipes in the futures scenarios. The land uses Industrial and institutional are more sensible to the distance and to which pipes are selected to perform the analysis. These results give an indication about the rules that can be used within the reverse engineering algorithm to position new pipes in the predicted new developments achieved by the cellular automata model.

The same analysis using the same pipes and corridors was done for different cell sizes and the results are similar for residential land use no matter the scale of the cells. For commercial the behavior is also similar. There were some changes for institutional and recreational specially the initial values of the areas covered within the first corridor of 100 meters. This analysis was performed for different selections of pipe trunks increasing the interval of the pipe size to incorporate more pipes and the results were similar.

The reverse engineering model consider the information from the new generated land use map coming from the cellular automata model, then it reads the location of the cell with the land use categories that gives better information for the positioning of the new pipes of the water distribution system. Then based on a boundary node specified by the user it will generate a network based on a clustering algorithm and the distance to the nearest cells and rules to create branches. The main idea is to create a layout of the network that keeps the profile that was found for the different land uses using the corridor analysis that was presented in figure 5. A first approach for the reverse engineering has been code using Delphi and it’s shown in figure 6.

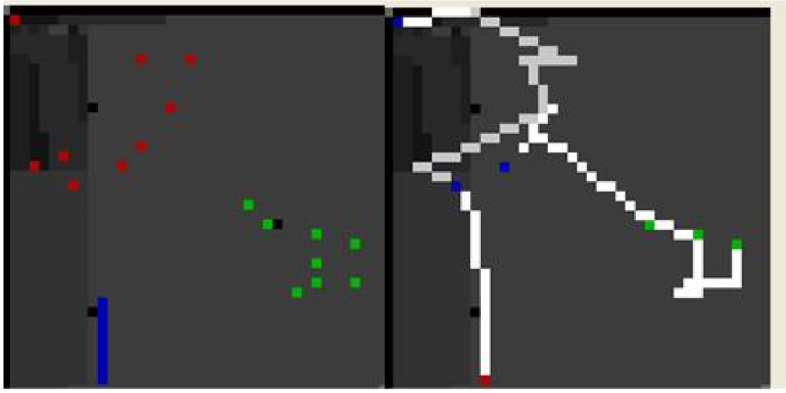


Figure 6. Reverse engineering model approach to new network layout

CONCLUSIONS

This paper has presented the preliminary results of an ongoing research effort to develop an integrated approach for integrated urban water analysis that can be used as a planning tool to learn and evaluated future scenarios in urban areas. Traditionally this type of analysis is done by using different tools in a fragmented way. The analysis done with the corridors along the main pipes and the distribution of land use can be used to find some of the rules to setup the reverse engineering algorithm. The reverse engineering algorithm can draw an updated layout of the network that can be used to derive a new performance of the system that plays in the following time steps of the cellular automata urban growth model. Certainly, the work presented here has its limitations, the approach and development of the algorithms is in its early stages of development and our intention is to improve the work and presents the results in a new paper.

Acknowledgement

This study has been carried out within the framework of the European research project SWITCH (Sustainable Urban Water Management Improves Tomorrow's City's Health). SWITCH is supported by the European Commission under the 6th Framework Programme and contributes to the thematic priority area of "Global Change and Ecosystems" [1.1.6.3] Contract n° 018530-2

REFERENCES

[1] Barredo J., Kasanko M., McCormick N., Lavalle C. "Modeling dynamic spatial processes: simulation of urban future scenarios through cellular automata." Journal of Landscape and urban planning. Vol 64. pp 145-160. Elsevier Science. (2003).

[2] Batty M and Longley P. "Fractal Cities. A geometry of form and function". Academic Press. London, UK. (1994).

[3] Engelen G., C. Lavalle , J.I. Barredo, M. va n de r Meulen and R. White. "The Moland modeling framework for urban and regional land-use dynamics" . In: Modeling Land Use change: Progress and applications. Edited by Koomen Eric, Stillwell John, Bakema Aldrik, Scholten Henk J. Springer. The Netherlands. (2007).

[4] Van Vliet J., and Van Delden H. "An activity based cellular automaton model to simulate land use changes". International Congress on Environmental Modelling and Software. (iEMSs). Barcelona, Spain. (2008).

