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AN INTEGRATED MODELING APPROACH FOR THE ASSESSMENT OF LAND USE CHANGE EFFECTS ON WASTEWATER INFRASTRUCTURES

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UN MODELLO INTEGRATO PER LA VALUTAZIONE DEGLI EFFETTI DELL'ESPANSIONE URBANA SULLE INFRASTRUTTURE DI DRENAGGIO E TRATTAMENTO DELLE ACQUE REFLUE

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DESCRIPTION OF FRANCESCA PRIMATIVO'S MAIN RESEARCH ACTIVITIES 2006-2009

The PhD research activities were mainly carried on at the Faculty of Engineering in Taranto of the Technical University of Bari (Politecnico di Bari) and at the Centre for Water Systems in the School of Engineering, Computing and Mathematics of the University of Exeter. In particular, Miss Primativo was appointed as Research Assistant (Honorary) at the University of Exeter.

Miss Primativo co-authored the following paper, published in an international scientific journal ISI:

1. Doglioni A., Primativo F., Laucelli D., Monno V., Giustolisi O. and Khu, S.T., (2009): "An integrated modelling approach for the assessment of land use change effects on wastewater infrastructures", Environmental Modelling and Software, Elsevier, the Netherlands, Vol. 24, n.12, pp. 1522-1528, doi:10.1016/j.envsoft.2009.06.006. ISSN 1364-8152. **Impact Factor 2.659 (2008)**.

Miss Primativo co-authored the following papers presented at international/national conferences:

1. Doglioni A., Primativo F., Savic D. and Giustolisi O., (2007): "Possible scenarios of contaminant diffusion in water distribution systems: which is the best moment to place a strike?", in proceedings of Computer and Control in Water Industry (CCWI) - Water Mangement Challanges in Global Changes – Ulaniki et al. (eds), Taylor & Francis Group, London, pp. 257-263, ISBN 978-0-415-45415-5.

2. Berardi L., Giustolisi O. and Primativo F., (2007): "Exploiting multi-objective strategies for optimal rehabilitation planning", in Proceedings of Computer and Control in Water Industry (CCWI) - Water Mangement Challanges in Global Changes – Ulaniki et al. (eds), Taylor & Francis Group, London, pp. 23-30, ISBN 978-0-415-45415-5.

3. Primativo F., Doglioni A., Laucelli D. and Giustolisi O., (2007): "La diffusione di contaminanti in rete: integrazione con un'analisi pressure-driven ed un modello di perdita", in La ricerca delle perdite e la gestione delle reti di acquedotto, 20-21 September 2007, Morlacchi Editore, Perugia, Italy, Marzo 2008, pp. 81-94, ISBN 978-88-6074-173-8.

4. Doglioni A., Primativo F., Laucelli D., Monno V. and Giustolisi O., (2008): "An integrated modelling approach for the assessment of land use change effects on wastewater infrastructures", in d'Antonio G., Lubello C., Proceedings of the International Symposium on Sanitary and Environmental Engineering, SIDISA 2008, 24-27 June 2008, Firenze, Italia, ISBN 978-88-903557-0-7.
5. Fu G., Khu S.-T., di Pierro F., Doglioni A. and Primativo F., (2008): "Development of an integrated framework for assessing the impact of urban planning on water quality", in Miquel Sànchez-Marrè, Javier Béjar, Joaquim Comas, Andrea E. Rizzoli, Giorgio Guariso (Eds.), proceedings of the iEMSs Fourth Biennial Meeting: International Congress on Environmental Modelling and Software (iEMSs 2008). International Environmental Modelling and Software Society, Barcelona, Catalonia, July 2008. Vol. 1, pp. 592-597, ISBN 978-84-7653-074-0.
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7. Doglioni A., Primativo F. and Giustolisi O., (2008): "Scenarios of contaminant diffusion on a medium size urban water distribution network", Proceedings of the 10th Annual Water Distribution Systems Analysis Conference WDSA2008, Van Zyl, J.E., Ilemobade, A.A., Jacobs, H.E. (eds.), 17-20 August 2008, Kruger National Park, South Africa, pp. 951-965. ISBN 978-07-8441-0240. doi:10.1061/41024(340)84.
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9. Doglioni A., Primativo F. and Giustolisi O., (2009): "An integrated modelling approach for the assessment of land use change effects on wastewater infrastructures", in A. Paoletti, G. Becciu, C. Di Mauro, R. Occhi, A. Rossi, U. Sanfilippo, Eds., Acqua e Città 2009 - 3° convegno nazionale di idraulica urbana, Milano, 6-9 October 2009. ISBN 978-88-903223-3-4.

During the PhD, Miss Primativo attended the following international events, during which she presented three works among those previously mentioned:

- Meeting of the European Project "Integrative Systems and the Boundary Problem" (ISBP), in Exeter (UK) 09-10 July 2007.
- "Water Management Challenges in Global Change" CCWI2007 and SUWM2007 Conference, in Leicester (UK) 03-05 September 2007 (oral presentation).
- "Water Distribution System Analysis" WDSA2008 Conference, to the Kruger National Park (South Africa), 17-20 August 2008 (oral presentation).
- Meeting of the European Project "Integrative Systems and the Boundary Problem" (ISBP), in Abisko (Sweden), 14-20 January 2009.
- "Computing and Control in the Water Industry Integrating Water Systems" CCWI2009 Conference, in Sheffield (UK), 01-03rd September 2009 (oral presentation).
- Research and collaboration with a group of the Centre for Water Systems in the School of Engineering Computer Science and Mathematics of the University of Exeter (UK) for a total period of seven months.

Miss Primativo was also involved in the following Research Projects:

- "Integrative Systems and the Boundary Problem – ISBP" – supported by the European Union's Framework 6 Programme New and Emerging Science and Technology (NEST) Pathfinder initiative, NEST-2005-Path-CUL(Contract 043199).
- "Multi-objective evolutionary optimization and data-driven techniques for water system management" – Internationalization of the Italian University System: Interlink – MIUR.

SOMMARIO

L'effetto dell'espansione urbana e della modifica del territorio, costituisce una fonte di impatto sul trasporto e trattamento delle acque reflue ed è pertanto un aspetto gestionale delle infrastrutture idrauliche imprescindibile. In particolare, spesso accade che le reti di drenaggio siano ampliate, connettendo ad esempio aree di nuova edificazione, senza uno studio modellistico preventivo delle conseguenze che tali interventi recheranno sulle infrastrutture esistenti quali rete fognaria ed impianto di trattamento (Butler & Davies, 2004).

La presente Tesi di Dottorato, prendendo spunto dalle attività svolte all'interno del Progetto di Ricerca Europeo Integrative Systems and the Boundary Problem (ISBP), tratta lo sviluppo e l'analisi applicativa di modelli di integrazione di fenomenologie aventi ripercussioni dirette e/o indirette sull'inquinamento delle acque. In particolare, l'integrazione fra modelli ha lo scopo di simulare il comportamento di un bacino urbano reale al servizio del quale esiste un impianto di trattamento e smaltimento reflui.

Lo studio di tali modelli si è incentrato sull'approfondimento di metodologie riguardanti la modellazione delle relazioni intercorrenti fra sviluppo urbano e tutela dall'inquinamento delle acque. Tale modellazione si è ottenuta attraverso l'implementazione di un *framework*, il cui scopo riguarda:

- dinamiche di processo, quali l'utilizzo del suolo e la qualità delle acque;
- il collegamento fra i processi suddetti, come l'aggregazione spaziale dei dati;
- l'integrazione dei modelli nello stesso ambiente di calcolo (Simulink).

Nella fattispecie sono stati integrati un modello di cambiamento di uso del suolo atto a simulare l'espansione urbana di un'area di nuovi insediamenti, con un solutore idraulico che simula il trasporto dei reflui e dei principali inquinanti in esso contenuti e infine un modello di simulazione di un impianto di trattamento reflui. Il modello di simulazione idraulica del bacino è basato sul solutore Storm Water Management Model (SWMM) implementato dalla US Environmental Protection Agency (USEPA), mentre il modello di simulazione dell'impianto di trattamento reflui è basato sul solutore sviluppato dall'IWA Task Group on Benchmarking of Control Strategies (BCS), in particolare sul modello BSM1.

Sulla base della simulazione di potenziali scenari di sviluppo si opererà una valutazione preventiva degli impatti delle espansioni urbane sulle reti di drenaggio e sugli impianti di trattamento e smaltimento reflui conseguenti allo sviluppo di nuove aree urbane secondo un approccio maggiormente sostenibile rispetto a tali infrastrutture, minimizzando il rischio di sversamenti diretti ed incontrollati di reflui nell'ambiente.

Il *framework* sviluppato consentirà di valutare e pianificare lo sviluppo urbano secondo un approccio innovativo che tenga conto dell'integrazione delle nuove opere con quelle già esistenti ed in uno scenario di eco-sostenibilità. Inoltre, il *framework* sviluppato potrà anche essere la base per possibili ulteriori integrazioni con altri strumenti di analisi ambientale e del territorio, dando l'opportunità ai pianificatori di decidere secondo un approccio che tenga in considerazione aspetti normalmente affrontati dopo che le politiche di sviluppo sono già decise. Ciò consente anche di produrre delle linee guida nuove nell'ambito della pianificazione territoriale.

L'obiettivo primario di questa Tesi è la descrizione ed il test del *framework* integrato costituito, come precedentemente accennato, da un modello di uso del suolo, un modello di drenaggio urbano ed un modello di un impianto di trattamento e smaltimento reflui urbani. Fra gli obiettivi da conseguire attraverso l'uso del predetto *framework* vi è lo studio di come la conoscenza empirica può essere utilizzata in modelli numerici o tecniche computazionali per lo sviluppo di una procedura di parametrizzazione automatica.

La prima parte della Tesi si articola sulla descrizione dei problemi di pianificazione rispetto ai potenziali impatti sulle infrastrutture idriche attraverso anche la rassegna della principale letteratura scientifica in merito ai problemi cosiddetti a dinamica complessa e gli aspetti legislativi concernenti il problema della tutela delle acque dall'inquinamento.

Nella seconda parte della Tesi è proposta una descrizione approfondita dei modelli utilizzati e di come essi siano stati integrati.

Ed infine, l'ultima parte della Tesi, presenta l'applicazione del *framework* sviluppato ad un caso studio e la descrizione dei risultati ottenuti da tale applicazione, ipotizzando alcuni potenziali scenari di sviluppo urbano.

ABSTRACT

The simulation of sewage systems and wastewater treatment plants is a strategic aspect for assessing the effect of new dwellings on the existing water facilities. This constitutes a quite common problem, since usually new edification areas are planned without looking at the effect that new scenarios will cause on the existent infrastructures.

In this Thesis integration of water pollution and land use change models is presented and applied to a case study. The water pollution is meant as the complex relationship between proposed housing development and wastewater pollution incident control. The aim of these models is about the impact of new edification areas on the existent watercourse.

This Thesis introduces an integrated framework made by a land use change model, a sewage system simulator and a wastewater treatment plant simulator. This is a complex system since each element is characterized by different dynamics. The land use change model simulates the expansion of an urban area according to planners' guidelines; the sewage system simulator investigates the response of the drainage system to the expansion as well as its flexibility. The wastewater treatment plant is simulated in order to assess the impact of the new inflowing discharges on the existing plant.

This Thesis describes the motivation, the rational and implementation details of a modeling framework namely Stochastic System Dynamics Integrative Model (SSDIM), which is an effort to bridge the gap of integrated models for decision making in urban planning. By combining automatic decision support tools with an integrated framework that brings together land use change and wastewater network infrastructure, it enables the analysis of the effect of alternative long-term urbanisation plans on the quality of the surrounding environment, measured through water indicator. The functionality of the SSDIM was demonstrated through a semi-hypothetical case study, in which three planning scenarios were evaluated for a new housing area against the quality of the wastewater drained by a sewer system and eventually treated by a wastewater treatment plant. On the one hand, the study highlighted the flexibility in representing planning scenarios and setting-up the sewer networks in the framework and demonstrated that the framework, as a conceptual and quantitative tool, can easily accommodate for the complexity involved in a real-world case study. On the other hand, the results emphasised that the framework was able to capture the evolving impact of urban planning over a long term period, which play an important role in understanding the existing system and environmental capacities, and thus SSDIM provides a valuable decision support aid in the urban planning process.

In the first part of this Thesis, the setting and motivation for the framework proposed and an extensive review of the studies available from literature are discussed as well as the legal background related to the problem at stake

The second part of the Thesis presents the elements of the models implemented: in particular, both the conceptual representation and the implementation details are discussed in depth.

Finally in the last part of the Thesis, an application of the developed framework to a real world environmental problem and the results of the application of the framework to a case study is described. The case study represents a sewage network of a town located in south west of Scotland and its wastewater treatment plant, where some urban development scenarios are assumed.

1 INTRODUCTION

1.1 GENERAL INTRODUCTION

In the late 80's and early 90's there are major changes in the policies of urban drainage through new concepts such as:

- sustainable development;
- management of water resources with ecosystem-wide approach;
- improving the knowledge base of the impacts resulting from spills;
- the integrated vision of urban drainage systems.

Until now, therefore, the two main instances that we tried to solve were the public health and protection from flooding. To date, however, there are still many points to address (Chocat *et al.*, 2001), including:

- problems related to the volume of runoff: large sealed areas causing peak flow and less infiltration, thereby increasing the erosive power of runoff, and groundwater depletion, and thus often subsidence.
- Problems related to the qualitative aspect of the outflows: the network is mixed or separate, the waters of rain wash away urban basins are recognized as a major source of pollutants to the receptors.
- Problems associated with ecology, and use of water. The urban drainage systems may alter the biodiversity of receptors, compromising the ecological integrity, and possibly even compromising usability for recreational purposes such as bathing, fishing.
- Problems associated with managing networks currently exist, particularly related to the management of treatment plants under high load, aging pipelines, climate change.

To address these new issues it is clear that we need an integrated way, able to take into account all the subsystems that interact in urban settings. Drainage network, sewage plant and receivers must be seen as part of a single system through an integrated view.

In recent years it is imposing a new approach in the management of urban drainage systems in which all components of the system are considered as mutually dependent. In a perspective of this type, the surface sources such as groundwater, the receiver, as the settlement itself, are seen as a single system and interacting. The integrated vision system involves a greater focus in the identification of intervention strategies. So far, the optimization process was carried out with the only purpose of improving the area of interest, without considering the impact on other subsystems.

A typical case is that of storm drains, built just to relieve portions of the network to carry in excess, or protect the delicate balances within the treatment plant from toxic shocks of rain water, sewers mixed. The construction practice, until a few years ago, did not take into account the self-purification capacity of the recipient, but merely laid down the criteria for sizing of the structures, regardless of the stream which would receive the flow unfilled. The integrated view also involves the evaluation of the relationship between the individual parts of the system.

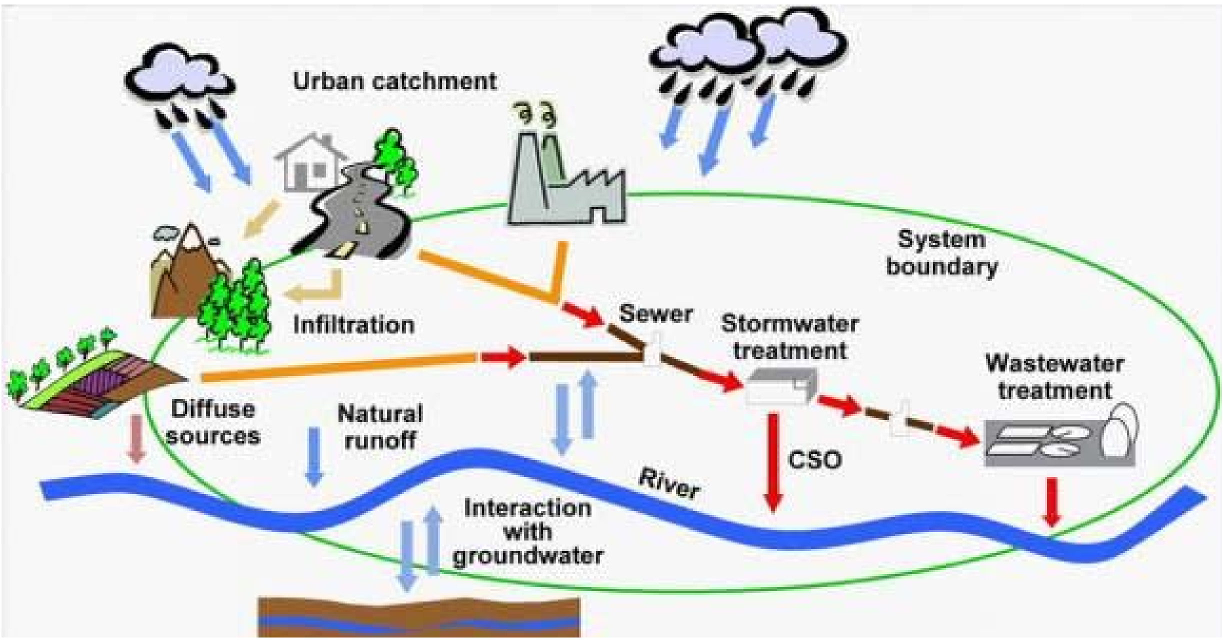

Figure 1-1. Schematic of the integrated urban drainage.

The sewage system interacts with the receptor through the storm drains. To reduce the impacts are possible different intervention strategies. But it's important to consider all possible consequences resulting from the remaining components of the system.

The simulation of sewage systems and wastewater treatment plants is a strategic aspect for assessing the effect of new dwellings on the existing water facilities. This constitutes a quite common problem, since usually new edification areas are planned without looking at the effect that new scenarios will cause on the existent infrastructures.

Land use planning is a crucial task that has large impact on our lives. It drives economic development, affects social structures, shapes the urban landscape and modifies the environment.

Although notorious, these effects are difficult to be quantified and assessed. Their impacts are not always self-explanatory, and then complex conceptual cause-effect networks must be devised in order to appreciate them.

Moreover, they typically unfold over a time-scale that prevents them from being effectively accounted for and budgeted in any today's decision making process.

The development of a new area can dramatically affect water flow and water quality of urban water systems in several aspects (Butler and Davies, 2004). Covering the ground with paved surfaces and land use changes increase the amount and speed of surface runoff, and thus accelerate the wash-off and transport of pollutants and sediments, particularly in the first flush period.

New domestic and industrial wastewater imposes increasing pressure on existing wastewater infrastructures (drainage and treatment), increasing the risk of sewer overflows in a combined system and of limits exceeding concentrations in receiving watercourses (after treatment processes).

In order to reduce these risks, and the costs of mitigation of the related impacts, planning for new development should be coordinated with the planning of provision of water infrastructures.

Moreover, this should be done taking into consideration that urban planning is usually undertaken over long term scenarios, that urbanisation evolves gradually, that engineering works are phased over time and the economical lifecycle of water infrastructures is in the order of 15-25 years.

1.2 INTRODUCTION OF THE PROBLEM

This Thesis focuses on sustainable urban planning in relation to the impact of urbanisation on urban water systems. The water pollution is meant as the complex relationship between proposed housing development and wastewater pollution incident control. The estimation of the impact of new development on existing watercourse is currently a statutory requirement in most EU countries. The EU Water Framework Directive (WFD), adopted in 2000, has set a number of deadlines to be met by Member States to reach good quantitative and qualitative status of all water bodies (CEC, 2000). There is a need to be able to model the complex interaction between infrastructure system (such as housing development and sewer networks), natural systems (such as catchment and watercourse) and social system (impact of flooding on livelihood).

The main purposes of the developed framework are:

- integration of component models via cyclic dynamic feedback relationships,
- quantifying the behaviour of different component models and sub-cyclic systems with the developed framework and
- understanding the system behaviour and its boundaries.

Thus, the system dynamics model must be capable of providing dynamic feedback relationships between:

- water pollution incidents,
- population growth and demographic change and
- infrastructure provisions.

In fact, there are still gaps in understanding the interrelationship of physical and economic behaviour of the wastewater infrastructure, how to model the infrastructure and the impact of different management strategies (Wirahadikusumah *et al.*, 2001). Even less well understood is the relationship between proposed land development and risk of water pollution events such as flooding caused by wastewater infrastructure failure.

Wastewater Infrastructure Planning and Management (WIPM) is undergoing significant rethinking: sewer performance, asset maintenance, flooding due to sewer overflow and the costs associated with provision of acceptable wastewater infrastructure services are beginning to play an important role when proposed housing developments are being considered.

The problems associated with deterioration of wastewater infrastructure and the consequences of inadequate maintenance plan are far from obvious; the occurrences of water pollution events are normally good indicators of sewer failures but the price to pay may be too high. Hence, there is a growing advocate that WIPM should be incorporated into land use plans. There is a strong case for sewerage service providers to demonstrate that their WIPM practices can deliver robust performance that meet regulatory requirements and those investments are sustainable as well as economically, socially and environmentally justifiable.

In outline, the integration among these problems should comprise the following functional components:

- housing development and Land Use Change model (LUC),
- Urban Drainage Model (UDM),
- Wastewater Treatment Plant model (WWTP).

This Thesis introduces an integrated framework, namely Stochastic System Dynamics Integrative Model (SSDIM), made by a land use change model, a sewage system simulator and a wastewater treatment plant simulator. The framework is implemented into Simulink, which allows for a system dynamics modeling of the different processes in various components and the interactions between them.

The housing development and Land Use Change Model (LUC) will allow the housing densities, types, locations etc. to be characterized and projected forward in time. It will be bounded geographically within the study area and socially via population preference of housing and affordability. It is envisaged that LUC is multi-agent based (Hercog and Fogarty, 2001).

The hydraulic simulator is based on the Storm Water Management Model developed by the US Environmental Protection Agency. The Urban Drainage Model (UDM) will allow the accounting of total water budget within the study area. It will have a hydrologic model that accounts for the amount of inflow and discharge, links to LUC and WWTP to account for runoff within the system. It will provide the main driver for any occurrence of sewer flooding.

The wastewater treatment plant model is based on the model developed by the IWA Task Group on Benchmarking of Control Strategies, in particular the BSM1 model. The Wastewater Treatment Plant model (WWTP) will be used to model the flow hydraulics and system performance in terms of dry weather flows, wet weather flows and sedimentation. A major operational concern for urban drainage systems is their performance under wet weather flows and especially the onset of hydraulic incapacity in system and any resultant flooding. This issue is being approached by reference to a series of design events with a range of return periods with the ability to alter the duration of the events. The proposed performance measure for hydraulic incapacity under wet weather flows is based on a modified performance assessment system (Cardoso *et al.*, 2002).

The integration of these components leads to a framework acting as an interactive platform between the policy level and the natural environment, herein an urban water system. It provides a simulation and decision support tool to assess both short- and long- term potential impacts of urban planning on the surrounding water systems, to suggest a broad class of preliminary options to scope, and to identify the best options given physical, economic and social management objectives.

Figure 1-2 shows the information flow diagram of the framework, and each of the components is described below. Looking at Figure 1-2, the planning scenarios are assumed by using the information which is provided by the urban planners. The spatial aggregation is a procedure which is claimed by the UDM in order to properly arrange the information returned by LUC.

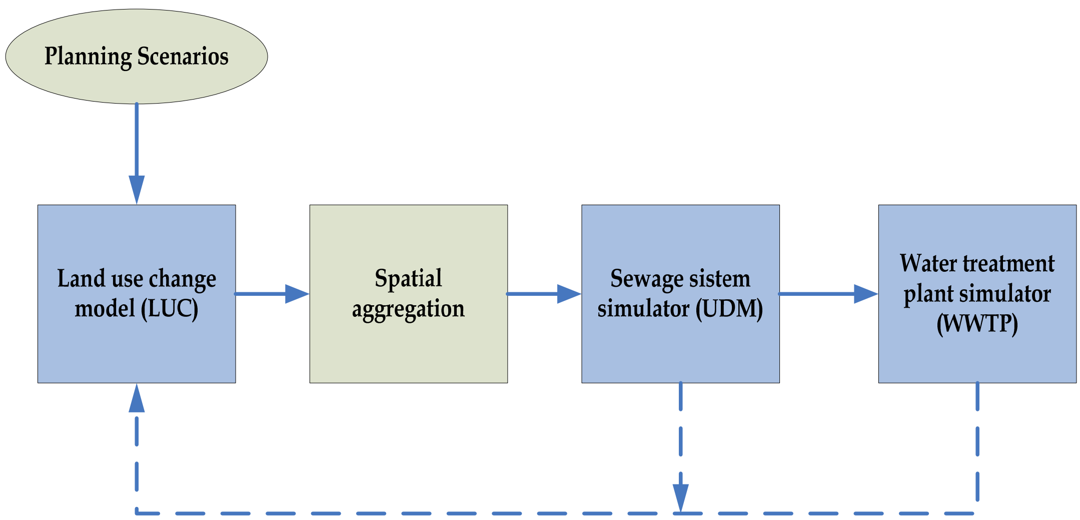

Figure 1-2. The information flow diagram of the integrated framework.

SSDIM is a modelling framework that aims at bridging the gap of integrated models for decision making in urban planning. By bringing together land use change and wastewater network infrastructure in an integrated modelling framework, it enables the analysis of the effect of different long-term urbanisation plans on the quality surrounding environment measured through water indicators.