Towards an Approach to the Evolution of Urban Drainage Networks Using Agent-Based Models

A. S. Torres[1], Z.Vojinovic[2], M. Waly[3]*

[1, 2&3] *UNESCO-IHE, Department of Hydroinformatics and Knowledge Management, Westvest 7, 2611 AX, Delft, The Netherlands*

Corresponding author:
**a.sanchez@unesco-ihe.org*
Tel: 0031152151759

Keywords: Agent-Based Models, Modelling Urban Drainage Network Growth, City Future Planning

Extended Abstract

Introduction

The rapid urbanisation and population growth; creates the need for better planning and management of the urban infrastructures. Urban drainage system is one of the vital services needed for any urban area and modelling its growth is a challenge because of the dynamic of its hydrology. Generating urban drainage network using agent-based models is a new trend to achieve artificial drainage network, and can provide the network distribution plan on the new developed urban areas depending on the existing system.

Background

Urban infrastructures are vital for any new urbanised area. In order to attain these infrastructures, prepared plans need to be available to connect the newly developed infrastructure with the existing one. Accordingly, many modelers are concerned with implementing integrated approaches; improve urban planning and decision support systems. There are some experiences in the literature that focused on the water and electric powers networks simulations .In this simulations growth patterns using geographically based urban growth models to have infrastructure distribution patterns were used. These patterns are can help planners and decision-makers at the city level to understand future scenarios of city expansion foresee bottlenecks and suggest possible solutions. Agent based models can be used to simulate phenomena that present characteristics of self-similarity and emergence like cities and drainage networks. Ghosh et al, 2006 developed an artificial network generator algorithm to test the performance of similar system in reality. This approach is based on the fact that the drainage networks possess fractal characteristics.

Modelling Frame Work

The proposed modeling framework for the evolution of urban drainage networks consist of doing a spatial analysis to find characteristics that connects the land use pattern distribution of an urban

area with the properties of the urban drainage system. Previous studies done by the authors using a similar approach has shown that there is a spatial relation between the land use distribution and the position of the water distribution pipes in an urban area. That knowledge can be incorporated in an agent based approach by defining the rules of behavior. The role of the agent will be based on the land use found in their vicinity identify using the knowledge from the existing system the direction in which new drainage network will be lay-down. The interaction between this algorithm and the cellular automata model for urban growth will define a new approach to explore scenarios of future growth and urban dynamics were water is at the center. The proposed framework is presented in figure 1.