One distinctive characteristic of SSDIM is the use of physically based models for various relevant components, compared with other systems designed to access environmental impact of urban planning for example EISP (Culshaw *et al*., 2006). This provides a facility to simulate various physical, chemical, biological processes occurred in relevant sub-systems, and enables understanding the detailed relationships between urban planning and its impact on the water quality. Further, this also provides a tool for optimal design and control of the overall system in order to reduce the impacts of new developments.

The considered influential factors on the surrounding water environment include:

- different long-term planning policies at a local or regional level, for example, urban growth patterns and future population increases;
- the refined characteristics of new developments, for instance, population distribution, housing density and percentage imperviousness, which can be provided by the land use change model given the annual population change and planning scenarios;
- design and/or expansion of the sewer network in new developments, which has a direct effect on Combined Sewer Overflow (CSO) discharges.

To measure the impact of the underlying relationships between the urban planning scenarios and the surrounding environment, a number of indicators are used as a proxy for its level of ‘stress’. The ambient water quality is represented by a number of possible pollutants including total suspended solid (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), ammonium, nitrogen oxides (NOx), and sulphates. These indicators for instance in the United Kingdom are strictly required with regard to legitimate uses of the water through so-called environmental quality standards (EQSs) based on environmental quality objectives (EQOs).

Generally, existing environmental quality standards have been implemented on the basis of statistically checking the compliance of routine samples against quality criteria (usually 90 or 95 percentile). Meanwhile, the standards have been derived to consider the following variables and their relationships: pollutant concentration, return period of an event in which that concentration is exceeded and duration of the event.

The impacts of land-use change discussed above relate primarily to the water quality. In a ‘new town’ development, for example, land-use may shift from agricultural, through construction, to industrial or residential.

To achieve a fully dynamic simultaneous simulation in the framework, conversions might be required for the different sets of pollutants, depending on the specific water quality models employed in relevant components. This has been regarded as one of the key problems in the context of integrated modelling of urban wastewater system, and it has a great effect on model performance and reliability. While developing consistent pollutant sets for various sub-systems still has some difficulties, a factors-based conversion method is usually used to convert the different pollutant sets between various sub-systems in the integrated model (Rauch *et al.*, 2002), and this method is also adopted by the WEST simulation tool (Vanhooren *et al.*, 2003), and SYNOPSIS (Schütze, 1998). A similar conversion method is used in this integrated framework to deal with the pollutant sets in the relevant components.

In this Thesis, a framework for modelling the complex relationship between proposed housing development and wastewater pollution incident control is therefore introduced.

The framework looking at the way formal computer models are parameterized by bounding regions in a definite parameter space is introduced. This is the point in the scientific process where socially constructed theory encounters empirical data and a range of data-driven and computational methods are necessary to natural resources management, particularly in respect of water pollution.

1.3 HOW TO CONTEND WITH PROBLEM OF PLANNING

As the EU expands, our ability to integrate diverse cultures without overt “cultural engineering” or suppressing cultural diversity will determine our success in finding peaceful solutions to problems of convergence. Convergence, in this sense, is the process of harmonising local administrative and political institutions with the principles of sound governance established for the

Community as a whole. Convergence invariably creates conflicts of interest on national, regional and local scales and the peaceful enlargement of the EU is probably the biggest challenge Europe has faced since the end of World War II.

Investment in cultural research is clearly necessary, not least because the integrative challenges we face now will soon be dwarfed by those of economic globalisation. Any general lessons we can learn about cultural ecodynamics will obviously be of strategic significance later in the century. Innovation involves work between epistemic communities that may bring physical, life and human scientists into contact with each other and stakeholder communities. It is hampered by clashes about whether boundary judgments - the definitions of systems and problems - are real and universal or expedient and socially constructed.

The project from which this Thesis originates, the Integrative Systems and the Boundary Problem (ISBP) project, will avoid extreme positions and explore ways of managing the tension between these ideas in integrative research. At one end of the spectrum we will study issues in cultural and natural resource management to understand how negotiating new institutional and epistemic boundaries can reduce tension between antagonised stakeholder communities and promote social cohesion. At the other, we will explore the ways of characterising problems in natural science using heuristic data-mining methods to search for boundary judgments that help make problems tractable. It is nowadays clear that effective land use planning cannot address the analysis of physical and human processes in isolation, but must rather focus on their interconnections and treat the land system in a holistic approach.

Increasingly over the last 15 years, various types of integrated models have been successfully developed to support policy making in addressing specific problems related to the changing land-use and land-cover pattern and their effect on the land system. Building upon the conceptualization proposed by Mather (2006), integrated models address the relations between human land-use activities and environmental change and they can be represented as human-environment systems with socio-economic as well as ecological and biophysical components as sub-systems.

Traditionally, the key driver of the integrated models proposed so far has been the component simulating the changing land-use and land-cover pattern, with problem domain varying from urbanization (e.g. Couclelis, 1997; Clarke *et al*., 1997), management of coastal zones (e.g. de Kock *et al*., 2001) and deforestation (e.g. Pontius Jr. *et al*., 2001), and with spatial scale ranging from local to global. From a conceptual point of view, this component integrates two different types of processes: those that pertain to the decision making and that ultimately alter the land system (e.g. urbanisation, deforestation, infrastructure provision, etc.), and those driving, or underpinning, the decision making process (e.g. socioeconomic structure, demographic change, technology, policy, etc.). Geist and Lambin (2002) refer to the former type as the proximate processes or causes, which usually operate at a local level, whereas the latter is called "underlying cause" and can operate at the local level but more often at a global scale.

The level of detail of the implementations describing proximate and underlying causes varies greatly over the models proposed (Heistermann *et al.*, 2006), with a representation of the underlying principles that can either be empirical-statistical, also referred to as inductive (.e.g. multivariate regression analysis to link socioeconomic variables to land-use suitability measure), or economic and process-based, also known as deductive. The land-use component usually sets the spatial resolution of the model, i.e. the scale at which both decision making and physical processes are described.

Different types of biophysical models have been coupled with a land-use component to simulate its interconnections with, and ultimately effect upon, the environmental system. Agricultural trade models (van Tongeren *et al.*, 2001; Balkhausen and Banse, 2004), economic models of deforestation (Angelsen and Kaimowitz, 1999) and traffic and transportation models (Miyamoto *et al.*, 1996) are only a few examples. Depending upon the flexibility of the tools implemented and their link to the specific domain for which they were originally developed, authors have referred to their models either as integrated models or integrated frameworks, although a clear definition is still lacking. Various reviews exist of land-system models, which, however, do not explicitly differentiate between land-use models and integrated models. Verburg *et al.* (2004) discuss models according to driving forces, spatial interaction or level of integration. Verburg *et al.* (2006a) and Agarwal *et al.* (2002) use model characteristics like spatial versus non spatial or dynamic versus static as discriminators. Parker *et al.* (2002) concentrate on multi-agent systems as opposed to cellular automata (CA), which are the most widely used approaches.

Clearly, a unifying classification method does not exist. However, features that are common to all integrated models/frameworks by definitions are:

- The coupling of models describing both human and biophysical processes (i.e. what are the processes described?);

- The relation describing the interconnections between the models (i.e. what is the level of integration?);
- The tools for supporting decision making (i.e. what type of analysis is automatically provided?).

Focusing on the features outlined above, the chapter 2 provides a critical review of the most recent developments of integrated models/frameworks presented in the scientific literature, with the view of highlighting strengths, limitations and therefore motivating the research effort herein presented.

1.4 TARGETS

The main objective of this Thesis is the full description and testing of the integrated framework made by a land use change model, a sewage system simulator and a wastewater treatment plant simulator. This objective will describes the motivation, the rational and implementation details of a modeling framework, SSDIM, which is an effort to bridge the gap of integrated models for decision making in urban planning.

However, it is possible to define further second level objectives, which will be the focus of each chapter. These targets can be summarized as:

1. State-of-the-art: literature review, legal background and methodology.
2. Description of the framework developed.
3. Application on a case study.
4. Possible future work on the framework, as integration in Water Distribution System.

1.5 LAYOUT

The Thesis will be divided into eight chapters (the present introduction is the first chapter). In the first part of the Thesis (Chapters 1 and 2) the setting and motivation for the framework proposed and an extensive critical review of the studies available in literature are discussed.

The second part of the Thesis (Chapters 3 and 4) presents the elements of the models implemented: in particular, both the conceptual representation and the implementation details are discussed in depth. The methodology for the complex model development can be divided into two parts: the earlier stage consists in the identification of the model components which can simulate single events concurring to the description of the complex system, the latter stage which consists in the integration of the single components into a common framework.

Finally in the latter part of the Thesis (Chapters 5 and 6), an application of the framework developed to a real world environmental problem and the results of the application of the framework to a pilot study will be described.

The network considered for the case study is situated in the city of Mauchline, a small town located in the county of East Ayrshire, in south west of Scotland.

The results show that the population growth rate has obvious effects on water quality. However, these effects do not compromise the functionality of the sewage system and of the treatment plants. An interesting effect seems to be caused by the rainfall event, but in this case the feedback could be the construction of a storage tank which limits the peak inflow to the treatment plant.

Such strategy applied to different planning assumptions may suggest effective mitigation options for sustainable land use planners to reduce the impact of new developments and thus achieve a better water environment.

2 LITERATURE REVIEW

2.1 INTEGRATION OF COMPLEX PROBLEM

CLUE (Conversion of Land Use and its Effects) (Verburg *et al*., 1999a) and the subsequent CLUE-S (Verburg *et al*., 2002) are modeling frameworks for quantitative multi-scale analysis of actual land-use and the modelling of land-use change scenarios. CLUE is a two-step model. First the suitability values of grid cells are evaluated based on statistical models that relate socio-economic, geographical and biophysical driving factors with land-use patterns. Then dynamic allocation of resources is undertaken between competing cells based on their suitability values and on national level demand changes for each land-use type (CLUE-S integrate this step with transition rules for each land-use type). Although CLUE/-S only provides land-use modeling capabilities (the former with a spatial resolution of 7×7km and 32×32km square grid, and the latter with a 1x1km grid), they have been integrated with other biophysical models to address specific problems. Verburg and van der Goon (2001) coupled CLUE with empirical emission factor models (IPCC, 1997) for the analysis of the effects of changes in rice cultivation area and livestock management on methane emissions for China. Priess *et al*. (2001) coupled a CLUE model (with a spatial resolution of 9×9 km) with the NUTMON tool (Smaling and Fresco, 1993) for the assessment of soil nutrient balances in tropical agricultural systems. NUTMON is a nutrient balance model to relate nutrient inputs such as fertilizer application and biological fixation to output fluxes in (among others) harvested products, crop residues and by gaseous losses. Verburg (2006) integrated the CLUE-S model to the process based LAPSUS model (Schoorl *et al*., 2004) in order to calculate the impact of land-use change on erosion erosion/sedimentation processes, and applied it to a region in Southern Spain. If the coupling CLUE-NUTMON is an open loop, the integration with LAPSUS is greater. In fact, erosion processes triggered by agricultural management are related to soil depth which in turn influences the suitability of grid-cells for agricultural purposes. All these studies provide limited functionalities for undertaking quantitative analysis and automatic planning and they have been typically employed to perform what-if scenarios.

GEONAMICA is a commercial application framework for constructing integrated models of the land system (supporting an hierarchical spatial representation, from macro/regional levels to grids, with a resolution typically ranging from 100×100 m to 500×500 m) based on the CA conceptualisation presented by White and Engelen (1997). The human sub-system consists of three models components: (1) water management, (2) land-use, and (3) crop choice and profit. The first component calculates water use of different land-use activities. The land-use model (Engelen *et al*., 1997) simulates land-use change on two different scale levels. On the regional level (macro-level), it calculates the land demands for different economic sectors such as agriculture, forestry and industry (de Kock *et al.*, 2001) by representing a mixture of underlying causes such as demography and market mechanisms, according to Geist and Lambin (2002). These land demands are then spatially allocated to the grid level (micro-level) through the constraint cellular automata approach introduced by White and Engelen (1997) taking into account the cell's suitability for different types of land-use, its spatial neighbourhood, zoning restrictions and accessibility of transport infrastructures. The crop choice and profit model then determines the best suited crop type for each cell that has been previously classified as agricultural use. This is done by portraying the decision making process on level of individual farmers, providing crop prices are variables. The environmental sub-model consists of a climate and weather model, a hydrology and soil model and a vegetation model. All these three models describe the corresponding physical processes at the grid level with different temporal resolution. The climate and weather model interpolate data from meteorological stations and general circulation models to the grid level. Interception, runoff, evapotranspiration, infiltration, soil moisture, aquifer recharge, river flow and transmission losses are implemented in the hydrology model, which processes this information, along with soil characteristics such as texture and thickness, to simulate soil erosion and sedimentation as well as soil and aquifer salinity. The vegetation model consists of two elements: the plant growth element determining structural components of plants and crop yields, and the natural vegetation element for calculating succession processes and the response of natural vegetation to exogenous perturbation through a rule-based approach. The human and environmental subsystems are highly integrated through numerous dynamic feedback mechanisms. GEONAMICA has been extensively used to develop decision support systems (DSS) and policy support systems (PSS). Examples are MODULUS (MODULUS, 2000; Oxley *et al*., 2004), which addresses physical, economic and social aspects of land degradation in the Mediterranean region, RamCo (de Kock *et al*., 2001), for coastal zone management in South Sulawesi in Indonesia, and MedAction for the support of planning and policy making in the fields of land degradation, desertification, water management and sustainable farming in Mediterranean watersheds (van Delden *et al*., 2007).

IMAGE 2.4 (Integrated Model to Assess the Global Environment) (MNP, 2006), (Alcamo *et al*., 1998) is a general dynamic integrated assessment model for the simulation at the global scale (a major scale with 24 world regions and a minor scale of approximately 50×50 km grid cells) of major societal and environmental processes of the Earth System and their feedbacks over a long temporal scale (usually 100 years). It has three components forming the human/decision making subsystem: an energy supply and demand model for each world region, a consumption and trade of agricultural products model and a land-use change model based on spatial allocation on the grid level. The environment sub-system consists of model components for terrestrial vegetation, terrestrial carbon, nutrient cycles, and biodiversity. All these components operate on grid level and are highly integrated both dynamically and across scales. IMAGE has been successfully applied in isolation to study the effect on the global scale of various processes, from land-use emissions (Strengers *et al*., 2004) as well as impacts of land-use change on ecosystems and the environment (Scenarios Working Group, 2005; Eickhout *et al*., 2006), and coupled with specific process models for various analysis, ranging from bio-energy potentials (Hoogwijk *et al*., 2005; de Vries *et al*., 2007) to the assessment of the impacts of land-use change on the carbon cycle (Sitch *et al*., 2003; Müller *et al*., 2007). IMAGE does not provide DSS integrated capabilities and it is usually used in large assessment studies for the analysis of long term strategic scenarios.

PLM (Patuxent Landscape Model) (Voinov *et al*., 1999a; Costanza *et al*., 2002) is an integrated framework for supporting water quality management on the watershed level (from 200×200 m up to 1×1 km spatial resolution) by simulating its relationship with nutrient loading resulting from changing land-use. The human sub-system is described by a Markov Chain-based economic model which computes the probability of conversion from agriculture or forest to residential land use based on factors like distance to public infrastructure and proximity to other land-use types as well as on historical land conversion decisions and land conversion costs. These probabilities are combined with assumptions of regional growth pressure for settlement development to generate the actual quantity of land-use change. The environment sub-system consists in an ecological component, which is organised in a grid level model and a spatial model. The former simulates ecological processes like forest, cropland, grassland, urban and open water within each grid cell using three components: the hydrology component (computing cell vertical water fluxes, including infiltration, transpiration and evaporation, the nutrient component, simulating the dynamics of phosphorus and nitrogen, and the he macrophyte component simulating processes of plant growth according to temperature, nutrient levels and water availability. The spatial model then computes the inter-cell horizontal fluxes previously generated at the grid level. The PLM model was originally developed for the Patuxent River watershed in the State of Maryland in the U.S.

ITE2M (Integrated Tool for Ecological and Economic Modelling) (Fohrer *et al*., 2002; Frede *et al*., 2002; Reiher *et al*., 2006) was developed to simulate the influence of changing land-use policy on environmental services like economic output, water balance and biodiversity. ITE2M operates at different scales that are specific to the model components, ranging from a 25×25 m grid over fields to sub-catchment level. The human sub-system is modeled by the models ProLand (Kuhlmann *et al*., 2002) and CHOICE (Borresch and Weinmann, 2006). The former simulates allocation of land-use systems dependent on legal and economic boundary conditions, and environmental factors. The latter consists of two parts: the first evaluates landscape functions based on an economic cost-benefit approach, while the second calculates price effects of agricultural policies. Processes of the environment sub-system are represented by the yield estimation module of ProLand and by different models used for the assessment of environmental services, including hydrology (SWAT, Soil Water Assessment Tool) (Arnold *et al*., 1993), biodiversity (cellular automata model ANIMO for habitat specific species numbers and botanical species richness) (Frede *et al*., 2002) and soil pollution. Its first application was the “Lahn-Dill Bergland” region (1200 km^2) in Germany. In terms of inter-components integration, the linkages are straight forward and do not account for feedback loops. Similarly to the other models/frameworks described, ITE2M does not provide automatically supporting decision making.

Various other integrated models exist whose primary focus is supporting a better understanding of the effects of land-use and agricultural policy change on various aspects of the land systems. Major examples are SITE, which also comprises an automatic calibration module based on genetic algorithms (Priess *et al.*, 2007) and LANDSHIFT (Alcamo and Schaldach, 2006).

Marquez and Smith (1999) reported a group effort by the CSIRO scientists that developed an integrated framework for evaluating the coupled effects of land use, transport and airshed process models in urban environment air quality. Two existing models, the land use–transport–environment (LUTE) from CSIRO BCE and the meteorological and photochemical model from CSIRO Atmospheric Research were linked through an effective interface (STEAM) that supported data transfer from different format and enabled extensive automatic calibration. LUTE supplies basic urban development scenarios consisting of land use, and associated urban infrastructure and activities, subdivided into homogeneous zones, and the population allocated to each activity within each zone for a given time period. A transportation gravity model is then applied to these land use scenarios to forecast the level of congestion in the road network. The level of congestion on each link, along with associated scenario information, provides the input to the emissions interface which calculates the distribution of emissions based on parameters provided by the Victorian Environment Protection Authority (EPAV). Four sources of emissions were considered:

1. link-based emissions come from mobile sources,
2. area-based sources generated by urban activities occurring over wide areas of land,
3. point sources individual sites and
4. biogenic sources from plants and vegetation.

These emissions are subsequently interpolated at grid level to be elaborated by the airshed model which, using the forecast meteorological conditions from the meteorological component track the movement of contaminants and calculate the rate of chemical reaction that lead to the formation of photochemical smog and secondary aerosols.

Irving and Moncrieff (2004) presented a modeling framework developed by the New Zealand minister of transport for integrated assessment of the effects of the variation of transport system (infrastructure and activity) on environmental indicators (air quality, and greenhouse gasses emissions). A fleet vehicle model generates NZ specific emission rates based on international data on pollutant generation rates by vehicle technology and on New Zealand specific data on exhaust emissions, fuel use, component wear, driving patterns, road and traffic types. The framework can accommodate for other process specific models to generate other spatially referenced emission rates or loading, which are then fed to an environmental capacity analysis component which assesses the stress level of the receiving environment according to sustainability thresholds. The level of integration of the various components is quite low and there is not an explicit land-use component that can support urban planning with respect to different activities.

Various others integrated modes/framework exist for the urban domain and a good review is given in (Kapelan *et al.*, 2006) where the authors focus on providing a classification of existing decision support tools for sustainable urban planning based on a set of criteria accounting for quantitative and qualitative analysis, stakeholder involvement and participatory decision making.

In spite of the large number of successful research projects and tools developed, today there is a distinct lack of methods and systems that reconcile land-use change, traffic and water infrastructure in an integrated network of processes that enable the analysis of the effect of urban plans on water and air pollution to support decision making for sustainable urban development.

2.2 LEGAL BACKGROUND

The preservation of water quality is highly affected in urban areas by continuous as intermittent immissions, it is necessary to adopt measures to intercept and treat these polluted flows. In particular during rain events, water quality is affected by Combined Sewer Overflow (CSO) activation. Built in order to protect the sewer system and the wastewater treatment plant by increased flows due to heavy rains, CSOs divert excess flows to the receiving water body. On the basis of several scientific papers, and of direct evidences as well, that demonstrate the detrimental effect of CSOs discharges, also the legislative framework moved towards a stream standard point of view.

The Water Framework Directive is the most substantial piece of water legislation ever produced by the European Commission, and will provide the major driver for achieving sustainable management of water in the UK and other Member States for many years to come.

It requires that all inland and coastal waters within defined river basin districts must reach at least good status by 2015 and defines how this should be achieved through the establishment of environmental objectives and ecological targets for surface waters. The result will be a healthy water environment achieved by taking due account of environmental, economic and social considerations.

The European Union Water Framework Directive (WFD), adopted in 2000, laid the foundation for a modern, holistic and ambitious water policy for the European Union and defined a clear implementation calendar to achieve its objectives, with intermediate deadlines for the achievement of specific tasks, among them:

1. December 2003: transposition of the WFD into national law (article 24), identification of river basin districts and set up of administrative arrangements (article 3).

2. December 2004: pressure and impact analysis of river basin districts, and economic analysis of water uses (article 5).
3. December 2006: establishment of the monitoring programmes for the assessment of water status (article 8).
4. December 2008: publication of the draft river basin management plans for consultation (article 14).
5. December 2009: adoption of the river basin management plans (article 13).
6. December 2012: programme of measures operational at the latest (article 11).
7. December 2015: achievement of good status for surface and groundwater (article 4) and first update of the river basin management plan

The Communication from the Commission to the European Parliament and the Council "Towards sustainable water management in the European Union - First stage in the implementation of the Water Framework Directive 2000/60/EC" and the accompanying Staff Working Document gave, in March 2007, an overview of the aims of the Directive and summarised the results of the implementation of the first two steps identified above.

This Report and the accompanying Commission Staff Working Document responds to WFD Article 18(3) which requires the Commission to publish a report on the progress of implementation of the WFD related to Article 8 on monitoring of water status. This report is based on the information submitted by Member States in accordance with WFD article 15(2), due on 22 March 2007.

The Water Framework Directive (EU/69/2000) sets new goals for receiving water quality, and groundwater as well, through an integrated immission/emissions phylosophy, in which emission limits are associated with effluent standards, based on the receiving water characteristics and their specific use. For surface waters the objective is that of a "good" ecological and chemical quality status. A surface water is defined as of good ecological quality if there is only slight departure from the biological community that would be expected in conditions of minimal anthropogenic impact. Each Member State authority is responsible for preparing and implementing a River Basin Management Plan to achieve the good ecological quality, and comply with Water Framework Directive (WFD) requirements. In order to cope with WFD targets, and thus to improve urban receiving water quality, a CSOs control strategy need to be implemented. Temporarily storing the overflow (or at least part of it) into tanks and treating it in the waste water treatment plant, after the end of the storm, showed good results in reducing total pollutant mass spilled into the receiving river.

Council Directive 91/271/EEC concerning urban waste water treatment was adopted on 21 May 1991 to protect the water environment from the adverse effects of discharges of urban waste water and from certain industrial discharges. On 27 February 1998 the Commission issued Directive 98/15/EC amending Directive 91/271/EEC to clarify the requirements of the Directive in relation to discharges from urban waste water treatment plants to sensitive areas which are subject to eutrophication.

The Urban Waste Water Directive, full title Council Directive 91/271/EEC of 21 May 1991 concerning urban wastewater treatment is a European Union directive concerning the "collection, treatment and discharge of urban waste water and the treatment and discharge of waste water from certain industrial sectors". The directive was adopted on 21 May 1991. Its stated objective is "to protect the environment from the adverse effects of urban waste water discharges and discharges from certain industrial sectors".

The directive requires the collection and treatment of waste water in agglomerations with a population of over 2000, and more advanced treatment in agglomerations with a population greater than 10,000 in sensitive areas.

Sensitive areas, within the meaning of the directive, include "freshwater bodies, estuaries and coastal waters which are eutrophic or which may become eutrophic if protective action is not taken"; "surface freshwaters intended for the abstraction of drinking water which contain or are likely to contain more than 50 mg/l of nitrates"; areas where further treatment is necessary to comply with other directives, such as the directives on fish waters, on bathing waters, on shellfish waters, on the conservation of wild birds and natural habitats, etc. The directive also provides for a derogation for areas designated as "less sensitive" and such derogations were approved for areas in Portugal.

By 31 December 1998 member states were required to ensure that wastewater treatment facilities were available for all agglomerations with a population of over 10,000 where the effluent was being discharged into a sensitive area. By 31 December 1998 member states were required to ensure that wastewater treatment facilities were provided for all agglomerations with a population of over 15,000, which discharged their effluent into a so called "normal areas" and biodegradable wastewater produced by plants of the food-processing sectors listed in the directive, and which discharged directly into receiving water bodies, fulfilled certain conditions.

By 31 December 2005 member states were required to provide collecting and treatment systems in all agglomerations with a population between 2000 and 10000 where the effluent is discharged into a sensitive area, and in all agglomerations with a population of 10,000 to 15,000 where the effluent is not discharged into such an area.

In 2004, Commission reported on implementation by the member states, the Commission noted that some member states, in particular France and Spain, were late in providing the required information, and infringement procedures had been initiated.

The report further mentioned a number of concerns regarding implementation in several countries, in particular the United Kingdom's interpretation and implementation of the directive about to the catchment areas of sensitive areas. According to the 2004 report, most member states planned to achieve conformity with the Directive by 2005 or 2008 at the latest.

The Urban Waste Water Directive marked a shift from legislation aimed at end-use standards to stricter legislation aimed at regulating water quality at the source. The directive applied both to domestic wastewater and to wastewater from industrial sectors, both of which account for much of the pollution. It also demonstrated the increasingly detailed nature of European Union legislation and resulted in significant costs in many member states.

Many years after the directive was adopted, considerable variations remained in the provision of sewage treatment in the different member states.

Numerous directives in the field of water supply and wastewater treatment have been exempted by the European Union (EU). Until recently, such abundance of cause-related regulations has been considered to be sufficient to manage water bodies from an environmental point of view. However, increasing problems related to water quantity and quality led to the development of an integrated approach for water management systems, including all water-related impacts (Saurer *et al.*, 2000). These efforts resulted in the amendment of the Water Framework Directive (WFD) (EU/2000/60/EC-WFD 2000) with the main objectives being the following (Holzwarth, 2002; Wiedemair, 2003):

1. Achievement of a ‘‘good ecological status’’ in all water bodies of the European Union until 2015 by applying an integrated approach for water management. Avoidance of deterioration of the present status of the water bodies.
2. Establishment of a coordinated river basin management within the EU and across the national borders (e.g., for the Danube, Rhine, Elbe, etc.).
3. Assigning a full costs recovery scheme to water supply and wastewater services (including environmental and resource costs). The polluter-pays principle has to be applied.
4. Preparation of periodically updated river basin management plans by incorporating all stakeholders.
5. Combined emission–water quality-based approach for the decrease of pollution from both point and diffuse sources.
6. Reduction (and finally the elimination) of emissions of single hazardous substances, according to a specified list of priority substances.
7. Periodically updated, legally binding programs for measures and monitoring of water quality and the development of management programs for control and planning purpose.

Because EU directives are not executable directly, they need to be translated into national legislation. Therefore, the factual implementation of the WFD is undertaken in the EU member states individually, with each of them being required to define its own standards and methods following the main objectives. The first step of the implementation process has been already accomplished with the adaptation of the member states national water legislations by the end of 2003. According to these targets, the WFD is among the most progressive water-related regulations worldwide.

3 DESCRIPTION OF THE MODEL

3.1 INTRODUCTION

The housing development and land use change model (LUC) allow the housing densities, types, locations, etc., to be characterized and projected forward in time. LUC is multi-agent based (Hercog and Fogarty, 2001) and simulates the land planning, urban growth and evolution processes over a given planning horizon. This model is a cellular automata-based model (Hercog and Fogarty, 2001), whereas the development is determined according to some transition rules (Fu *et al.*, 2008). The implemented rules are: driven by population growth, the model distributes the population spatially over a predefined development area and provides the land use type, number of houses, and number of people for each residential land use cell. The cell-based information is transformed and linked to the node-based sewage network.

The urban drainage model (UDM) allows the accounting of total water budget within the study area. UDM is based on a robust and broadly used solver, the EPA storm water management model (SWMM) (Lager and Smith, 1974; Huber and Dickinson, 1988). SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth and quality of water in each pipe and channel during a simulation period comprised of multiple time steps (Rossman, 2005).

The wastewater treatment plant model (WWTP) is used to model the flow hydraulics and system performance in terms of dry weather flows, wet weather flows and sedimentation. It is based on that developed by the IWA Task Group on benchmarking of control strategies (BCS) for wastewater treatment plants (Copp, 2002). WWTP simulates the municipal facility, which treats the wastewaters from the existing sewage network. The activated sludge model No. 1 (ASM1) is used to simulate the biological processes in the reactors (Henze *et al.*, 1986) and the secondary settler is modelled as a non-reactive 10-layer process using a double exponential settling velocity model developed by Takacs *et al.* (1991).

The methodology for the complex model development can be divided into two parts: the earlier stage consists in the identification of the model components which can simulate single events concurring to the description of the complex system, the latter stage which consists in the integration of the single components into a common framework. In this chapter a description of the single model components is given.

3.2 LAND USE CHANGE MODEL

The land use change model (LUC) represents the land planning and evolution process and is used to simulate the urban growth over a given planning horizon.

This model is a cellular automata-based model (Hercog and Fogarty, 2001), in which the development state of each cell is determined in terms of its own state and the states of its nearby neighbors at the previous time step, according to some transition rules (Fu *et al*., 2008).

A few types of transition rules have been implemented, and new rules can be easily integrated to allow for the analysis of the impact of different expansion patterns on the water quality. Driven by population growth, the model distributes the population spatially over a predefined development area according to the transition rules chosen and provides the land use type, number of houses and number of people for each residential land use cell.

The cell-based information, see Figure 3-1, is transformed and linked to the node-based sewage network in the spatial aggregation model according to the geographic information of the catchment and the topology of the newly designed/expanded network.

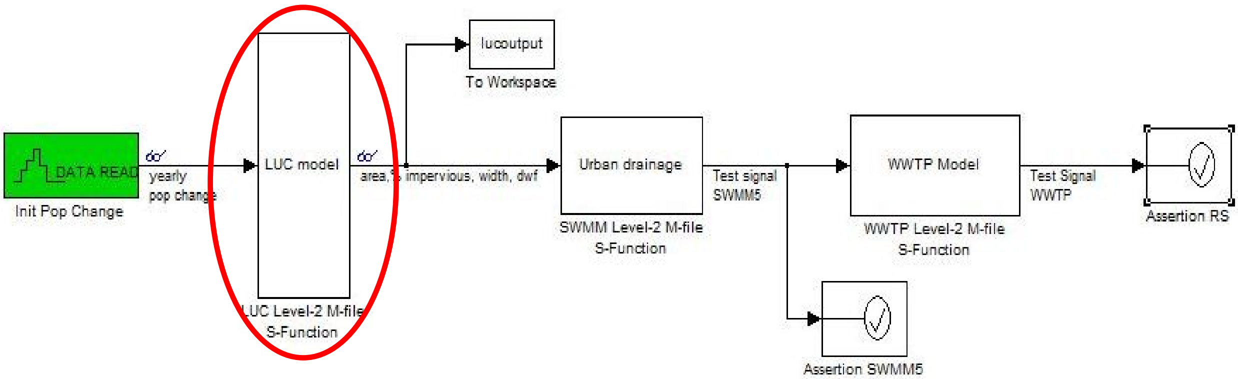

Figure 3-1. LUC component (circled in red).

3.2.1 BACKGROUND: URBAN GROWTH PATTERN AND CELLULAR AUTOMATON

Various theories have been developed to understand the spatial structure of urban growth. The concentric ring model, also known as the Burgess model, was the first to explain the spatial distribution of social groups in urban areas. The model depicts the urban growth in concentric rings with different land uses: from the centre outwards, the typical zones are the central business district (CBD), factory zone, the transition zone, working class zone, residential zone, and commuter zone. This model assumes a correlation between the distance from the CBD and the wealth of the inhabited area. The sector model is a modified model on the basis of the concentric ring model. While accepting the existence of a CBD area, the zones expand outward from the city centre along transport networks, for example, railways, motorways. These types of urban growth have many limitations, for example, without considering physical constraints, urban regeneration, and advance in transport.

After World War II, multiple nuclei model was developed on the basis of the increase in movement due to increased car ownership, which allows for the specialization of regional centres. Contemporary urban growth is characterized by suburbanization and dispersion, and this trend is the result of a variety of factors, for example, the advances in transportation and communication technologies, the decentralization of jobs, services, and residences from traditional urban centres to suburban settings. One phenomenon is the appearance of urban sprawl, which describe the form of urban growth in scattered isolated land parcels. Urban sprawl is criticized for inefficient use of land resources and energy and for large-scale encroachment on agricultural land.

Mathematical models are often used to simulate existing urban forms by representing various influencing drivers and their interactions, such as population, economic development. However, these traditional urban models were limited in representing the complexity of urban growth, particularly, the spatial distribution. Effective advances in the spatial representation of urban growth occurred only by the end of the 1980s, when cellular automaton was first used in urban system simulations (Batty, 1997).

A cellular automaton (CA) has a root in complexity and computer science (O'Sullivan and Torrens, 2000). It is a recursive iterative process suitable for modelling complex systems. It consists of a regular grid of cells, each in one of a finite number of discrete states at discrete time steps. The state of a cell at time t is updated by the state of the cell's neighbourhood at time t-1, according to predefined transition rules. The spatial complexity and system dynamics can be represented by defining various configurations of the elements of the CA design, including lattice, cell, neighbourhood, transition rules and temporal increments.

In recent years, CA has been widely used in various urban fields (White and Engelen, 1993; Batty, 1998; Wu, 1998; Torrens, 2000). The classical CA is a spontaneous, self-organising model which the global structure is emerged from local events in terms of a set of rules. To order to simulate urban growth, CA needs to be extended to accommodate the complexity and constraint of urban environments. For example, many urban phenomena simply do not emerge solely from local interactions, such as, transport infrastructure and planning systems; cities cannot grow indefinitely without constraints and they are affected by many top-down processes (such as central planning). It is particularly the case when using CA as decision support systems for urban planning because many policy interventions are non-local, and these can be inserted into models as external constraints or non-uniformities in the applicability of transition rules.

Transition rules play a central role in dynamic modelling of urban development using the CA model. These rules define how a grid can be conversed from one state to another state, and usually the probability of conversion is calculated as a measure, by considering local (neighbourhood), regional, and global factors. The factors can be classified as follows.

- *Neighbourhood*. A neighbourhood consists of a cell itself and a number of cells in a given configuration around the cell. The commonly used neighbourhoods are the Moore neighbourhood consisting of eight first order adjacent cells around a cell, and the von Neuman neighbourhood consisting of the four cardinal cells around a cell. The neighbourhood could change over time or space. For example, initially the new state of a cell could be determined by the horizontally adjacent cells, but for the next time step the vertical cells might be used. While much research used regular shape grids, irregular grids were also investigated by a few researchers, for example, Voronoi polygons (Flache and Hegselmann, 2001; Pang and Shi, 2002) and cadastral land parcels (O'Sullivan, 2002; Stevens *et al*., 2007). The difficulty in defining irregular spatial neighbourhoods and computational complexity for irregular grids are amongst the main reasons limiting their applications although these can better represent the real world.

- *Proximity*. The effect of proximity on urban growth originated from the monocentric bid-rent theory. With the increase in the distance to the city centre, accessibility decreases and transport cost increases. This factor has been extended for more city features as shown in Table 3-1.

Table 3-1.The proximity factors considered by Yang *et al*. (2007)

Proximity variable	**Description**
Major city centre	distance to the major (city proper) urban areas (unit: m)
Town centre	distance to the closest town centres (unit: m)
Road	distance to the closest roads (unit: m)
Railway	distance to the closest railways (unit: m)
Motorway	distance to the closest expressways (unit: m)

While the conventional CA models use the discrete 'if-then' rules to determine the state of each cell, mathematical functions have also been widely used to calculate the probability of a particular state transition, which is estimated from the hierarchy of various factors. Batty and Xie (1994) deployed the nested neighbourhood space and a distance decay function from the seed of development to determine transition probability. Wu (1998) defines a utility score to indicate the attractiveness of the site before estimating the probability of development. The utility of selecting a cell for development is calculated by the linear combination of various types of attractiveness. Wu and Webster (1998) applied multi-criteria evaluation into CA simulation to account for nondeterministic transition rules. Torrens (2001) integrated CA and multi-agent approaches to support the exploration of what-if scenarios for urban planning and management.

As linear transition rules cannot adequately accommodate the nonlinear characteristics of complex urban systems, nonlinear transition rules have been developed. For example, a logistic function was used to transform the utility score into probability (Wu, 2002).

The definition of CA rules has been explored in representing various types of urban forms and structures. The bottom-up representation from basic spatial units can generate realistic and desired global development patterns (Batty and Xie, 1994; Yeh and Li, 2001). White and Engelen's (1993) study also indicates that cellular approaches can achieve a high level of spatial detail and realism. Similar fractal dimensions are found between cellular cities and actual cities. The two different types of development, sprawl and compact patterns, are also simulated by the use of different model parameters. For example, Wu (1998) develops a CA model to simulate the formation of sub-centres from a mono-centre through a series of stochastic `errors'. The clusters of development are generated by the cumulative and aggregated self-organizing process. Yeh and Li (2001) investigated seven different types of urban forms and developments that range from compact - monocentric, compact - polycentric, compact - monocentric - environmental, compact - polycentric - environmental, dispersed, highly dispersed, to very highly dispersed developments.

3.2.2 MODEL DESCRIPTION

The land use change model uses the raster grid spatial structure to represent the landscape, which is considered as popular for the broad scale models. This data structure can be easily visualised in a GIS platform. The typical resolution of grid cell is by default set to 100 m × 100 m, although it can be changed to other resolutions indicated by the user. The land use types identified in the model can be categorised into three groups:

1. the urban housing group, including flats, cluster homes, semi-detached houses, detached houses, and terraced houses;
2. the urban non-housing group, including brown fields, retails, offices, industrial, schools, hospitals, and public green space;
3. the non urban group, including arable, grazing, airport, water bodies, forest, and other natural land covers.

Transformation from one land use type to another for each grid cell depends on the probability calculated by using transition rules. Incorporation of transition rules is made easy in this model in order to investigate the impacts of different growth patterns that can be represented by different transition rules. Currently, two different definitions of rules have been tested: stochastic distribution and the method given by Yeh and Li (2001). In the end, elicitation of different types of rules may provide a base for an expert system that will support the identification of alternative/innovative planning scenarios.

The planning policies that can be implemented in this model might include the following elements:

1. housing density, which can be designated at the grid cell level;
2. development constrains, for example, the green belts that must be protected from development;
3. land use type for each grid cell;
4. house type that can be developed for each cell.

Meanwhile, there are other planning elements that can be materialised through definition of transition rules, for example, different growth patterns (compact or dispersed development, multi- or mono-centric development).

The land use change model is to distribute population in the new development areas in terms of relevant urban planning policies and then drive the two pollution cycles: wastewater and air. A detailed description of model parameters and I/O table is given in the section of SSDIM implementation, in the next chapter.

3.3 URBAN DRAINAGE SYSTEM MODEL

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from urban areas (Rossman, 2005). The original version of SWMM was developed for the U.S.

EPA in the 1970s and has undergone several major upgrades since then. SWMM comprises 4 computational blocks and several other utilities to process data. The 4 engineering blocks are:

1. RUNOFF Block, for modeling the complete hydrologic cycle including winter storm recovery of infiltration and storages and sophisticated pollutant buildup and washoff process,

2. STORAGE/TREATMENT Block for simulating the quality and quantity aspects of stormwater ponds, infiltration basins and other BMPs;

3. TRANSPORT Block, for dry weather flow generation in sanitary sewers, sewer infiltration modeling and routing pollutographs and hydrographs typically generated by RUNOFF or STORAGE/TREATMENT through natural channels and sewer structures; and

4. EXTRAN Block, for complex, looped hydraulic calculations. The first three computational blocks can be used in continuous water quality modeling; EXTRAN, however, is computationally intensive and does not currently route pollutants and typically is applied to detailed or final design and complex analysis of events occurring in the continuous simulation (Zoppou, 2001; Vaze and Chiew, 2003).

Table 3-2. Characteristics & capabilities of SWMM urban storm water quality models (Christopher and Josef, 2007).

Model	Simulation Type	Simulated pollutant	Outputs/ Strengths	Limitations
SWMM	Continuous, Single Event	BOD, COD, TC, TN, TP, SS, SSa, O & G,	Pollutographs at any point in the watershed; seasonal and annual summaries of outputs; frequency analysis of any time series; predict sewer overflows; evaluate BMPs.	Weak in representation of the true physical, chemical, and biological processes; Extran block cannot simulate runoff quality; cannot model detailed sewer sediments processes.

Where COD is Dissolved & particulate chemical oxygen demand; TC is Total Coliform; TN is Total Nitrogen; TP is Total Phosphorus; SS is Suspended Solids; SSa is Settleable Solids; O & G is Oil & Grease.

The urban drainage model (UDM), see Figure 3-2, allows for the accounting of total water budget within the study area. It is based on a hydrologic model that accounts for the amount of inflow and discharge and links to LUC and WWTP to account for runoff within the system. Therefore, it provides the main driver for any occurrence of sewer flooding. In particular, this component is used to simulate the various water quantity and quality processes in the sewage system, which expands towards the new urbanized areas for draining wastewater discharges.

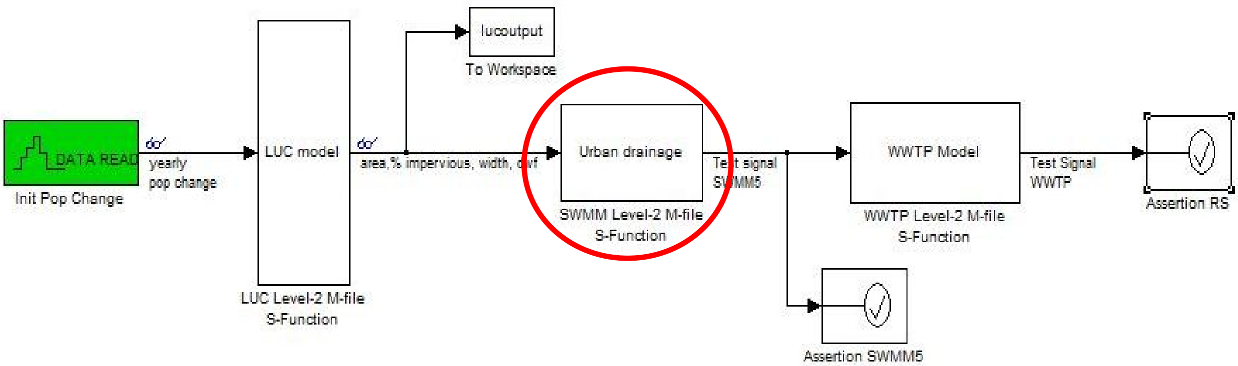

Figure 3-2. UDM component (circled in red).

SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth and quality of water in each pipe and channel during a simulation period comprised of multiple time steps (Rossman, 2005). Complex biochemical processes can occur while pollutants are transported throughout the sewage networks, which have a significant effect on the urban water system. The organic matter was modeled in two fractions: slowly and readily biodegradable. This has an advantage in modeling the effect of treatment plant effluents that might contain very different organic matter in terms of biodegradability (Schütze, 1998). This model also considered dissolved oxygen (DO) and ammonium.

The purpose of the UDM is to simulate the hydraulic behaviour of the sewage system in which the new urbanized areas discharge the wastewater flows. Therefore, UDM is integrated into an Automatic Network Expansion Model (ANEM). ANEM consists of two components. The earlier component is responsible for connecting the infrastructure necessary for the new dwellings to the existing sewer network. This is undertaken under a broad assumption about the number of inhabitants and the new urbanized area extension made by the urban planner. Therefore, once a new area is located, it is connected to the existing sewage network by a sewer, which is designed according to the demographic projection on the new zone. This procedure is repeated for all the new zones. The latter component is responsible for upgrading the network infrastructure when, on the basis of the results generated by the hydraulic simulation, overflow is observed in parts of the network. In this event, ANEM doubles the barrel of the overflowing channel and adds a storage unit at the end of the doubled channel. The volume of this storage corresponds to the overflowing volume plus an extra 10% of the volume for safety reasons. ANEM expands the network, if needed, every time LUC provides a variation which may affect the wastewater discharge; this implies that ANEM has the same time-step of LUC.

3.3.1 BACKGROUND

The urban drainage model (UDM) simulates the routing of wastewater discharge through the sewage system within the study area, and various water quality processes occurring as the flow moves towards the outlet of the system. It provides the link between LUC and WWTP and enables the quantitative and qualitative analysis of the effect of the runoff of the evolving land-use system on the load and concentration of pollutants at the inlet of the treatment plant.

UDM is based on a robust and broadly used solver, the EPA Storm Water Management Model (SWMM) (Lager and Smith, 1974; Huber and Dickinson, 1988), which features a good and updated hydraulic and pollutant transport engine. It shows a good flexibility, besides being open source and easy to be encapsulated into Simulink as shown in Figure 1.

The original EPA SWMM, one of the first computer based runoff models, was co-developed by the EPA and released in 1971. It was written in Fortran and ran on mainframe computers. Several major improvements have been made since then including: version 2 released in 1975, EXTRAN module added by Camp Dresser McKee (CDM) in 1977, version 4 released in 1988 and Windows SWMM released in 1994 to assist in TMDL analysis. The current EPA supported SWMM (version 4.3) is DOS based (Huber, 1988; Roesner *et al.*, 1988). The EPA did not actively support SWMM during most of the 80's, but the model became self-sustained by outside interest. Most notable refinements include the addition Graphical User Interfaces (GUI), such as XP-SWMM and PCSWMM. Model work was beginning to develop in Europe, such as Hydroworks, from Wallingford Software in Great Britain, and MikeSWWM / MOUSE GIS from the Danish Hydraulic Institute (DHI) and CDM. Many model modifications exist, such as UD-SWMM, modified by the Urban Drainage and Flood Control District of Denver, Colorado.

3.3.2 MODEL DESCRIPTION

SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth and quality of water in each pipe and channel during a simulation period comprised of multiple time steps (Rossman, 2005). Complex biochemical processes can occur while pollutants are transported throughout the sewage networks, which have a significant effect on the urban water system. The organic matter is modelled in two fractions: slowly and readily biodegradable. This has an advantage in modelling the effect of treatment plant effluents that might contain very different organic matter in terms of biodegradability (Schütze, 1998). This model also consideres dissolved oxygen (DO) and ammonium. A sketch of how SWMM operates is given in Figure 3-3.

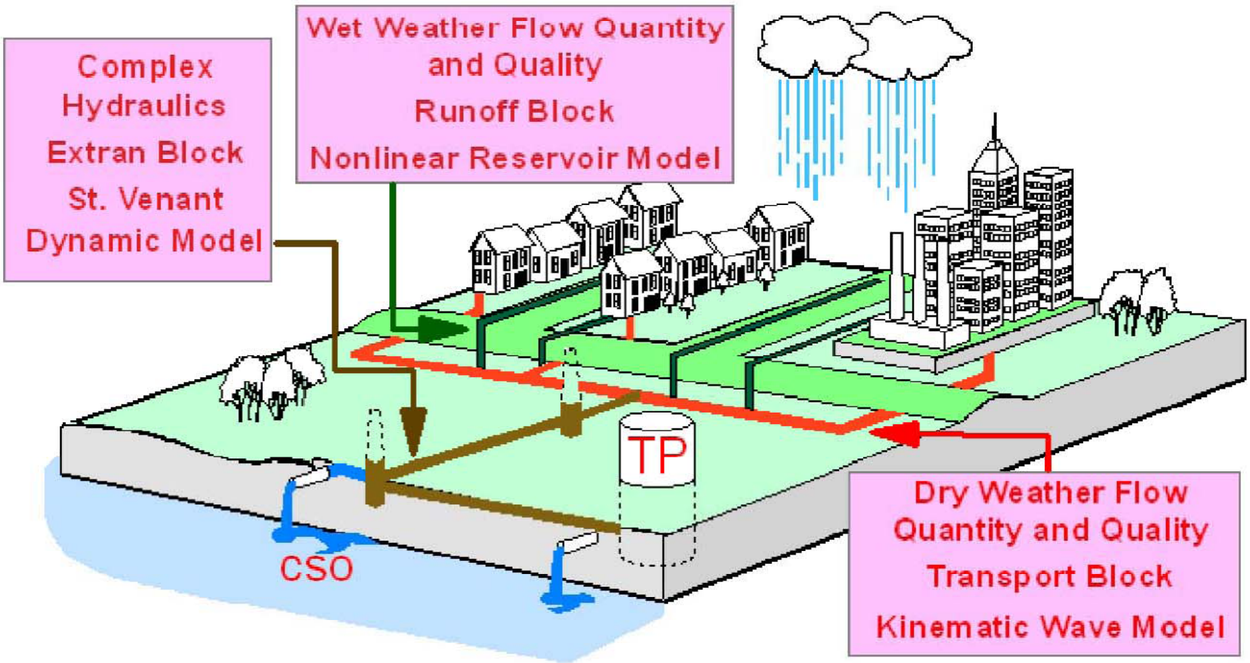

Figure 3-3. SWMM model of an urban catchment.

Among the main hydraulic/hydrological features of SWMM, it is important to emphasize that:

- handles drainage networks of any size.
- accommodates for various conduit shapes as well as irregular natural channels.
- models pumps, regulators, storage units.
- allows external inflows from runoff, groundwater, RDII (Rainfall Dependent Inflow and Infiltration), sanitary, DWF (Dry Weather Flow), and user-supplied time series.
- uses flexible rule-based controls for pumps and regulators.
- models various flow regimes, such as backwater, surcharging, reverse flow, and surface pounding.