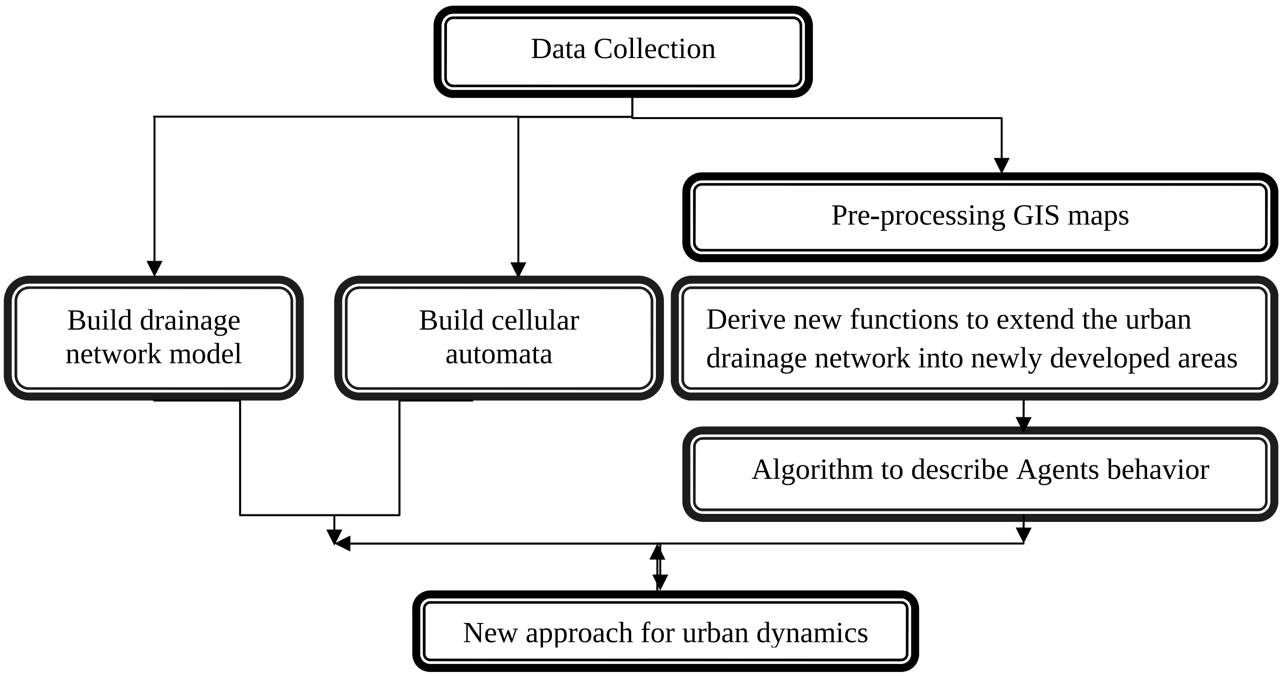


Figure 1. Modeling Approach

The expected result of this modeling framework is a new approach for urban drainage planning and modeling of future scenarios in an integrated way. Such a tool can be used in reality for municipalities and engineers to evaluate several scenarios of future growth.

The Agent based approach to simulate the evolution of the drainage network in the future is a promising approach caused it makes a relation of the drainage system to topography (stream network) and land use (including major roads). With this approach the revised and extended network serving the existing and new developed areas can be realistically estimated.

Acknowledgement

This study has been carried out within the framework of the European research project SWITCH (Sustainable Urban Water Management Improves Tomorrow's City's Health). SWITCH is supported by the European Commission under the 6th Framework Programme and contributes to the thematic priority area of "Global Change and Ecosystems" [1.1.6.3] Contract n° 018530-2

Reference

Indrian Ghosh, Fredi. L. Helleweger and Todd. G.Fritch (2006). Fractal Generation of Artificial Sewer Networks for Hydrologic Simulations. Proccedings of The 2006 ESRI International User Conference, San Diego, California .

Determining the route for a water main in a new urbanising area.

Arlex Sanchez Torres *, Zoran Vojinovic and Roland Price

*a.sanchez@unesco-ihe.org
Department of Hydroinformatics and Knowledge Management
Unesco-IHE
Westvest 7, 2611 AX
Delft, The Netherlands
Tel: 0031152151759

Keywords: Land use changes, City Future Planning, Water Distribution planning, integrated modelling.

Abstract

Cities around the world are currently facing considerable pressure to cope with urban development, population and economic growth. Urban planning is therefore very important to improve the effectiveness of the investments and interventions that take place in the urban system, in particular the water infrastructure. In this paper an approach to integrate cellular-based land use change model with physically based hydraulic models of the water distribution network is presented. The approach aims to determine the expansion of the water infrastructure and its performance in delivering adequate water services in the future and how this can shape the urban development process. The objective is to design the water distribution in the urbanising areas of a city based on the characteristics of the existing networks, and to rehabilitate the system so that it is sustainable. New tools were developed consisting of a clustering and a distance rule algorithm to derive the new network layout based on the land use map. The output of this model is a network layout and the distribution of water demand based on the land use per cell and the proximity to the nodes (Voronoi diagram). This algorithm has been integrated with a hydraulic model to simulate the performance of the system and size the network using an optimisation engine to determine the best option in terms of cost(least cost) and pressure (performance of the system) . The approach is promising since it can resemble the original layout of the existing system in terms of the spatial position of the main trunks and the size of the pipes. The integration of these models allows the exploration of several planning scenarios to asses the impact of certain actions, policies, regulations and to explore several urban futures. The expected result is a new approach for urban water infrastructure planning which help water companies and municipalities to have a dynamic planning tool to improve the effectiveness of their investments and to be more environmentally efficient.

Acknowledgement

This study has been carried out within the framework of the European research project SWITCH (Sustainable Urban Water Management Improves Tomorrow's City's Health). SWITCH is supported by the European Commission under the 6th Framework Programme and contributes to the thematic priority area of "Global Change and Ecosystems" [1.1.6.3] Contract n° 018530-2.