The solution scheme which is adopted in this framework is based on the use of the Dynamic Wave routing. It solves the complete one-dimensional Saint Venant flow equations (Rossman, 2005) and therefore produces the most theoretically accurate results. These equations consist of the continuity and momentum equations for conduits and a volume continuity equation at nodes, which correspond in the order to:

$$\frac{\partial Q(s,t)}{\partial s}+\frac{\partial A(s,t)}{\partial t}=q(s,t)$$

$$\sum \mathrm{F}=\frac{\partial}{\partial t}\int_W \rho v dW-\int_\Omega v\rho(v\cdot n)d\Omega$$

Given a channel of the network, Q is the discharge flowing through the channel section of size A, q is the sum of the inflows/outflows through the channel, evaluated as discharge per unit of length. In the latter of equations, W is the control volume whose lateral surface is Ω, ρ is the density of the fluid, v is the local velocities vector and finally Σ **F** is the resultant force acting on the volume W. In its most general form, **F** is made of the following components: weight force, friction forces, forces due to change of the channel shape, pressure forces, shallow interaction forces.

Solving the equations according to the dynamic wave routing approach allows for representing pressurized flow when a closed conduit becomes full, such that flows can exceed the full normal flow value. Flooding occurs when the water depth at a node exceeds the maximum available depth, and the excess flow is either lost from the system or can pond atop the node and re-enter the drainage system.

Moreover, dynamic wave routing can account for channel storage, backwater, entrance/exit losses, flow reversal, and pressurized flow. Because it couples together the solution for both water levels at nodes and flow in conduits it can be applied to any general network layout, even those containing multiple downstream diversions and loops. It is the method of choice for systems subjected to significant backwater effects due to downstream flow restrictions and with flow regulation via weirs and orifices. This generality comes at a price of having to use much smaller time steps, on the order of a minute or less (SWMM will automatically reduce the user-defined maximum time step as needed to maintain numerical stability). This routing methods employs the Manning equation to relate flow rate to flow depth and bed (or friction) slope.

Normally in flow routing, when the flow into a junction exceeds the capacity of the system to transport it further downstream, the excess volume overflows the system and is lost. An option exists to have instead the excess volume be stored atop the junction, in a ponded fashion, and be reintroduced into the system as capacity permits. In dynamic Wave routing, which is influenced by the water depths maintained at nodes, the excess volume is assumed to pond over the node with a constant surface area. This amount of surface area is an input parameter supplied for the junction.

SWMM also accounts for the water quality routing within conduits, assuming that the conduits behave as continuously stirred tank reactors (CSTR). Although a plug flow reactor assumption might be more realistic, the differences will be small if the travel time through the conduit is on the same order as the routing time step. The concentration of a constituent exiting the conduit at the end of a time step is found by integrating the conservation of mass equation, using average values for quantities that might change over the time step such as flow rate and conduit volume.

Water quality modeling within storage unit nodes follows the same approach used for conduits. For other types of nodes that have no volume, the quality of water exiting the node is simply the mixture concentration of all water entering the node (Rossman, 2005).

In particular the water quality solver allows for modelling:

- pollutant buildup over different land uses.
- pollutant wash-off during runoff events.
- reduction in buildup from street cleaning.
- inflows from user-defined sources and sanitary dry weather flow.
- water quality routing through the drainage network.

Building on SWMM, the UDM can simulate the hydraulic behaviour of the sewage system in which the developing urban areas discharge the wastewater flows. In the UDM, the pollutants considered include suspended solids, volatile suspended solids, chemical oxygen demand (COD), soluble COD, ammonium and nitrate: this enables simulating the impact of land use changes on the runoff water quality.

UDM provides an Automatic Network Expansion Model (ANEM), which consists of two components. One component is responsible for connecting the infrastructure necessary for the new dwellings to the existing sewer network based on the assumption about the number of inhabitants and extension of the new urban areas made by the urban planner. Once a new area for urban expansion is located, it is connected to the existing sewage network by a sewer, which is designed according to the demographic projection on the new zone.

The second component is responsible for upgrading the network infrastructure when, on the basis of the results generated by the hydraulic simulation, overflow is observed in parts of the network. In this event, ANEM doubles the barrel of the overflowing channel and adds a storage unit at the end of the doubled channel. The volume of this storage corresponds to the overflowing volume plus an extra 10% of the volume for safety reasons.

3.4 WASTEWATER TREATMENT PLANT

In the mid 90s, work began on the development of a simulation-based protocol (a ‘simulation benchmark’) that would be used for the objective comparison and evaluation of wastewater treatment plant control strategies. The work was initiated by the ICA Specialist Group (IWA Task Group on Respirometry, in particular) in cooperation with the EU COST Action 682. The reason for initiating this work was that numerous control strategies had been proposed in the literature.

However, the literature did not provide a clear basis for comparison of these strategies because of the many confounding influences that have an impact on the system. The cooperation of the IWA Task Group and COST Actions resulted in the development of a ‘benchmark protocol’ called the Benchmark Simulation Model no. 1 (BSM1), which enables the unbiased evaluation of activated sludge control strategies related to organic and nitrogen removal. The IWA Task Group on Respirometry published an early version of the simulation benchmark in the Scientific and Technical Report No. 11.

The wastewater treatment plant simulator (WWTP) is based on that developed by the IWA Task Group on Benchmarking of Control Strategies (BCS) for wastewater treatment plants (Copp, 2002). It allows for simulating both the water treatment, as activated sludge process, and the sludge treatment. WWTP simulates the municipal facility which treats the wastewaters from the existing sewage network. The simulation of a wastewater treatment plant is important for understanding how an existing plant responds to new discharges and pollution loads and how to avoid that an abnormal quantity of pollutants is discharged into the receiving water body. For this reason, WWTP reproduces every single process occurring in the plant allows for locating the possible weak links of the treatment and the potential overflows. Moreover, the simulator quantifies the pollutant buildup and the flows.

In this way it will be possible to assess alternatives to the network expansion which delays the peak flows in order to avoid that an excessive flow or pollutant concentration arrives to the wastewater treatment plant.

Besides, it will be possible to assess what is the breakpoint at which the existing treatment plant has to be expanded and improved or a new one is required. The BCS model was originally developed in Simulink, hence it is encapsulated into the framework as a subsystem. This subsystem can be summarized according to the chart in Figure 3-4.

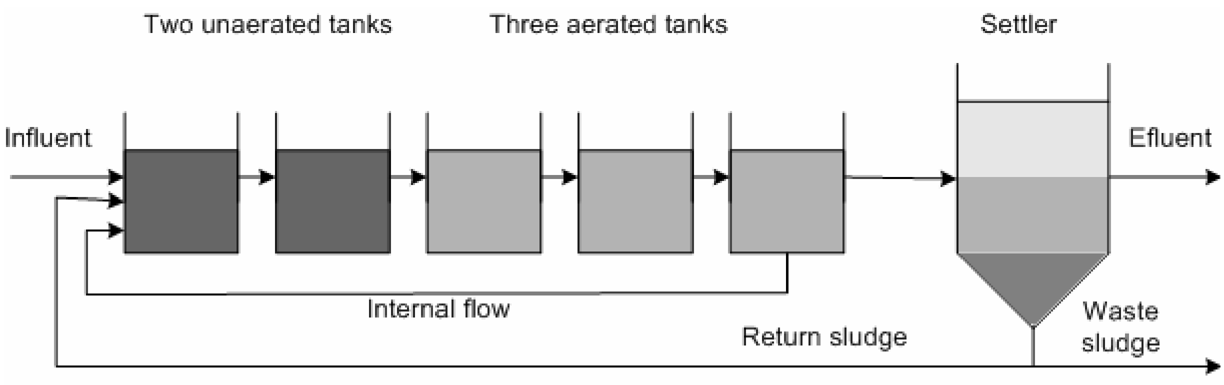

Figure 3-4. Schematic representation of the benchmark plant.

This benchmark model represents a denitrification plant, consisting of a five-compartment reactor with an anoxic zone and a secondary settler. A basic control strategy is used to control the dissolved oxygen and nitrate levels.

The Activated Sludge Model No. 1 (ASM1) is used to simulate the biological processes in the reactors (Henze *et al.*, 1986) and the secondary settler is modeled as a non-reactive 10-layer process using a double exponential settling velocity model developed by Takács *et al.* (1991).

As shown in Figure 3-4, there are two internal recycles: nitrate internal recycle from the 5th tank to the first tank and return sludge recycle from the underflow of the secondary settler to the first tank. In addition, waste sludge is pumped away continuously from the settler.

3.4.1 BACKGROUND

A major operational concern for urban drainage systems is their performance under wet weather flows and especially the onset of hydraulic incapacity in system and any resultant flooding. The wastewater treatment plant model (WWTP), see Figure 3-5, is designed to simulate the flow hydraulics and treatment performance in terms of dry weather flows, wet weather flows and sedimentation inside a treatment plant. It provides the link between UDM and enable the qualitative analysis of the effect of the evolving urbanization on the load and concentration of pollutants at the outlet of the treatment plant. The performance measure proposed for hydraulic incapacity under wet weather flows is based on a modified performance assessment system (Cardoso *et al.*, 2002).

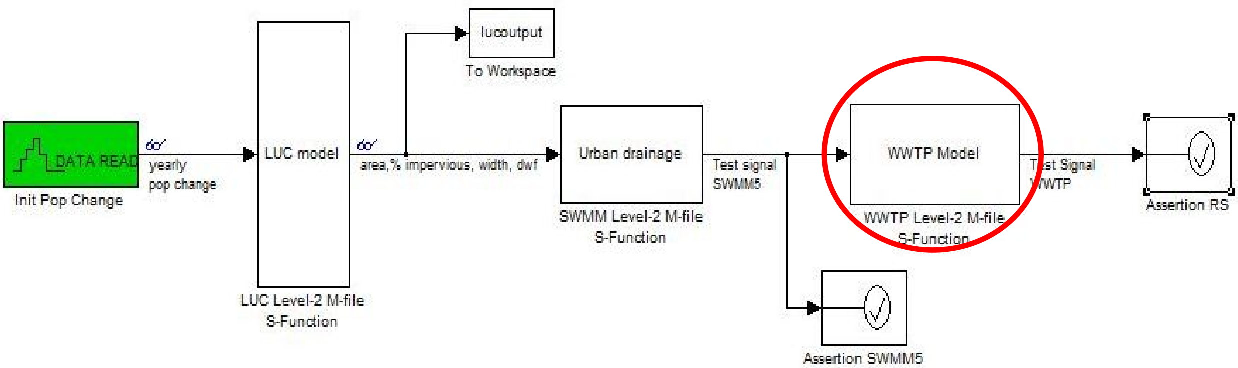

Figure 3-5. WWTP component (circled in red).

3.4.2 MODEL DESCRIPTION

The standard activated sludge plant (ASP) consists of 3 CSTRs in series and a settler, and was designed to operate at 15 °C. The influent is fed to the first tank, a step-feed possibility has also been modeled. This configuration was chosen because it is commonly used in practice, it provides flexibility for plant modifications or expansions, and it enables fast calculations during simulations. For example, an anoxic zone and step-feed can be easily integrated into the model.

Three design cases have been considered: a carbon removal system that does not include nitrification, a carbon removal system with nitrification, and a system with both carbon and nitrogen removal. An original design was calculated using literature values for biomass and volumetric loading rate. This design was then refined after a few simulations to obtain more realistic working conditions.

The plant which is simulated is designed to treat a population equivalent of 5,000 and for an average influent dry-weather flow rate of 922.3 m^3/d, with an average biodegradable COD in the influent of 300 g/m^3. Its hydraulic retention time (based on average dry weather flow rate and total tank volume – i.e. biological reactor + settler – of 12,000 m^3) is 14.4 hours. The biological reactor volume and the settler volume are both equal to 375 m^3. The wastage flow rate equals 385 m^3/d. This corresponds to a biomass sludge age of about 9 days (based on the total amount of biomass present in the system).

4 DESCRIPTION OF THE INTEGRATION

4.1 ASSUMPTION

The semantic network underpinning the implementation of the SSDIM framework is simple. The planning process impacts on the evolution of the land use types and population density. These, in turn concur to defining on the one hand the distribution and type of pollutants. The former impact on the amount of pollutants discharged into the drainage system and ultimately treated. The latter affects the amount, type and concentration emissions generated and pollution eventually deposited back on the ground.

The processed involved and described above are represented by four key modelling components, which form the core of SSDIM framework:

- Land Use Change model (LUC);
- Urban Drainage model (UDM);
- Waste Water Treatment Plant (WWTP) model.

Figure 4-1 provides the information flow between the components of SSDIM. Given long-term population projections and a land use plan that sets the land-use types available for urbanisation and identifies the constraints for the expansion areas, the LUC evolves the population distribution and land-use allocation using a cellular automata model with inductive rules. The resulting urbanisation configuration determines the pollutant loads been discharged to the drainage network as a consequence of rain wash-off. The UDM routes the pollutant loads according to pre-determined rainfall events and simulates the pollutant discharge at the inlet of a WWTP.

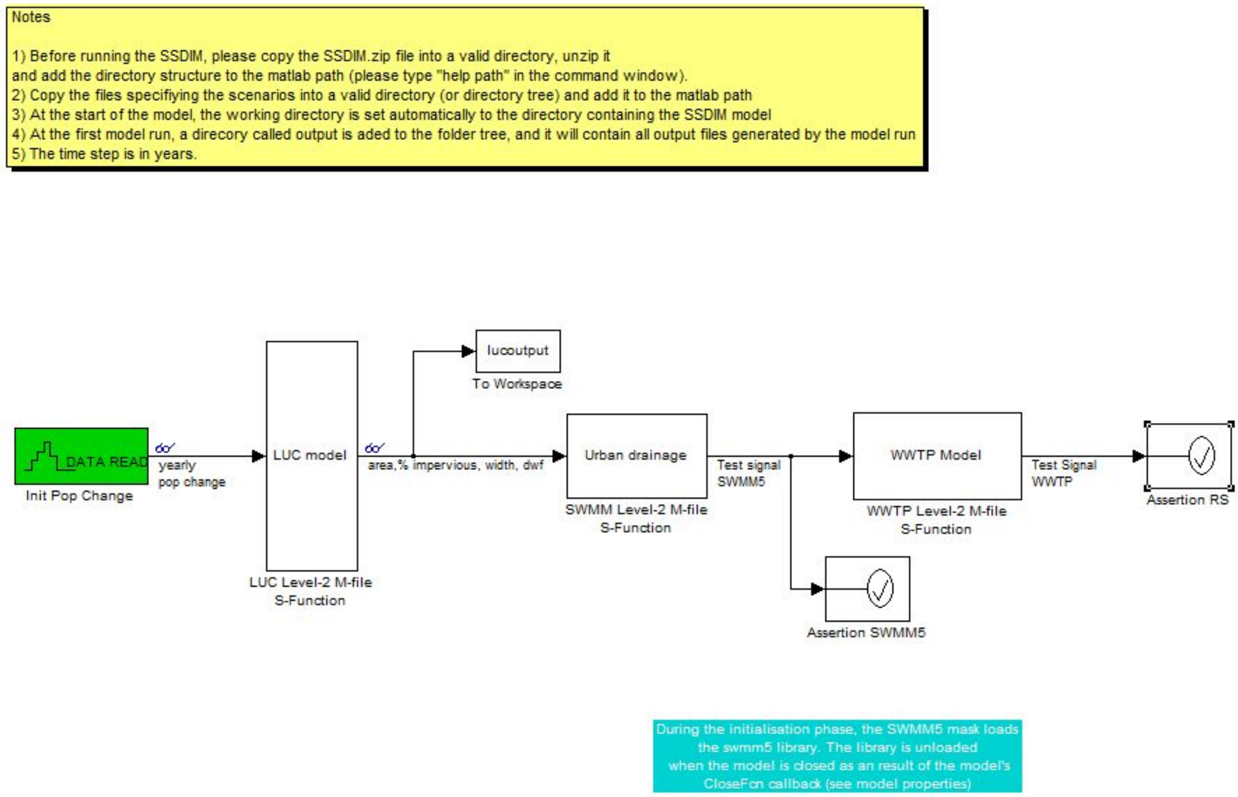

Figure 4-1. Components of the SSDIM framework and information flow.

The purpose of the SSDIM framework is to enable exploring both short term and the long term evolving impacts of new developments, which typically occurs over 20 to 50 years. The processes involved and described earlier occur at different rates. Accordingly, the time steps of the corresponding model components are different and they were chosen to allow for an accurate enough description of the underlying processes. The time step of land use change model was set to one year; the urban drainage and treatment plant models are simulated at a small step however (for example, 30 mins or one hour), in order to capture the system dynamics arising from urban runoff and dry weather flow, which is important to assess the capacity of the existing infrastructure (both distribution and treatment) to cope with the mounting peak of pollutant loads.

The underlying assumption for the different time steps is that the urban wastewater system is simulated for a rainfall events-based period, within each annual time step for other components. The events chosen will have to represent the characteristics of the catchment given a specific return period, for example, design rainfall events, and the events-based method has been widely used in system design because of its simplicity, computational efficiency, and less-data-intensive requirement compared with the continuous method. The patterns of dry weather flow (for example, diurnal pattern) will be considered to describe the short term dynamic fluctuation of sanitary flows, which plays an important role in determining the design/expansion of urban drainage, treatment plant performance, and thus river water quality. Further, a default base case control strategy is assumed for the urban wastewater system, while the facility for control optimisation is provided in the framework.

A major requirement for SSDIM to become a practical tool supporting communication and decision making amongst the parties involved in urban planning is providing flexibility for tuning the model components to represent the features of specific application areas and for integrating new model components to represent other application specific processes.

After a functional review of the existing commercially available software for simulation and system dynamics, Simulink was chosen as the best candidate for it not only fulfils the requirements set, but it also provides a rapid prototyping environment, it is computationally fast and supports the integration of models that are implemented using various programming languages and defined at different spatial and temporal resolution. Moreover, Simulink can directly exploit the suit of analysis tools provided by Matlab. These range from statistical analysis, optimization and data feed, hence minimising development time for providing the SSDIM framework with ad hoc functionalities.

Models implemented in Simulink can be directly nested into the framework as subsystems; those developed in other programming languages, prior conversion to Dynamically Linked Libraries (DLL), can be integrated by embedding them into level-2 mfile S-function blocks. Details of the integration of each model are given in the next paragraph.

SSDIM has been implemented as a discrete system with variable time step; the dynamic of each model component is hidden by the other components and therefore the system evolves as a sequence of triggered subsystems.

The SSDIM simulates the evolving urbanisation and corresponding effects on the water quality indicator over a period of 6 years. The driver of the simulation is the LUC model, which (as described in the previous chapter) has a time step of 1 year. Therefore a complete model iteration occurs every ear and to complete a model run (6-year simulations) a basic model loop is iterated 30 times. For each iteration (excluding the initialisation step), the execution sequence of the models is the following:

1. LUC updates the land use type allocation and population distribution;
2. UDM simulates the routing of the new pollutant loads through the network given a design rainfall event;
3. WWTP updates the pollutant concentration at the outlet of the treatment plant.

4.2 HOW TO DEAL WITH SINGLE INPUT-OUTPUT

4.2.1 LAND USE CHANGE MODEL

The LUC model, developed in Matlab, was embedded into a level-2 m-file s-function block and integrated into the SSDIM framework. The LUC block has a number of parameters that can be specified by the user through a simple interface. With reference to Figure 4-2, these are:

- *The total area* – extension of the development area;
- *Square grid resolution* – grid division, used for grid-based model set-up;
- *Initial land use type map* – existing land use types;
- *Initial population map* – existing house number;
- *Land use allocation map* – cells to be allocated for development of a particular density;
- *Maximum housing density map* – maximum number of houses for each cell;
- *Urban designation map*;
- *House type allocation*;
- *Urban location*;
- *Road networks*;
- *Housing para* – types of houses that can be developed for each cell;

- *Per capita waste water discharge* – discharged wastewater per person per day, used to calculate the total volume of domestic wastewater discharged from new developments;
- *No of workspaces per premises* – services production;
- *Network connection nodes for the new sub-catchments*;
- *Definition of road zones*;
- *Location of city centre*;
- *Location of sub-centre*;
- *Dispersion factor* – it is 0 for compact and 1 for high dispersion;
- *Weight* – for centre and sub-centre;
- *Connection between grid cells and network nodes*.

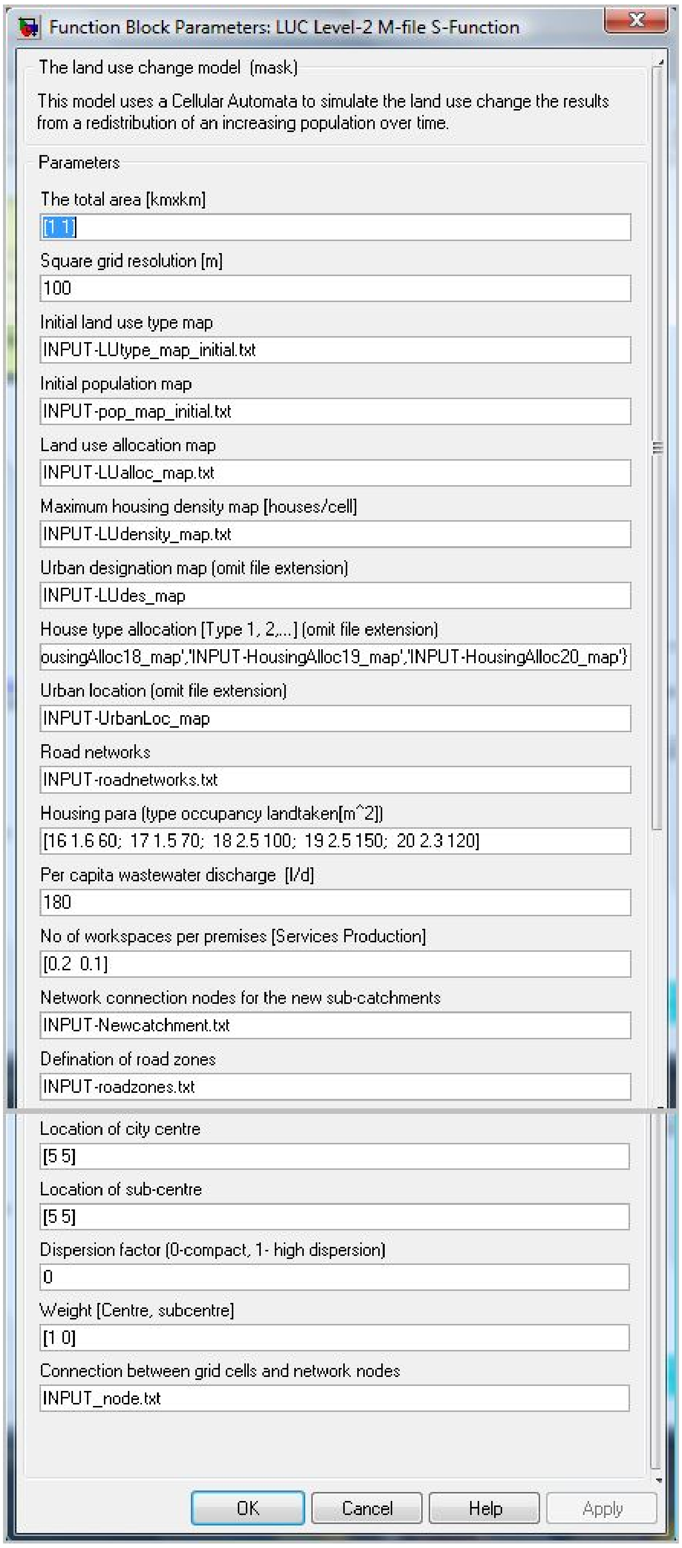

Figure 4-2. Parameters of the LUC block.

4.2.1.1 I/O Table

Table 4-1 provides the I/O summary of the LUC block. For each element, it provides a brief description, units (if appropriate), origin/destination and format.

With the exception of the input used during the initialisation stage (i.e. those with “initialisation” in the field “From/to” of the I/O table), all input and output are respectively fed to and produced by the block every time it is triggered, i.e. at each iteration of a loop of the SSDIM model.

Table 4-1. I/O of the LUC block.

	Data	**Units**	**Description**	**From/to**	**Format**
Input					
	Annual population change	persons	The population projection	Init Pop Change block	Signal
Output					
	Built-up area	ha	The total area of the newly developed area	SWMM	Signal
	Percentage imperviousness	%	The percentage of the impervious area	SWMM	Signal
	Catchment width	m	The widest width of the newly developed area	SWMM	Signal
	Dry weather flow	m^3/s	The domestic wastewater from the newly developed area	SWMM	Signal
	House number	houses	The number of houses for each grid	Luc\output	File
	Population size	persons	The population for each grid	Luc\output	File
	Land use type	–	The land use type for each grid	Luc\output	File

4.2.2 URBAN DRAINAGE MODEL

The UDM was originally implemented in C++. In order to integrate it into the SSDIM framework, it was first converted into a dll and then embedded into a level-2 m-file s-function block. The UDM block has a number of parameters that can be specified by the user through a simple interface. With reference to Figure 4-3, these are:

- *Existing urban drainage network setup* – .inp data file containing the description of existing sewage network;
- *File name for the manually update networks* – the name of the file containing the network updated;
- *Rainfall event* – the name of the file containing the rainfall events;
- *Simulation start day* – beginning of the hydraulic simulation;
- *Simulation start time* – beginning of the hydraulic simulation;
- *Simulation end day* – end of the hydraulic simulation;
- *Simulation end time* – end of the hydraulic simulation.
- *Report start day* – report of the beginning of the hydraulic simulation;
- *Report step* – report of the step;
- *Node of CSOs* – node connect to the wastewater treatment plant;
- *Node of treatment influent* – node connect to the wastewater treatment plant.

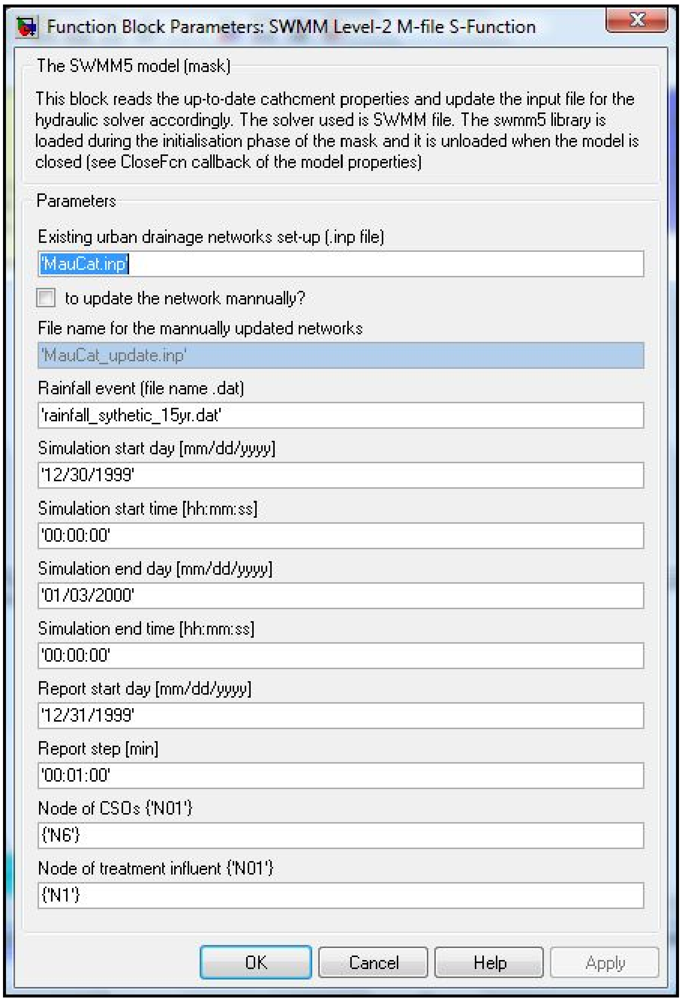

Figure 4-3. Parameters of the UDM block.

4.2.2.1 I/O Table

Table 4-2 provides the I/O summary of the UDM block. For each element, it provides a brief description, units (if appropriate), origin/destination and format. With the exception of the input used during the initialisation stage (i.e. those with "initialisation" in the field "From/to" of the I/O table), all input and output are respectively fed to and produced by the block every time it is triggered, i.e. at each iteration of a loop of the SSDIM model.

Table 4-2. I/O of the UDM block.

	Data	Units	Description	From/to	Format
Input					
	Dry weather flow	m^3/d		LUC/UDM	.txt
	Rainfall intensity	mm/d		Data File/UDM	.dat
	Network topology			Data File/UDM	.inp
	Topology of viable network expansion plans			Data File/UDM	.inp
	Macro subcatchment parameters			LUC/UDM	.txt
	Pollutant		Pollutant generated by the traffic and/or parking as deposition on the ground	Data File/UDM	.inp
Output					
	Flow wave	m^3/d	Flow wave generated by the new expansion areas	UDM/WWTP	.rep
	Flow wave	m^3/d	Flow wave generated by the whole network, i.e. existing and expanded sewers	UDM/WWTP	.rep
	Overflows	m^3/d	Potential overflows, in terms of location, duration and volumes	UDM/WWTP	.rep
	BOD	mg/l	Biochemical Oxigen Demand	UDM/WWTP	.rep
	COD	mg/l	Chemical Oxygen Demand	UDM/WWTP	.rep
	TSS	mg/l	Total Suspended Solids	UDM/WWTP	.rep
	NOx	mg/l	Nitrogen Oxides	UDM/WWTP	.rep
	Sulphates	mg/l	UD/WWTP	.rep	Sulphates

4.2.3 WASTEWATER TREATMENT PLANT MODEL

The WWTP model was originally developed in Simulink. Although a direct integration was possible, it was first converted into a dll and then integrated it into the SSDIM framework. This was necessary for license agreement since the underlying model is commercial software. For the same reason, working parameters of the model cannot be accessed through a user interface. If modifications are required, those must be implemented using the model source code, available only through a licence agreement.

Through the block parameter interface, the user can specify the SWMM report step, as shown in Figure 4-4.

4.2.3.1 I/O Table

Table 4-3 provides the I/O summary of the WWTP block. For each element, it provides a brief description, units (if appropriate), origin/destination and format. With the exception of the input used during the initialisation stage (i.e. those with “initialisation” in the field “From/to” of the I/O table), all input and output are respectively fed to and produced by the block every time it is triggered, i.e. at each iteration of a loop of the SSDIM model.

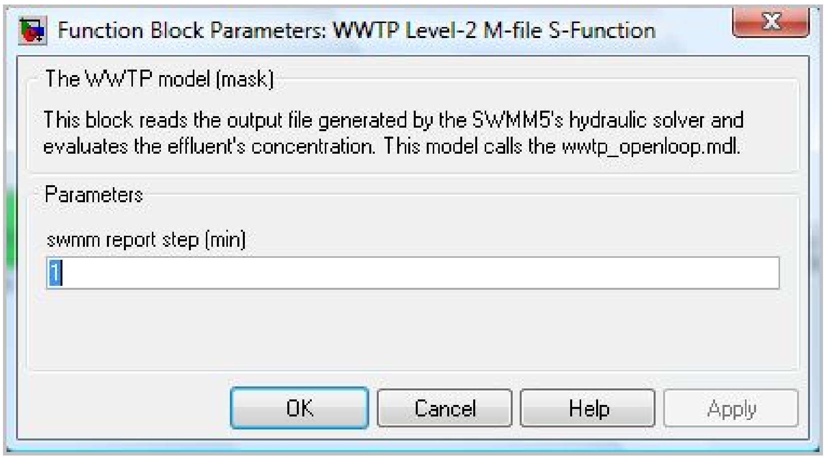

Figure 4-4. The parameter interface of the WWTP model.

Table 4-3. I/O of the WWTP block.

	Data	Units	Description	From/to	Format
Input					
	Flow wave	m^3/d	Flow wave generated by the new expansion areas	UDM/WWTP	.rep
	Flow wave	m^3/d	Flow wave generated by the whole network, i.e. existing and expanded sewers	UDM/WWTP	.rep
	Overflows	m^3/d	Potential overflows, in terms of location, duration and volumes	UDM/WWTP	.rep
	BOD	mg/l	Biochemical Oxigen Demand	UDM/WWTP	.rep
	COD	mg/l	Chemical Oxygen Demand	UDM/WWTP	.rep
	TSS	mg/l	Total Suspended Solids	UDM/WWTP	.rep
	NOx	mg/l	Nitrogen Oxides	UDM/WWTP	.rep
	Sulphates	mg/l		UDM/WWTP	.rep
Output					
		mg/l	The pollutant load of the discharge in the water body	WWTP	.txt
		m^3/d	The overflow discharge, in case of an excessive inflow from the sewage system	WWTP	.txt
			The unit/units which are not properly working during the treatment	WWTP	.txt
			The discharge downstream in the water body and its concentrations	out	.txt

4.3 INTEGRATION AMONG THE COMPONENT

The aforementioned models are integrated into a common framework, which allows for the evaluation of the effects of land use change on the sewage system and on the wastewater treatment plant. This common framework allows the single component to communicate even if the integrated components do not share the same time step and are serially run each one with its own time step.

Table 4-4 summarizes the purposes, input, and output of each model component.

In particular, the LUC is run first and then the new urban scenario is generated. LUC is run on an annual time step, assuming that 1 year is the minimum time to observe a variation of the population. The LUC allows for the evaluation of the new ratio between urban impervious areas and pervious areas, moreover given the new number of inhabitants, it is possible to estimate the new dry weather flow which is discharged into the existing sewage system. The update of the impervious areas allows for the estimation of the contribution given by the new subcatchment in terms of first flush to the sewage system. The LUC is run on an annual time step, assuming that one year is the minimum time to observe a variation of the population. The outputs of the LUC are the house distribution and density, the population distribution and density, the dry weather flow generated by the new inhabitants of the new subcatchment and the percentage of the new subcatchment made of impervious areas. In particular, the new dry weather flows and the new values of the impervious areas are passed to the UDM.

The UDM performs an extended period simulation, whose length is a parameter assumed by the user. In addition, UDM can incorporate into the simulation one or more rainfall events, whose hyetograph is assumed by the user in terms of shape and duration. The UDM produces the following output: the wastewater flow at the connection of the sewage network with the wastewater treatment plant, the overflow discharge, if any exists, at the divider placed downstream the link with the wastewater treatment plant, the wastewater flow at the connection of the new urbanized area with the existing network. Moreover, at the same locations where flows are returned, UDM produces also the concentrations of water in terms of Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), total Nitrogen (TotN), meant as ammonium and nitrate ($NO_3^- + NH_4^+$). Those concentration values have been chosen since the impact which is investigated is exclusively related to domestic uses of water, while industrial uses are not considered. A further important characteristics in a combined sewage system is the overflow discharge, which is generated when the inflow exceeds the maximum treatment plant influent. These discharges are directly discharged into receiving body and could have a significant impact on the downstream system's quality.

Table 4-4. Summary about the components of the framework.

Model component	Purpose	Input	Output
LUC	New ratio between urban impervious areas and pervious areas New number and distribution of inhabitants	Transition rules Location of new development areas Boundary conditions and constraints	House distribution and density Population distribution and density Dry weather flow generated by the new inhabitants Percentage of the new subcatchment made of impervious areas
UDM	Extended period simulation of the sewer system – hydraulics and quality	Subcatchment features Dry weather flow Rainfall hyetograph Pollutants' buildup Time variability of discharges and pollutants' concentrations	Wastewater flow upstream the treatment plant Wastewater flow at the connections with new urbanized areas Wastewater overflow at the divider (excess of flow spilled over by the network) Concentrations of at the same links whereas flow is returned: Total Suspended Solids (TSS), Chemical Oxygen Demand (COD) Biochemical Oxygen Demand (BOD_5) total Nitrogen (TotN)
WWTP	Simulates the treatment of the wastewater incoming from the sewage network	Wastewater coming from the sewage system Concentration of incoming pollutants	Treated water discharge (upstream the receiving water body) Pollutant concentration (TSS, COD, BOD_5, TotN)

The WWTP simulates the treatment of the wastewater incoming from the sewage network. A fixed 15 min time step is assumed for the simulation. The analysis is carried on a regime condition, while the start-up phase, which is done by the model, is not accounted. The 15 min time step was chosen in agreement with what is reported by Copp (2002); indeed that time step is the minimum which could be set for the model.

It is also important to emphasize that the transition between the UDM and the WWTP does not take into account for the delay due to the storing of the incoming wastewater in the equalization tank. Outcomes from urban drainage and wastewater treatment plant will be used to provide urban planners with feedbacks in the view of identifying alternative and more sustainable development patterns. Therefore, the incoming discharge is instantly equalized and then treated by the plant. The aforementioned divider is placed upstream the equalization tank, this separates the surplus of water which cannot be treated by the wastewater treatment plant, discharging the overflow directly into the receiving water body. The flow at the outlet of the sewage system, i.e. at the connecting node between the wastewater treatment plant and the sewage system is given as input to WWTP as well as the previously mentioned concentration parameters. In ASM1 model, there are 8 processes incorporating 13 different components, which are classified into soluble components and particulate components. A factor-based conversion method is used here to convert different pollutants (Schutze, 1998). In particular, the results of the simulation include the occurrence of sewer flooding and treatment plant effluent compliance to requested standards. In particular the WWTP produces the following output used to monitor the plant: flow towards the receiving water body, COD, TSS, BOD_5 and NH_4^+.

In particular these values in according with Alex *et al.* (2008) are verified to be lower than the limits reported in Table 4-5.

Table 4-5. Effluent quality limits.

Variable	**Upper limit (g/m^3)**
TotN	< 18
COD	< 100
TSS	< 30
BOD_5	< 10

Finally, in the following Fig. 4-5 and Fig. 4-6, a schematic representation of the framework and its feedbacks is given.

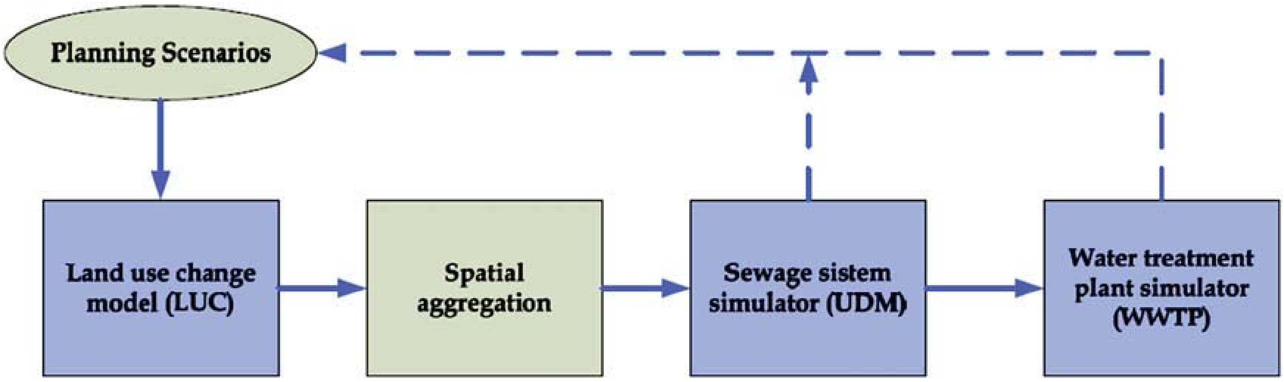

Figure 4-5. Overview on the integrated framework.

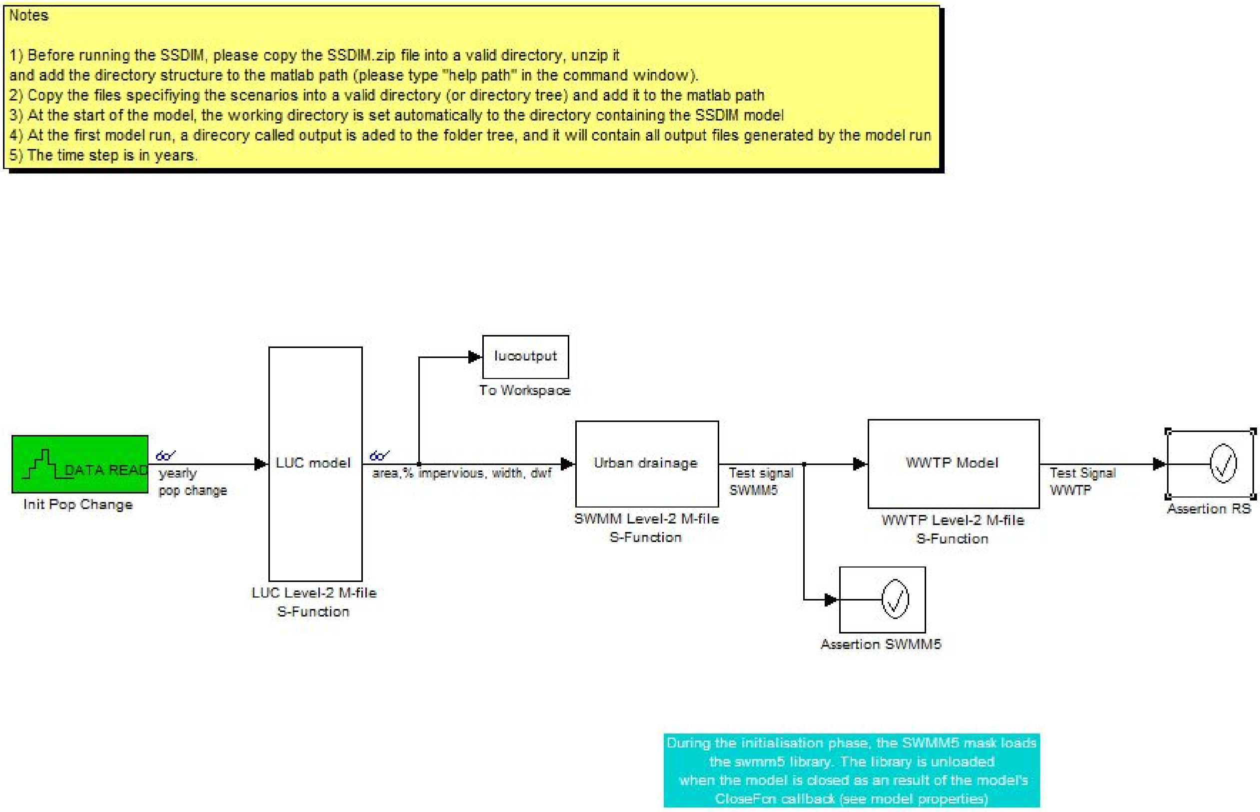

Figure 4-6. Overview on the Simulink integrated model.

5 CASE STUDY

5.1 INTRODUCTION

The aim of this Thesis is to show how SSDIM can be used to measure the impact of the implementation of different local scale urbanisation strategies on the quality of an urban catchment. It will be shown that the coupling of high-level strategic models of urban planning with low-level detailed physical models of urban water drainage and treatment provide valuable indications on the effect of the increasing water pollution loadings on the behaviour of the water infrastructures.

The network considered for the case study is situated in the city of Mauchline, located in East Ayrshire, in Scotland. The 2001 census had a recorded population of 4105. It lies by the Glasgow and South-Western railway line, 8 miles (13 km) east-southeast of Kilmarnock and 11 miles (18 km) northeast of Ayr. It is situated on a gentle slope about 1 mile (2 km) from the River Ayr, which flows through the south of the parish of Mauchline. In former days Loch Brown was about 1 mile west of the town, but was drained when the railway line from Kilmarnock was built.

In the following Figure 5-1 a sketch of the sewage system is given. The flows are diverted downstream via two outfalls: Out1 and Out6. Node Out1 is connected to the wastewater treatment plant and node Out6 is the outlet of the channel sewer coming from the divider. The divider is placed in node N17. Both node Out1 and Out6 discharge into the same water body, even if what comes from node Out1 passes through the treatment plant before being discharged.

Figure 5-2 shows a satellite image of the study area, in Scotland, and it provides the layout of the water infrastructures described.

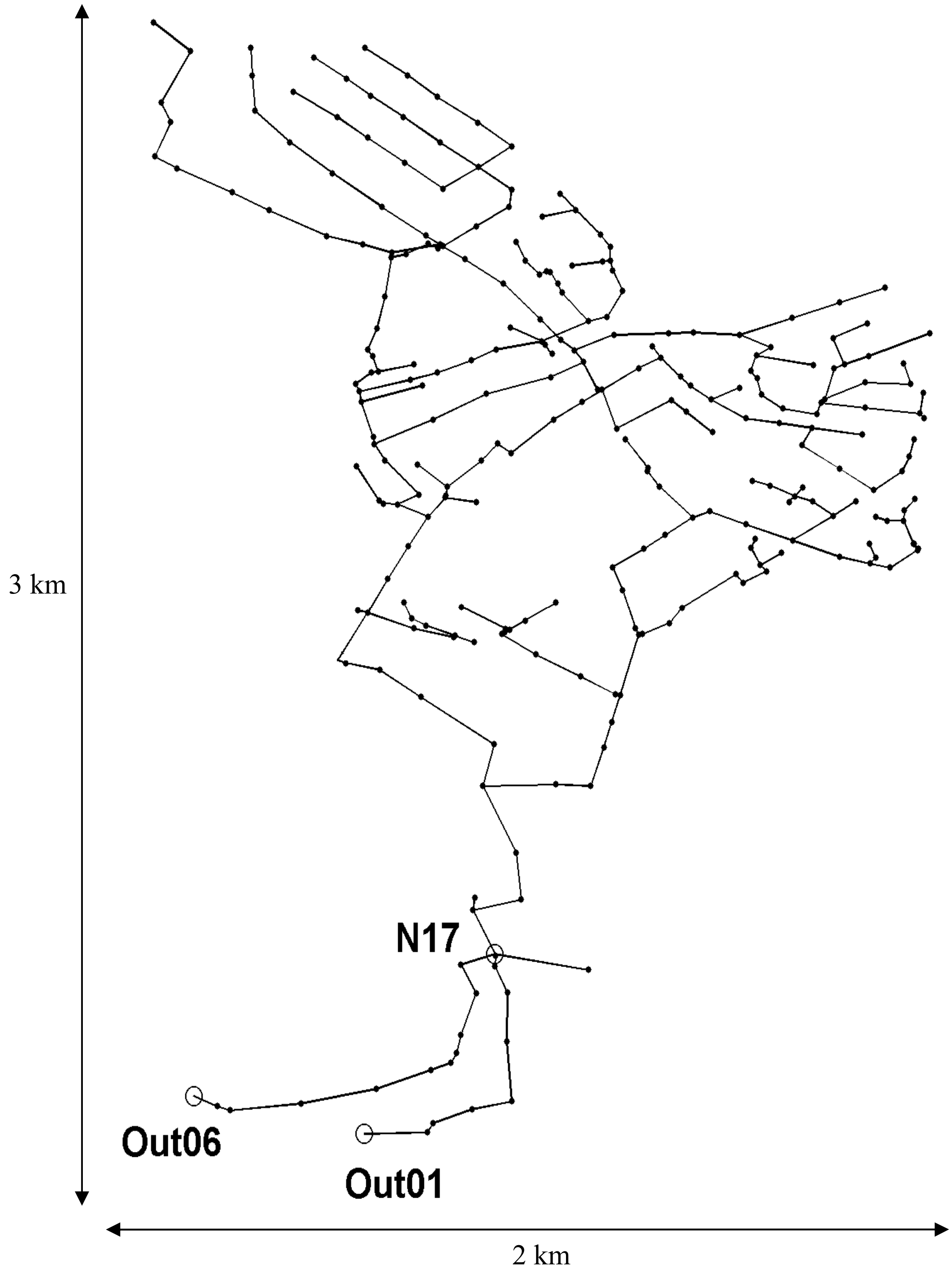

Figure 5-1. A sketch of the sewage system.

Figure 5-2. Study area and layout of the sewer system.

No data related to the waste water treatment plant were available. Therefore, a benchmark plant was considered for the purpose of demonstrating the use of the software. The capacity of the benchmark model was originally designed for a population of 10,000.

In order to match the size of the urban catchment studied, the reactors in the benchmark model were downsized. Further, a retention tank has been added to the system, which increases the flexibility of control. This facility will be studied for optimal control of the system in a future work, and it has not been used for the current case study.

The criteria chosen to assess the performance of the existing sewer system and drive its expansion to cope with increasing urban growth is the event-based approach. Sewer systems are normally designed for storms with a return period from 5-20 years. A 5 minute design rainfall with a relatively high return period of 15 years was chosen as shown in Figure 5-3 to show the impact of urban planning not only on the receiving water quality but also on the surface flooding.

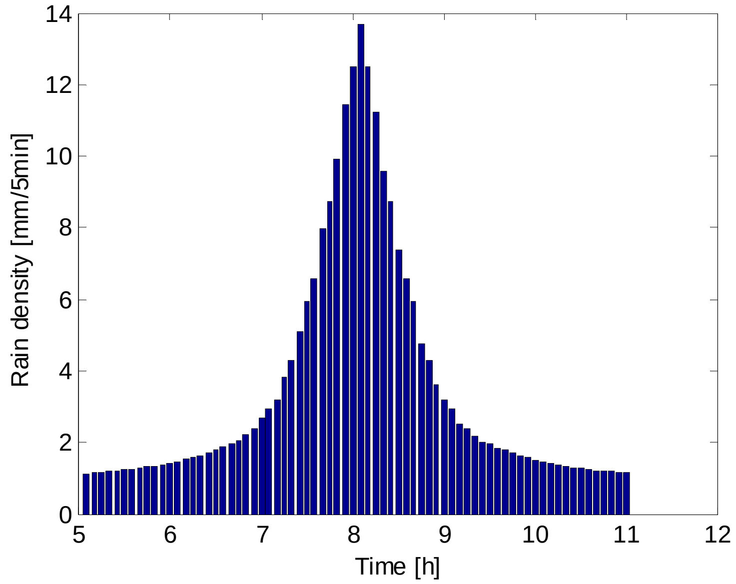

Figure 5-3. Synthetic hyetograph of the rain event used for the simulation.

The pollutants simulated in the sewer system include TSS, COD, BOD_5, and total nitrogen (nitrates and ammonia). The indicators used to measure system performance include CSO volumetric discharges and pollutant loadings (TSS, COD and total nitrogen), sewer flood volume, and wastewater treatment plant effluent quality (BOD_5 and total nitrogen).

The process execution chart of SSDIM is presented in Figure 5-4.

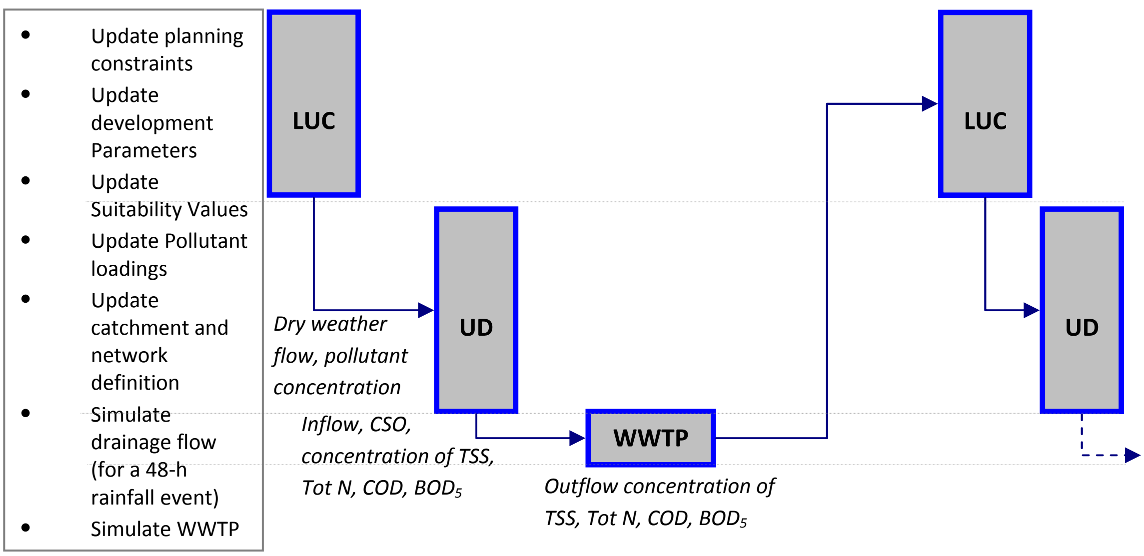

Figure 5-4. SSDIM process execution chart.

The time steps of the corresponding model components are different and they were chosen to allow for an accurate enough description of the underlying processes.

The time steps of land use change model is set to one year; the urban drainage and treatment plant models are simulated at a small step however (for example, 30 mins or one hour), in order to capture the system dynamics arising from urban runoff and dry weather flow, which is important to assess the capacity of the existing infrastructure (both distribution and treatment) to cope with the mounting peak of pollutant loads.

The underlying assumption for the different time steps is that the urban wastewater system is simulated for a rainfall event-based period, within each annual time step for other components.

Dry weather flow patterns (for example, diurnal pattern) are used to describe the short term dynamic fluctuation of sanitary flows, which plays an important role in determining the design/expansion of urban drainage and treatment plant performance. Further, a default base case control strategy is assumed for the urban wastewater system.

5.2 DEVELOPMENT OF URBAN PLANNING SCENARIOS

Two planning scenarios are assessed in this Thesis, whereas the population is assumed to grow of 1,000 new individuals on a 6-years time window, this corresponds to:

- **Scenario 1.** Spatially constrained urbanization.
- **Scenario 2.** Spatially diffused urbanization.

In particular, Scenario 1 comprises three further sub-hypothesis:

- **Hypothesis I (low density increase).** The maximum housing density is set to 40 households per ha.
- **Hypothesis II (normal increase).** The maximum housing density is set to 60 households per ha.
- **Hypothesis III (high density increase).** The maximum housing density is set to 80 households per ha.

Scenario 2 comprises just the Hypothesis II (normal increase), whereas the maximum housing density is set to 60 households per ha.

The population increase is assumed to be equally distributed over each year, for instance, in the base case scenario, 1,000/5 = 200 persons are distributed to the new development each year. During the first year, population does not grow, thus it is possible to assess which are the model outcomes when no urban development takes place.

The development pattern of this area arises from a series of assumptions and from a set of interaction rules implemented by a cellular automata model that simulates how the distribution of people over the area evolves from local interactions.

These urban planning hypotheses are assessed in terms of a set of water quality indicators including the TSS, COD, BOD_5 and TotN concentrations upstream the treatment plant, downstream the treatment plant, i.e. after the wastewater is treated but not discharged into the receiving water body, and downstream of the CSOs discharges, i.e. quota of exceeding water from the sewage system, before being discharged into the water body.

The wastewater load generated by this area is conveyed by a new conduit which is connected to the existing sewage system through the node N61 in **Scenario 1**, at the location shown by Figure 5-5, while the numerical assumption about the area are shown by Table 5-1.

Scenario 2 is characterized by multiple areas linked to the existing network, through nodes N17, N61, N143, N259, N283, located as shown by Figure 5-5, while the numerical assumption about the area are shown by Table 5-2. The purpose of this scenario is analysing the impact of a diffuse urbanization around the existing developed areas. The area for potential new development is divided in a number of sub-catchments, each connected to the existing sewer system through a new conduit that is responsible to convey the wastewater load generated.

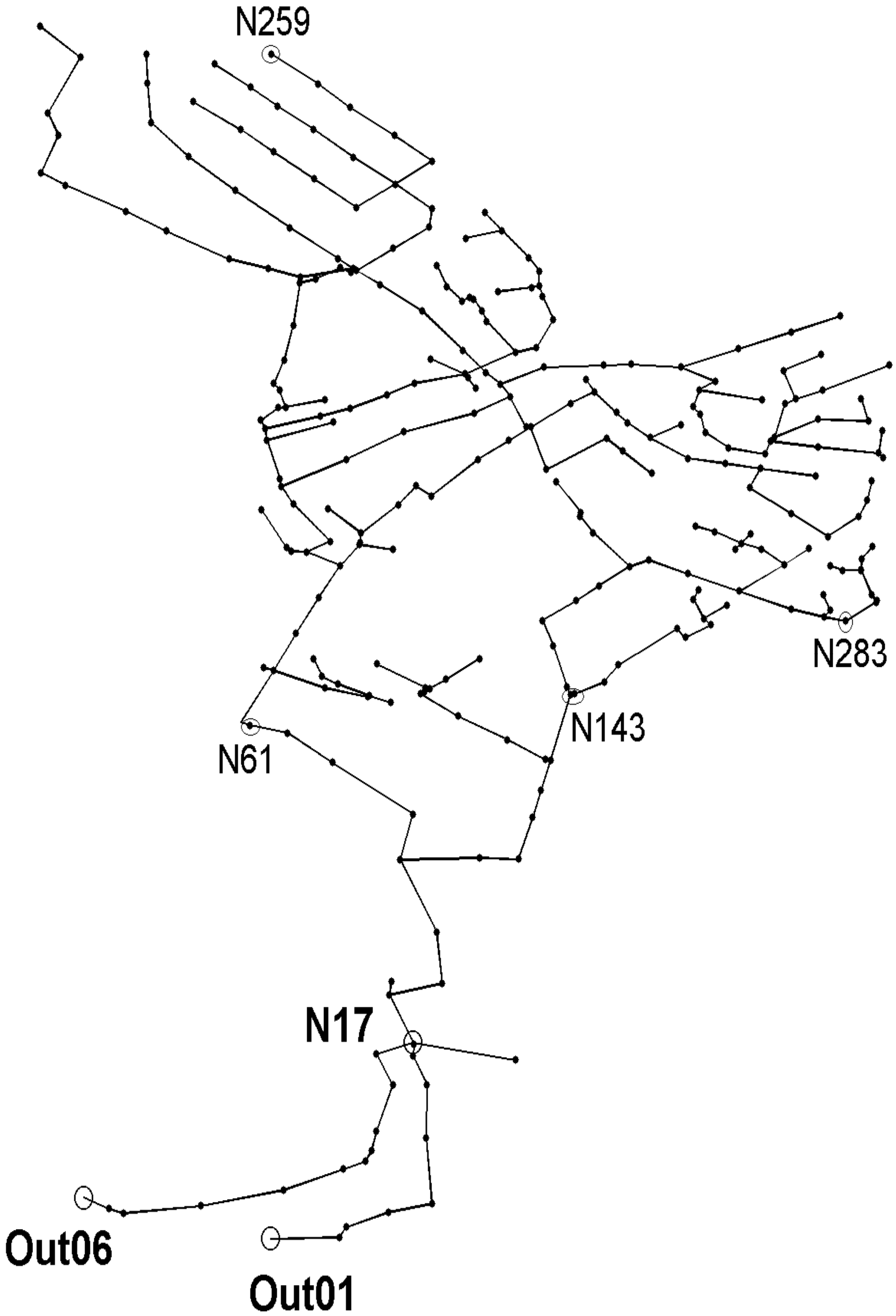

Figure 5-5. Nodes, circled in the map, connecting the new areas to the existing network.

Table 5-1. Values of the node N61 in Scenario 1.

	Density 40 households per ha		Density 60 households per ha		Density 80 households per ha	
N61	Total Area	Pcnt. Imperv	Total area	Pcnt. Imperv	Total area	Pcnt. Imperv
Year 1	0,00	0,00	0,00	0,00	0,00	0,00
Year 2	3,00	41,80	2,00	54,00	2,00	61,20
Year 3	6,00	40,00	3,00	84,00	3,00	72,80
Year 4	8,00	44,10	5,00	76,32	4,00	79,50
Year 5	10,00	46,56	7,00	71,18	5,00	90,00
Year 6	12,00	47,48	8,00	77,25	6,00	92,28

Table 5-2. Values of the nodes N17, N61, N143, N259, N283 in Scenario 2.

Year 1	Outlet	Total area	Pcnt. Imperv	**Year 2**	Outlet	Total area	Pcnt. Imperv
	N17	0,00	0,00		N17	2,00	15,78
	N61	0,00	0,00		N61	2,00	21,6
	N143	0,00	0,00		N143	5,00	23,04
	N259	0,00	0,00		N259	1,00	28,80
	N283	0,00	0,00		N283	2,00	30,00
Year 3	Outlet	Total area	Pcnt. Imperv	**Year 4**	Outlet	Total area	Pcnt. Imperv
	N17	3,00	21,60		N17	3,00	21,60
	N61	5,00	27,84		N61	5,00	27,84
	N143	8,00	26,10		N143	12,00	25,40
	N259	3,00	17,60		N259	8,00	24,30
	N283	4,00	31,20		N283	6,00	29,20
Year 5	Outlet	Total area	Pcnt. Imperv	**Year 6**	Outlet	Total area	Pcnt. Imperv
	N17	3,00	21,60		N17	3,00	21,60
	N61	8,00	28,50		N61	8,00	28,50
	N143	16,00	24,15		N143	17,00	24,85
	N259	13,00	24,92		N259	17,00	24,00
	N283	6,00	29,20		N283	6,00	29,20

5.3 DESCRIPTION OF THE CASE STUDY

The functionality of the framework is demonstrated by an analysis of the impact of 4 medium term urbanisation patterns in a small town in Scotland, on the combined sewage system collecting the water from the urban catchment and on the existing treatment plant. A combined sewer system provides the infrastructure for draining the catchment runoff and routing the wastewater from the town to the treatment facilities.

The network has 346 manholes, 7 Weirs and 2 outfalls. It has a total conduit length of 22,482 metres and the pipe gradients vary from 0.0001 to 0.0439. The treatment plant influent is controlled by a weir. It has an inlet offset of 0.165 m and a vertical height of opening 1.0 m. The flow exceeding the maximum influent is directly discharged into the receiving river through Out 6. The treatment plant was adjusted in order to treat a larger amount of wastewater than that produced by the initial population, i.e. 5000 equivalent people. Initially, the number of inhabitants served by the network is 1740 people.

In Scenario 1 and in Scenario 2, an area of 100 ha was identified for possible future residential development and a grid cell size of 100 m × 100 m was used by the LUC for population distribution. The basic assumption on dry weather flow is that the pro-capita discharge is 180 l/d, whereas the specific organic load is assumed 60 $gBOD_5$/e.p./d. This corresponds to an average total increase of 180 m^3/d of wastewater.

The plant which is simulated is designed for an average influent dry-weather flow rate of 922 m^3/d and an average biodegradable COD in the influent of 300 g/m^3. Its hydraulic retention time is 14.4 hours. The biological reactor volume and the settler volume are both equal to 375 m^3. The wastage flow rate equals 385 m^3/d. This corresponds to a biomass sludge age of about 9 days (based on the total amount of biomass present in the system).

Note that the WWTP is not upgraded in order to accomplish with the new requirements of the urban expansion. Even if temperature can influence the treatment process, here for simplicity its effect is not considered in the analysis and a constant value of 15 °C is assumed.

The UDM covers a period of three days, 72 hours, containing an ordinary rainfall event of 2 hours and a dry weather flow production related to an average consumption of water of civil users. In this case the time step of simulation is assumed of 5 minutes.

The main assumption about the case study are provided in the following Table 5-3.

Table 5-3. Main features of the case study.

Maximum housing density	40 households per ha	60 households per ha	80 households per ha
Initial number of inhabitants	1740	1740	1740
Extension of the area for future developments	100 ha	100 ha	100 ha
LUC grid cell size	100 m x 100 m	100 m x 100 m	100 m x 100 m
Number of new inhabitants	1000	1000	1000
Time horizon for urban expansion	6 years	6 years	6 years
Pro-capita discharge	180 l/d	180 l/d	180 l/d
Specific organic load	60 $gBOD_5$/e.p./d	60 $gBOD_5$/e.p./d	60 $gBOD_5$/e.p./d
Total increase of wastewater flow	180 m^3/d	180 m^3/d	180 m^3/d
Average design influent dry-weather flow to WWTP	922 m^3/d	922 m^3/d	922 m^3/d
Average biodegradable COD in the influent to WWTP	300 g/m^3	300 g/m^3	300 g/m^3
Hydraulic retention time	14.4 hours	14.4 hours	14.4 hours
Biological reactor and settler volume	375 m^3	375 m^3	375 m^3
Wastage flow rate	385 m^3/d	385 m^3/d	385 m^3/d
Biomass sludge age	c.a. 9 days	c.a. 9 days	c.a. 9 days
External temperature during the process	15 °C	15 °C	15 °C

A divider is placed upstream the equalization tank of the WWTP, this separates the surplus of water which cannot be treated by the wastewater treatment plant, discharging the overflow directly into the receiving water body. The flow at the outlet of the sewage system, i.e. at the connecting node between the wastewater treatment plant and the sewage system is given as input to WWTP as well as the previously mentioned concentration parameters.

A diurnal pattern for wastewater release was also assumed (Lessard, 1989) and it is shown in Figure 5-6.

19 different land use types subdivided in 3 classes, with only 5 representing the urban housing class. Their list, along with related parameter values, is provided in Table 5-4.

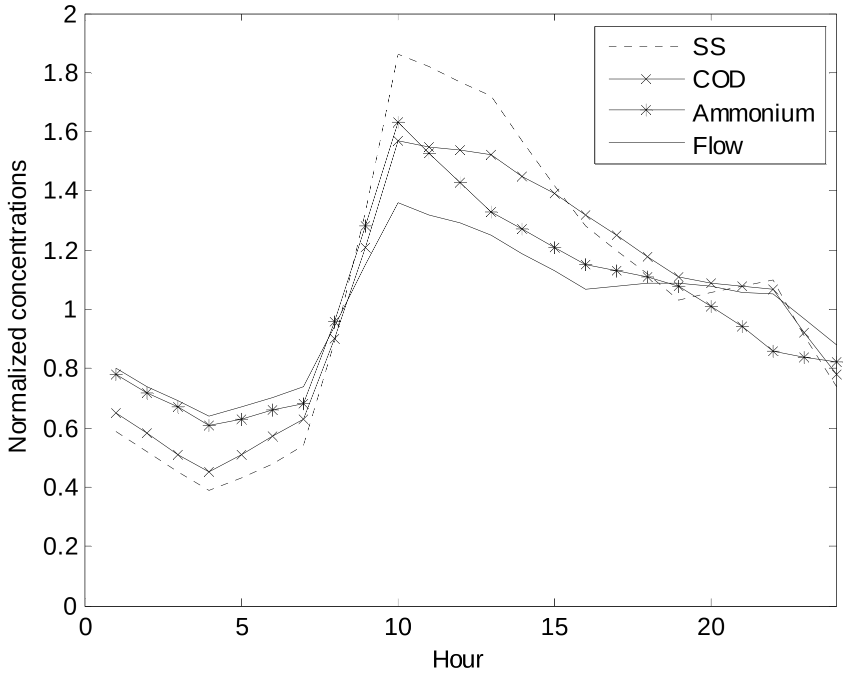

Figure 5-6. Diurnal patterns for dry weather flow.

Table 5-4: Urban land use types and related parameter values.

Class	Land use type (representative number)	Occupancy	Area
Urban housing	Flats (16)	1.6	50
	Cluster homes (17)	1.5	50
	Semi-detached houses (18)	2.5	70
	Detached houses (19)	2.5	100
	Terraced houses (20)	2.3	50

6 APPLICATION TO THE CASE STUDY

The water infrastructures before the new development are assumed to work properly, without abnormal overflows or crisis of the WWTP. In addition to the population increase, a rainfall event is assumed to take place on the catchment. This implies that an additional runoff due to the new urbanization of the development area will be drained by the combined sewage system. This hypothesis is interesting in order to evaluate the effect of the first flush on the WWTP. When the population grows, no upgrades of the network as well as of the WWTP are made.

The following Figures, from 6-1 to 6-42, shows the results obtained from the case study concern the **Scenario 1**, where the new area is connected to the existing network at the node N61.

The following Figures, from 6-1 to 6-18, shows the difference among potential scenario due variable household density’s at the beginning of the simulation, when the year is assumed fixed, i.e. the case base scenario for the three density profiles.

The water quality in terms of COD, BOD_5 and TotN has deteriorated continuously with the population increase in the new development, while the water flow increases steadily over time. The increased flow results from the new development, in which more runoff is generated from the rain event because of the increase in impervious area and more domestic wastewater is discharged because of the population increase. Most of the increased volume of water is discharged into the river through CSO overflows because the maximum treatment plant influent has been reached for the simulated rain event, even for the existing catchments, and this results in the deterioration of the water quality.

Figures from 6-1 to 6-6 shows the situation of the inflow, outflow (in Out1) and overflow (in Out6) discharge and its concentrations in terms of TSS, COD, BOD_5 and TotN, after the 1-year period of urban expansion, considering maximum housing density of 40 households per ha.

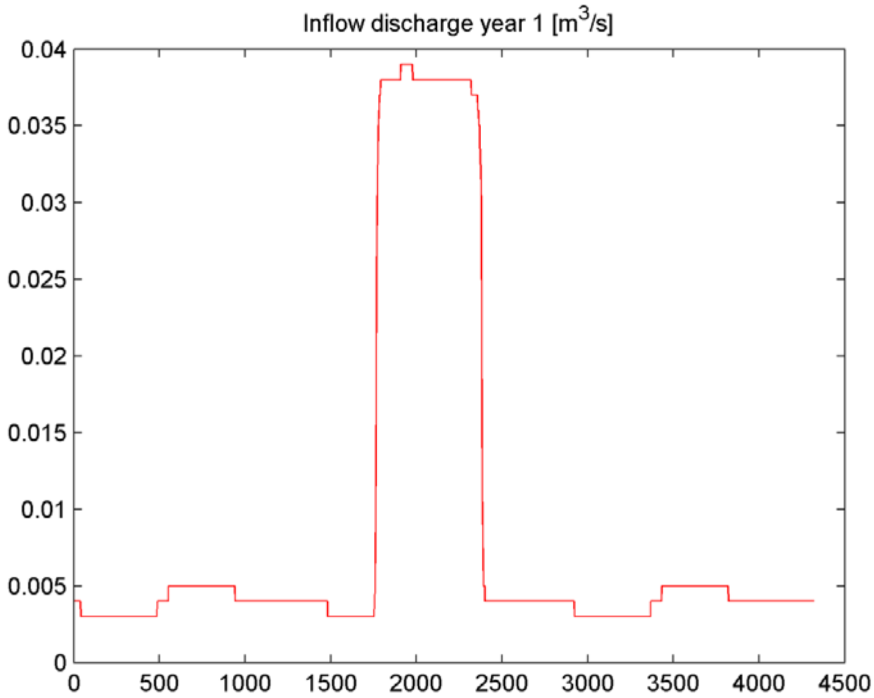

Figure 6-1. Simulated inflow discharge after the first year of urban growth: low housing density (40 houses/ha).

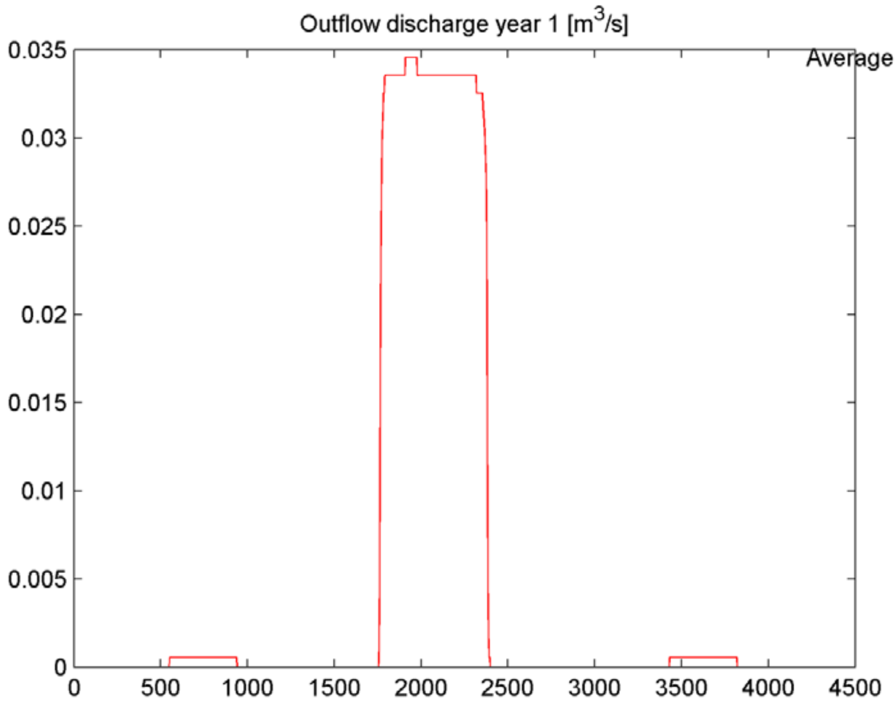

Figure 6-2. Simulated outflow discharge after the first year of urban growth: low housing density (40 houses/ha).

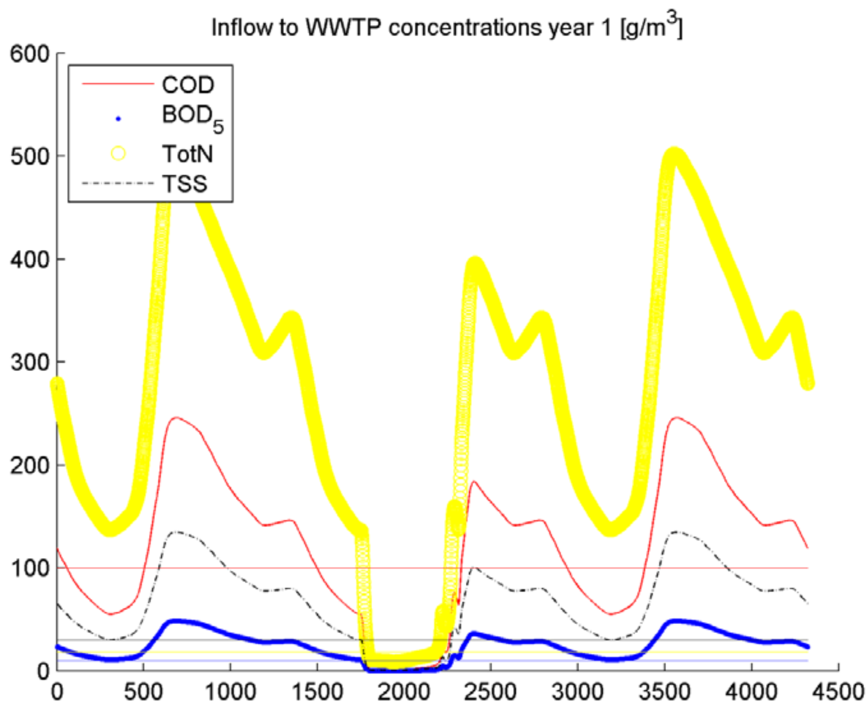

Figure 6-3. Simulated inflow concentrations after the first year of urban growth: low housing density (40 houses/ha).

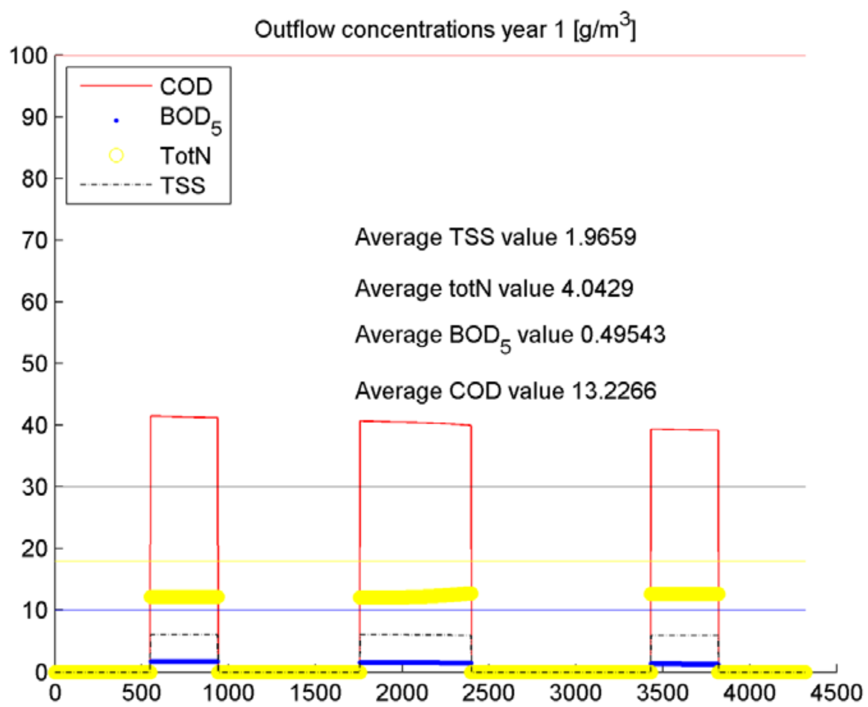

Figure 6-4. Simulated outflow concentrations after the first year of urban growth: low housing density (40 houses/ha).

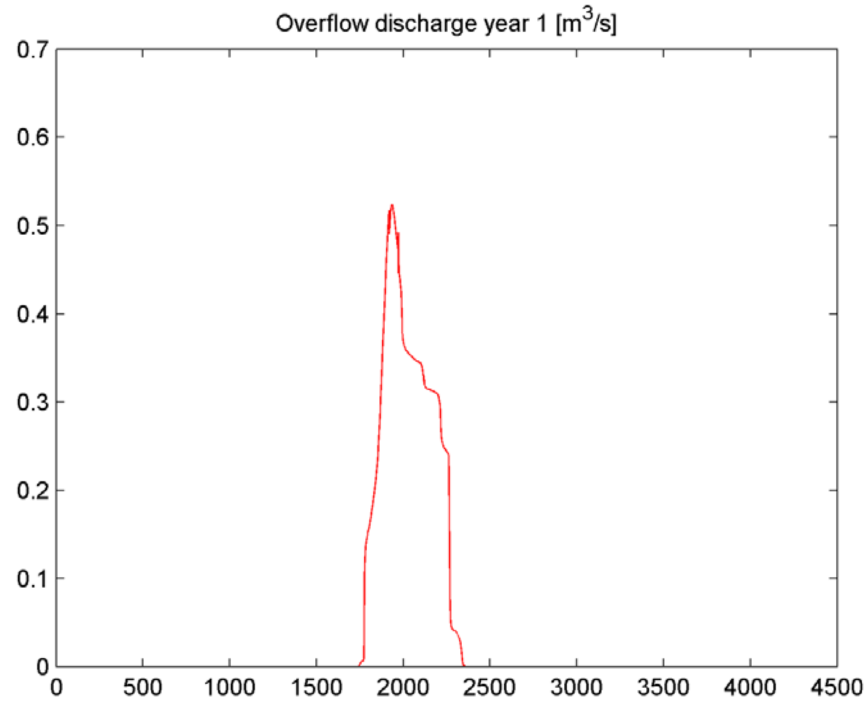

Figure 6-5. Simulated overflow discharge after the first year of urban growth: low housing density (40 houses/ha).

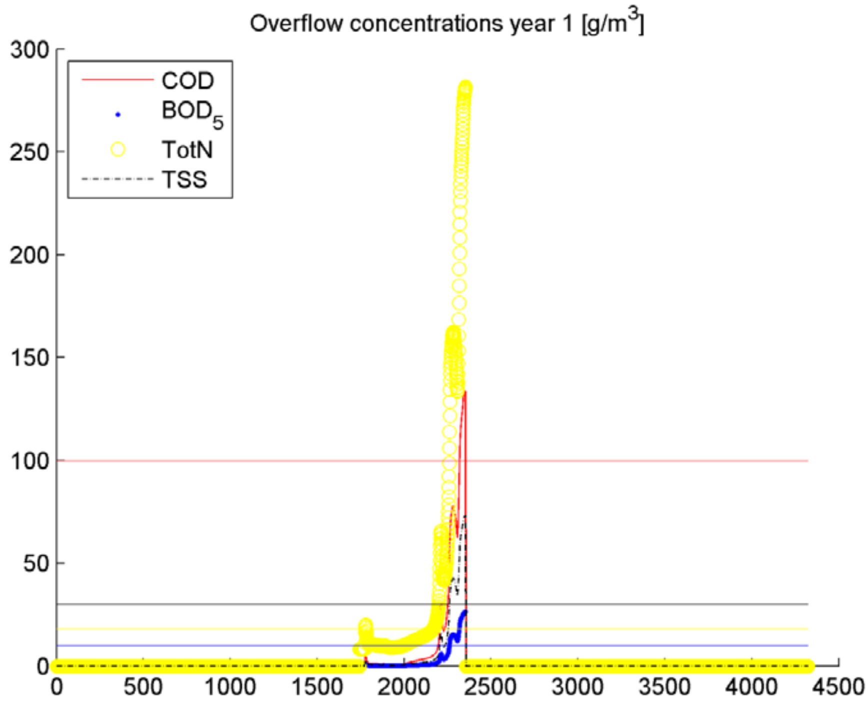

Figure 6-6. Simulated outflow concentrations after the first year of urban growth: low housing density (40 houses/ha).

Figures from 6-7 to 6-12 shows the situation of the inflow, outflow (Out1) and overflow (Out6) discharge and the concentration profiles of TSS, COD, BOD_5 and TotN, in the 1-years period of urban expansion, considering maximum housing density of 60 households per ha.

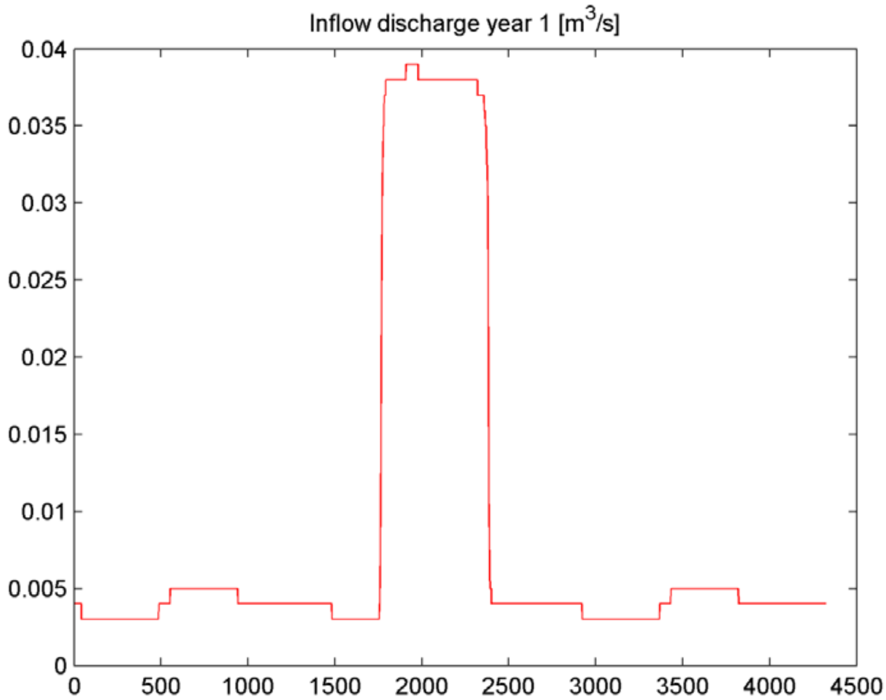

Figure 6-7. Simulated inflow discharge after the first year of urban growth: medium housing density (60 houses/ha).

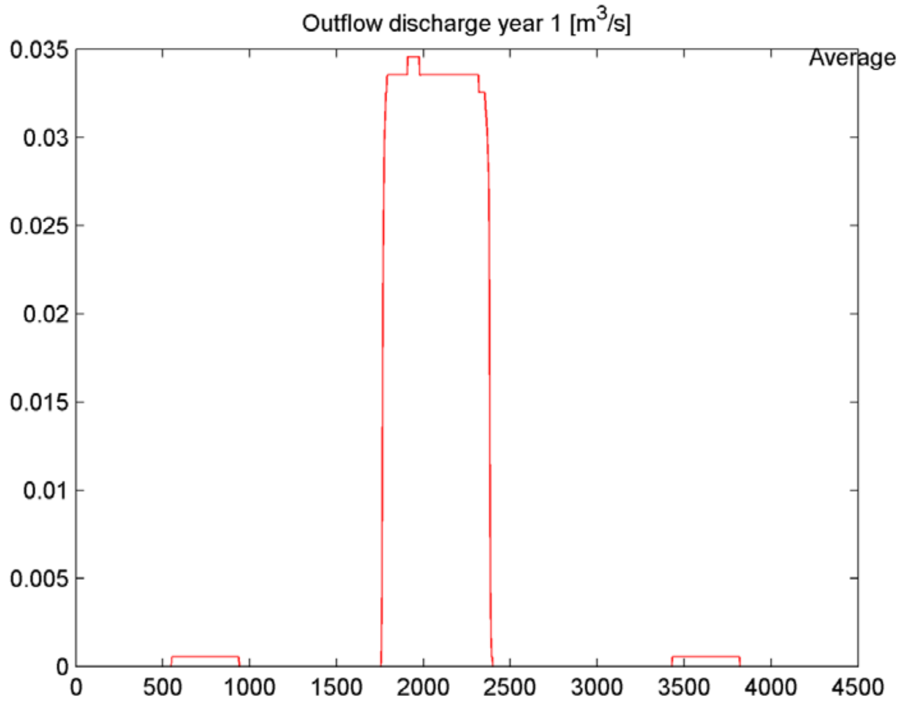

Figure 6-8. Simulated outflow discharge after the first year of urban growth: medium housing density (60 houses/ha).

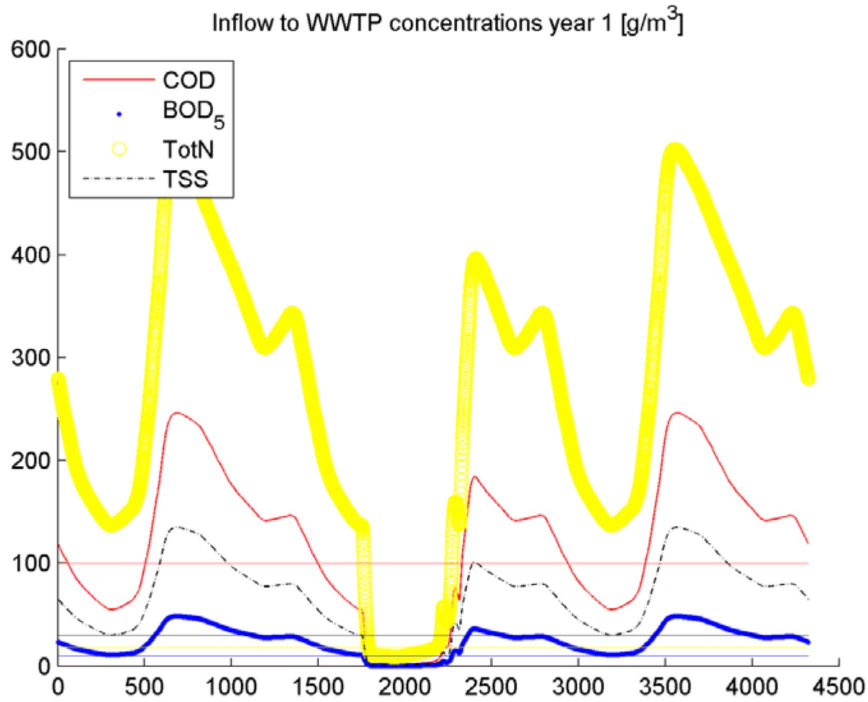

Figure 6-9. Simulated inflow concentrations after the first year of urban growth: medium housing density (60 houses/ha).

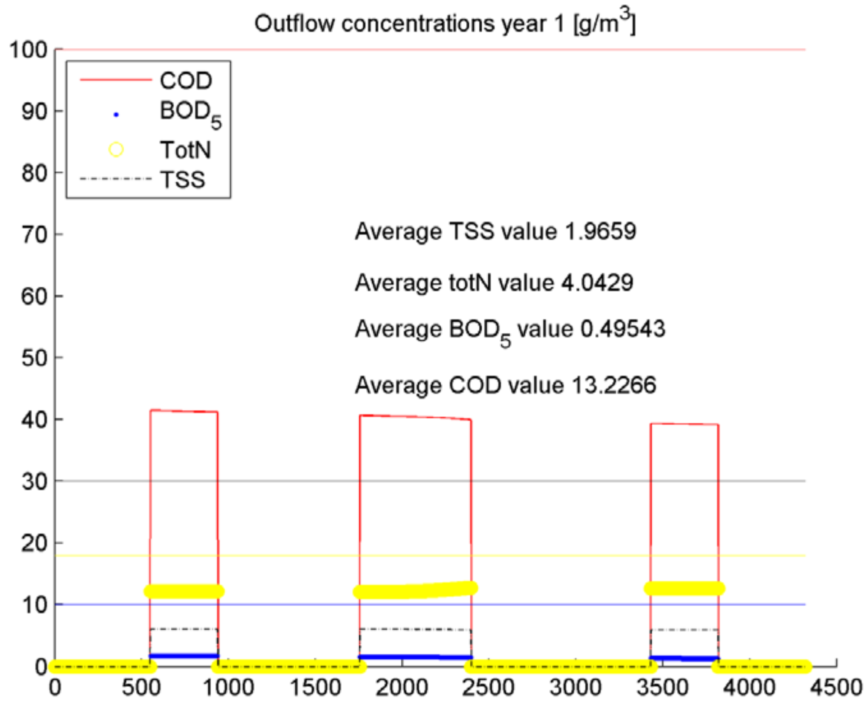

Figure 6-10. Simulated outflow concentrations after the first year of urban growth: medium housing density (60 houses/ha).

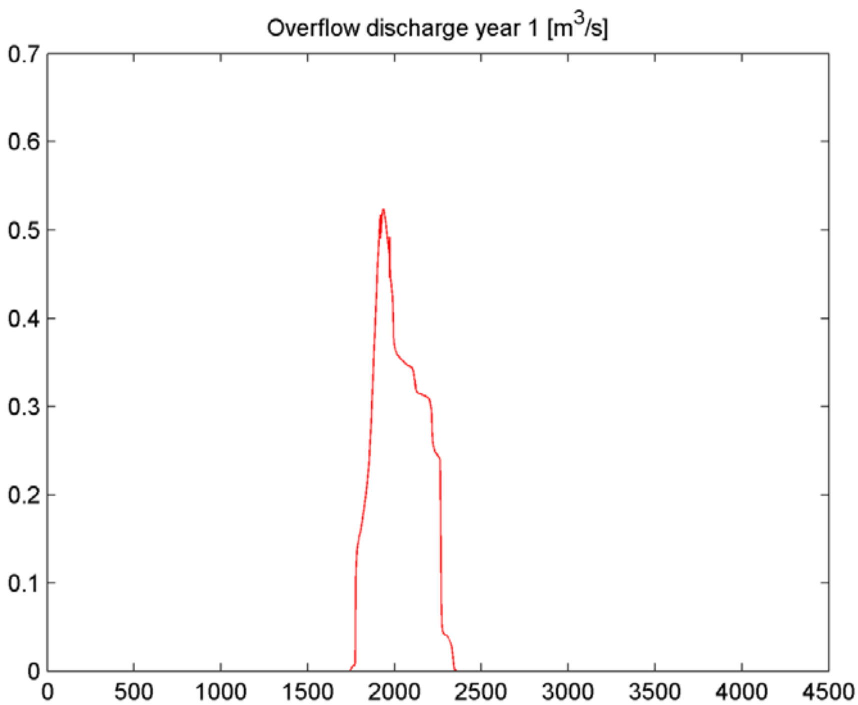

Figure 6-11. Simulated overflow discharge after the first year of urban growth: medium housing density (60 houses/ha).

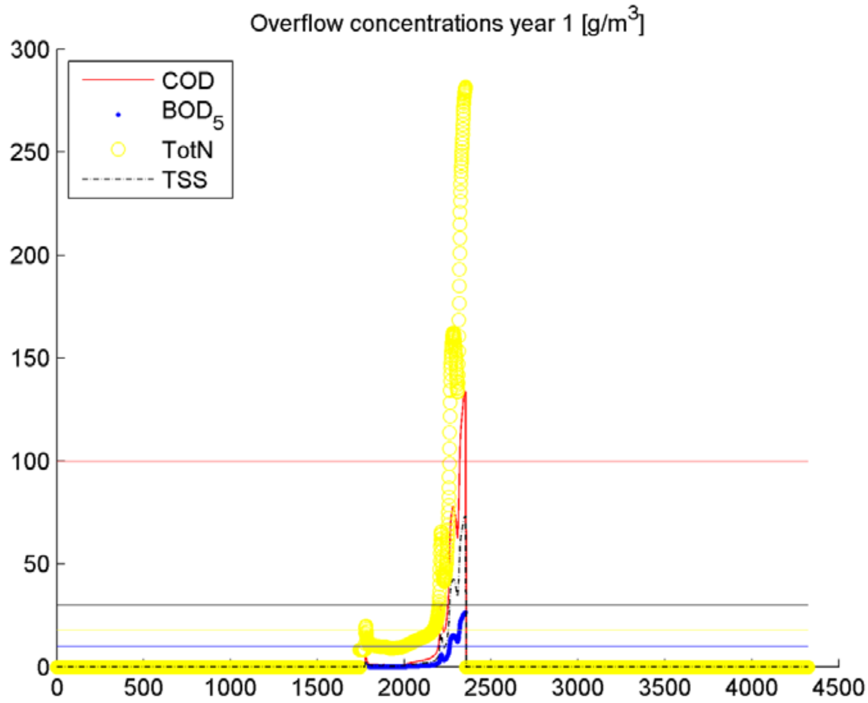

Figure 6-12. Simulated overflow concentrations after the first year of urban growth: medium housing density (60 houses/ha).

Figures from 6-13 to 6-18 shows the situation of the inflow, outflow (Out1) and overflow (Out6) discharge and the concentration profiles of TSS, COD, BOD5 and TotN, in the 1-years period of urban expansion, considering maximum housing density of 80 households per ha.

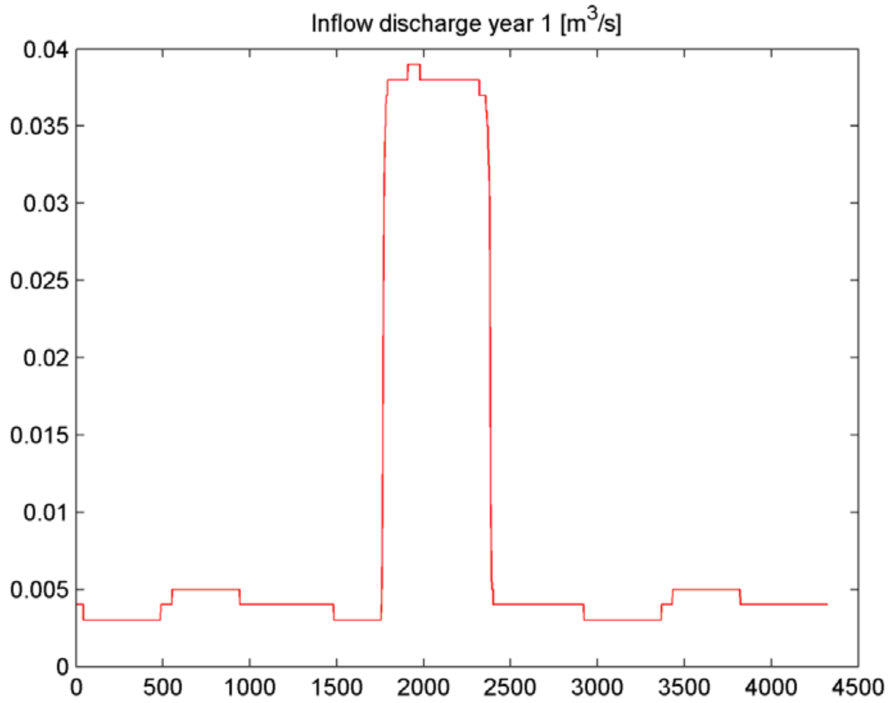

Figure 6-13. Simulated inflow discharge after the first year of urban growth: high housing density (80 houses/ha).

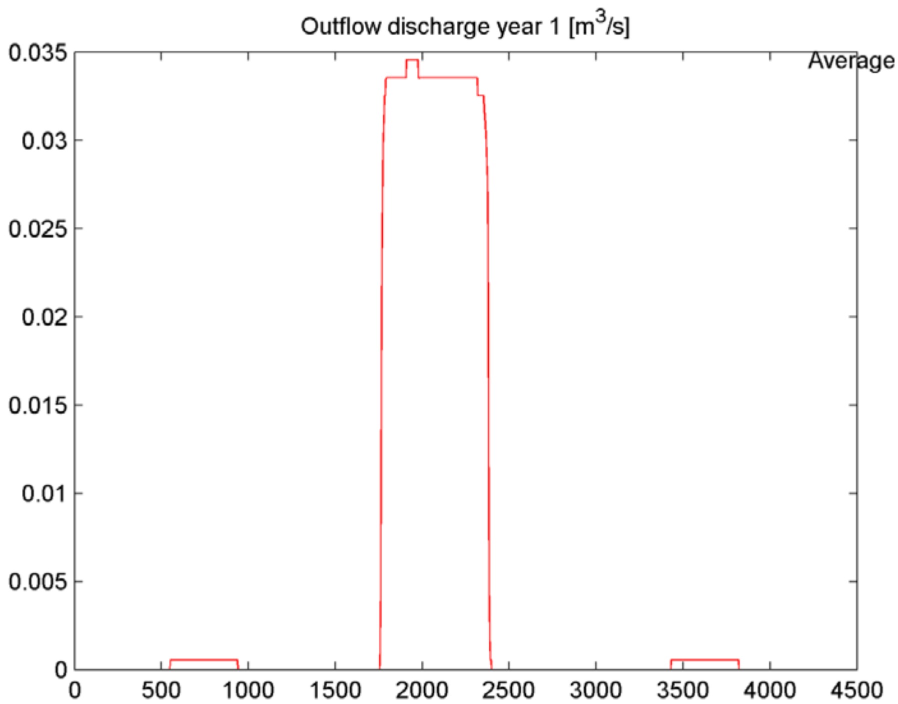

Figure 6-14. Simulated outflow discharge after the first year of urban growth: high housing density (80 houses/ha).

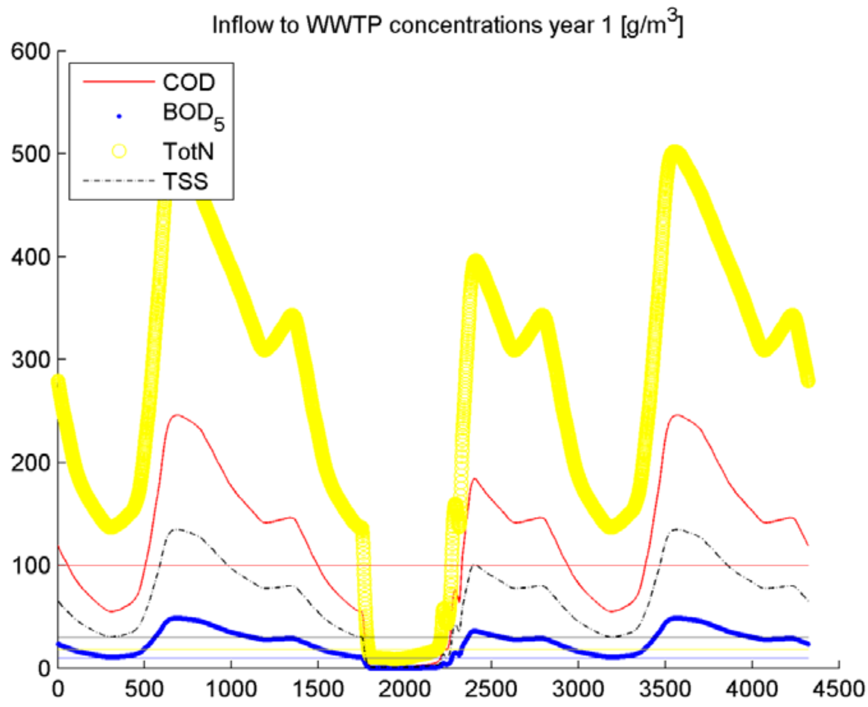

Figure 6-15. Simulated inflow concentrations after the first year of urban growth: high housing density (80 houses/ha).

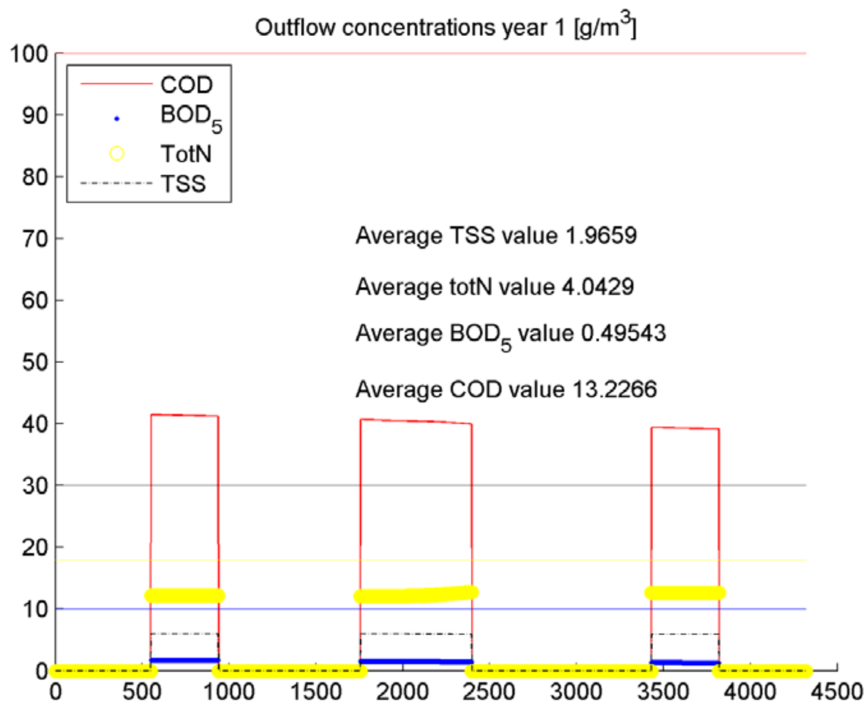

Figure 6-16. Simulated outflow concentrations after the first year of urban growth: high housing density (80 houses/ha).

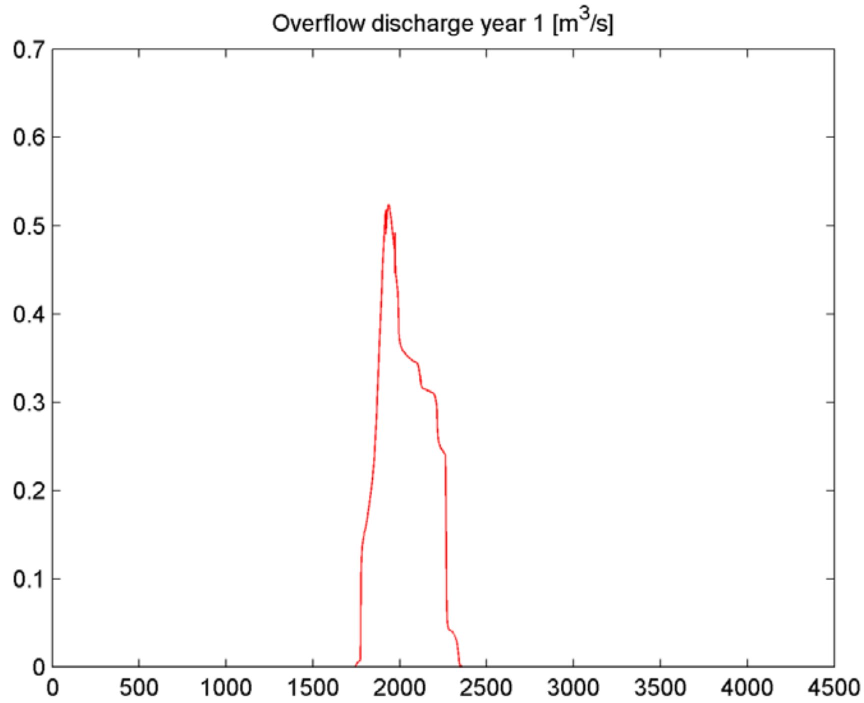

Figure 6-17. Simulated overflow discharge after the first year of urban growth: high housing density (80 houses/ha).

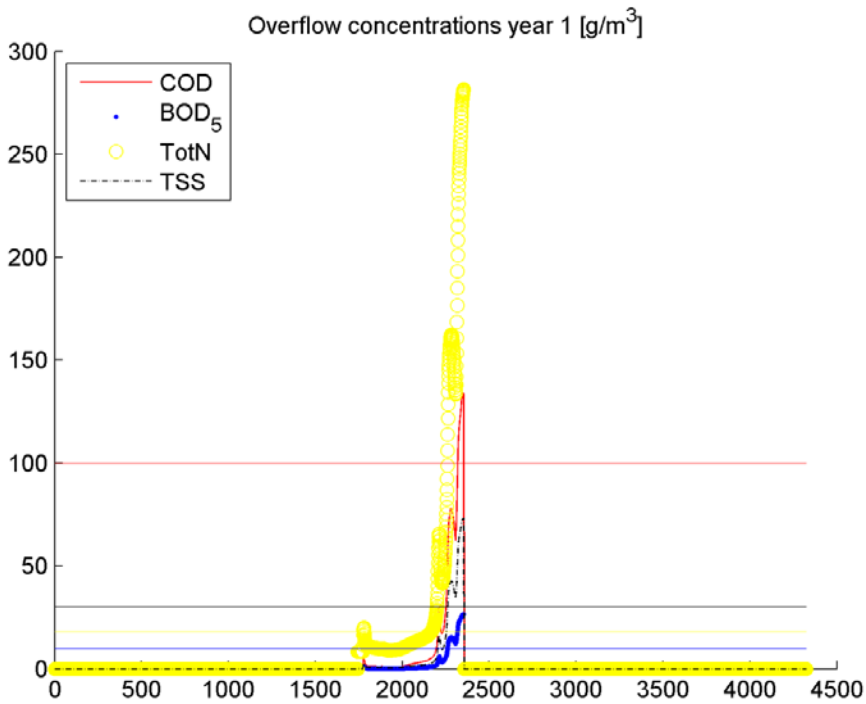

Figure 6-18. Simulated overflow concentrations after the first year of urban growth: high housing density (80 houses/ha).

The following Figures, from 6-19 to 6-36, shows the difference among potential scenario due variable year period of urban expansion, when the household density's is assumed fixed.

Compared with the base case scenario, it is clearly shown that the water quality of the low density scenario deteriorates when the population size is doubled and housing density is kept unchanged. However, for all the water quality indicators, the impact of the high density scenario is roughly the same as the base case scenario.

Both the population size and housing density for the new development have a clear impact on the water quality. However, increasing the housing density has a positive impact on water quality. This is probably due to the fact that less land is transformed into urban land uses at a higher housing density so that less runoff are generated and discharged into the urban wastewater system. Thus, the impacts of population increase can be reduced to some extent as illustrated by the high density scenario. This may be suggested as an effective mitigation option for land use planners to reduce the impact of new developments and thus achieve a better water environment.

Figures from 6-19 to 6-24 shows the situation of the inflow and outflow discharge, with maximum housing density of 60 households per ha, considering the 1-year, 3-year, 6-years period of urban expansion.

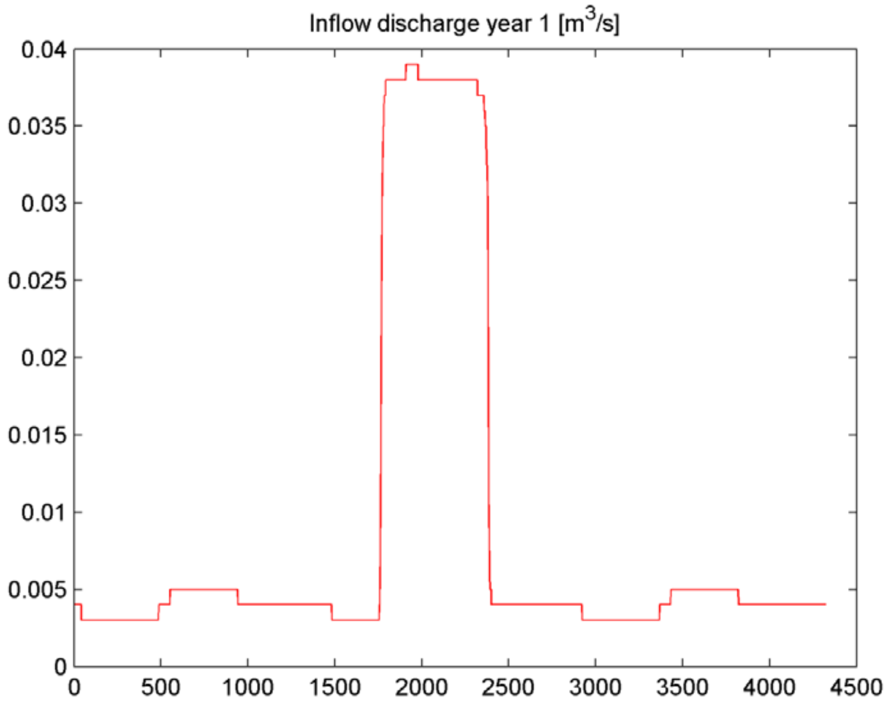

Figure 6-19. Simulated inflow discharge after the first year of urban growth: medium housing density (60 houses/ha).

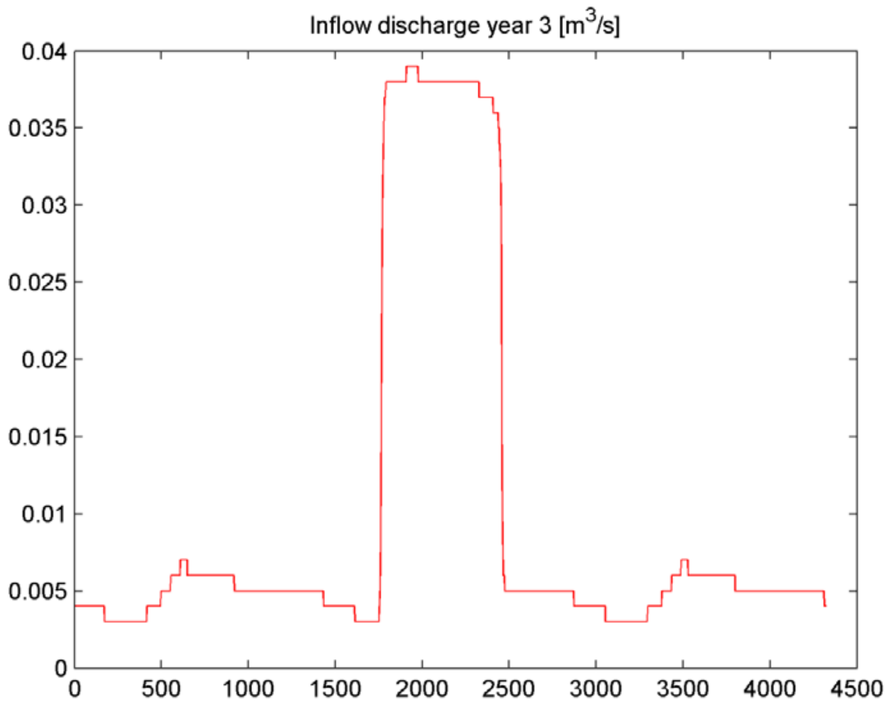

Figure 6-20. Simulated inflow discharge after 3 years of urban growth: medium housing density (60 houses/ha).

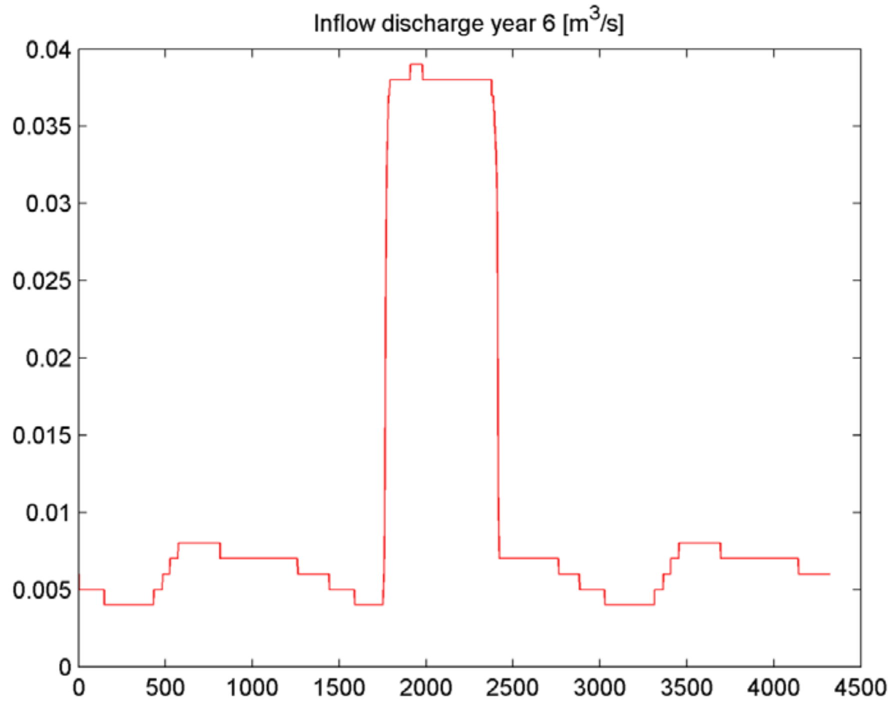

Figure 6-21. Simulated inflow discharge after 6 years of urban growth: medium housing density (60 houses/ha).

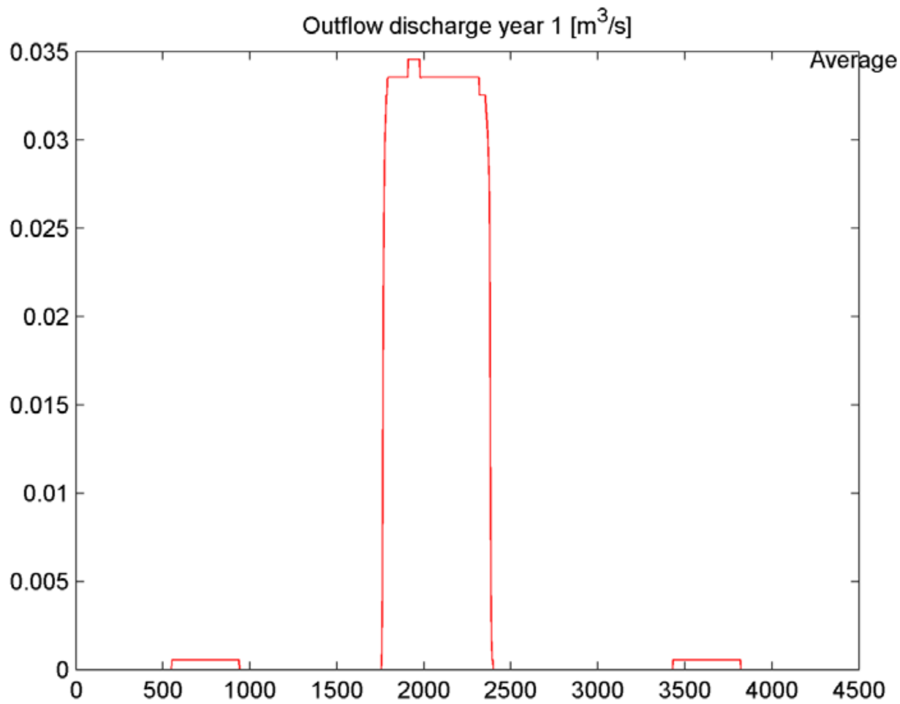

Figure 6-22. Simulated outflow discharge after 1 year of urban growth: medium housing density (60 houses/ha).

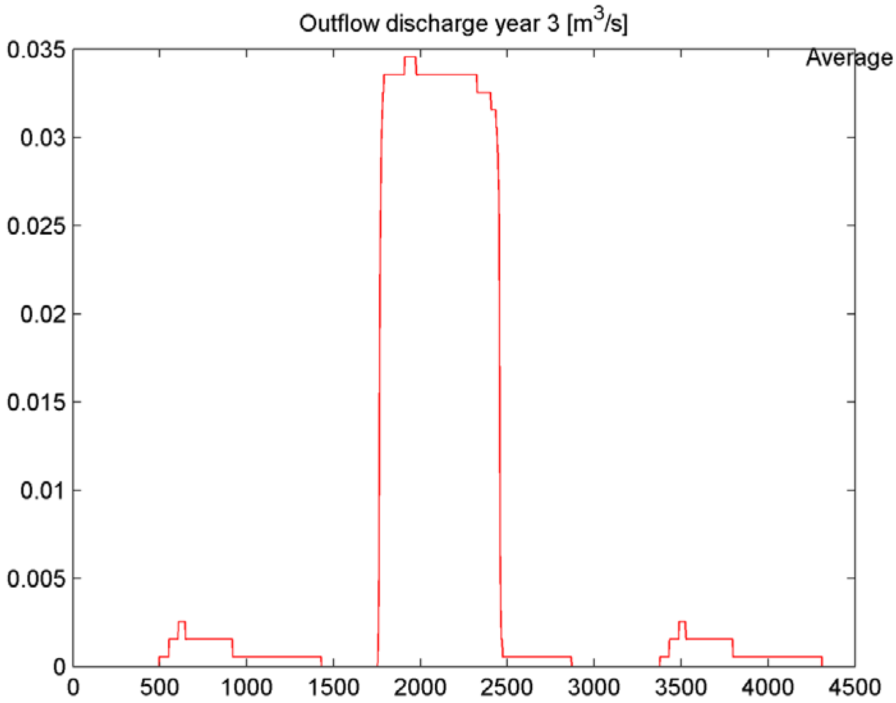

Figure 6-23. Simulated outflow discharge after 3 years of urban growth: medium housing density (60 houses/ha).

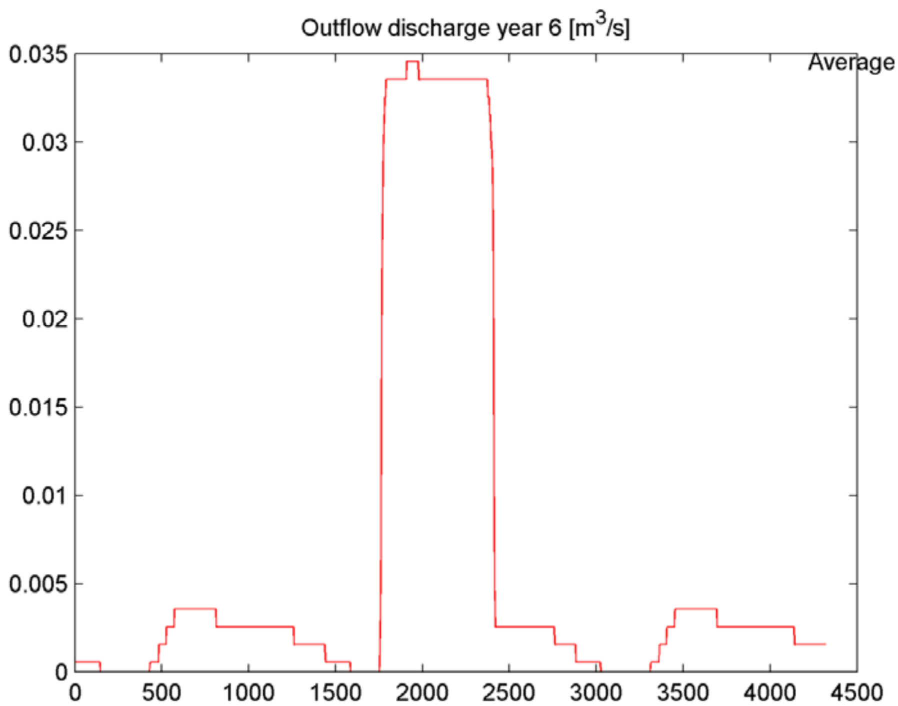

Figure 6-24. Simulated outflow discharge after 6 years of urban growth: medium housing density (60 houses/ha).

Figures from 6-25 to 6-30 shows the concentrations profile of TSS, COD, BOD_5 and TotN, before and after the treatment, with maximum housing density of 60 households per ha, considering the 1-year, 3-year, 6-years period of urban expansion.

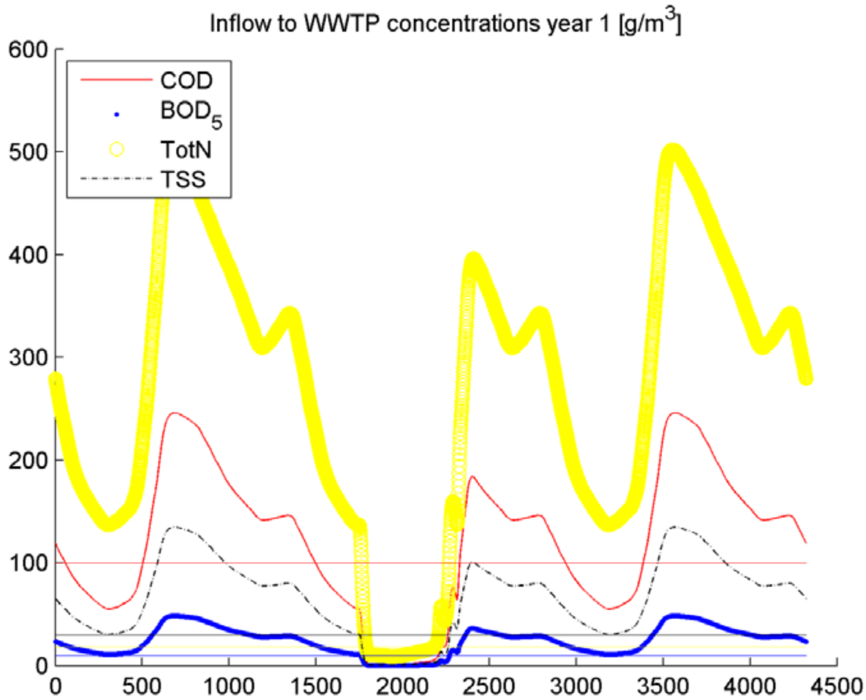

Figure 6-25. Simulated inflow concentrations after 1 year of urban growth: medium housing density (60 houses/ha).

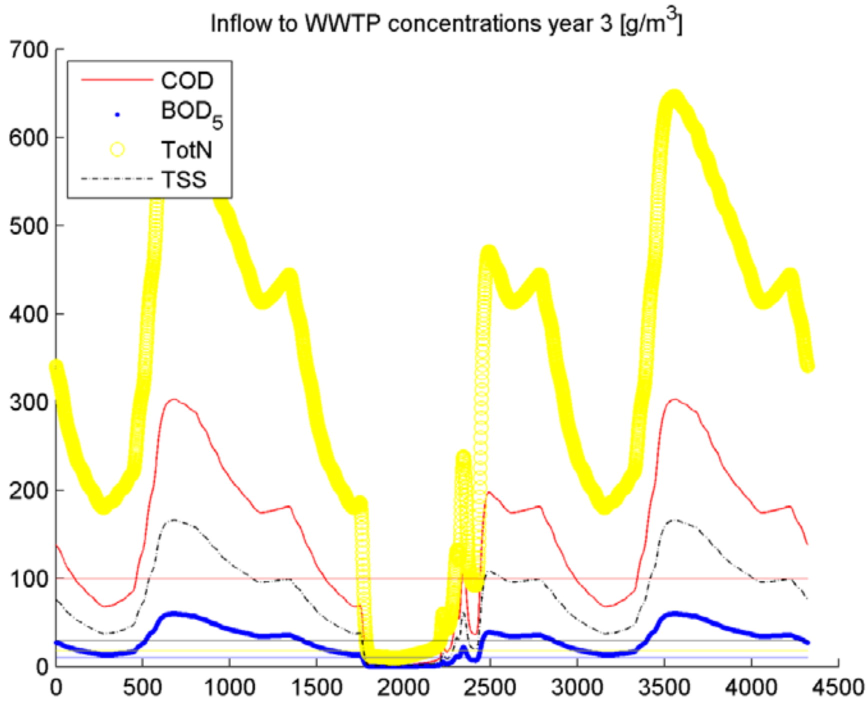

Figure 6-26. Simulated inflow concentrations after 3 years of urban growth: medium housing density (60 houses/ha).

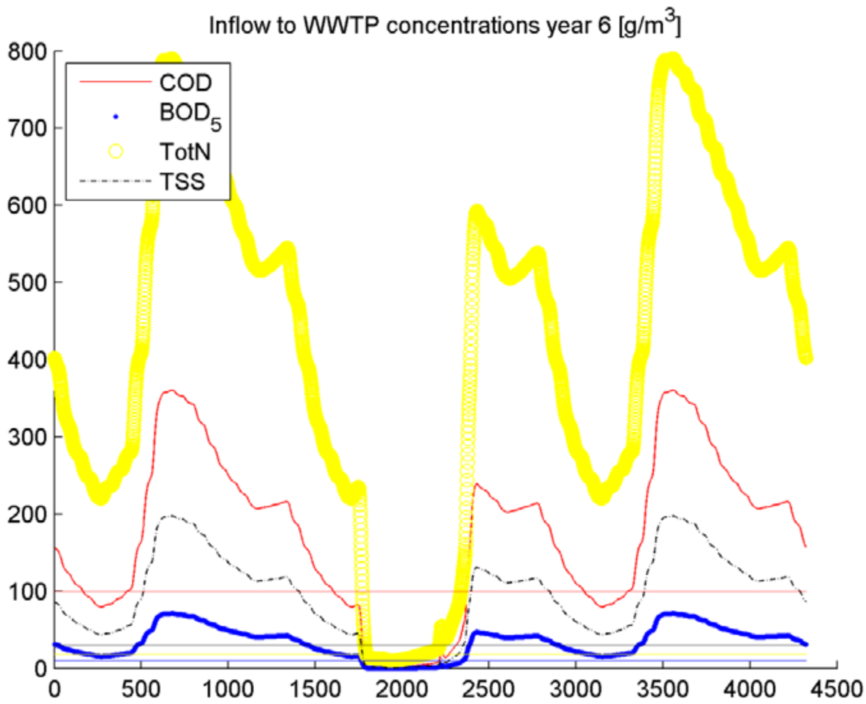

Figure 6-27. Simulated inflow concentrations after 6 years of urban growth: medium housing density (60 houses/ha).

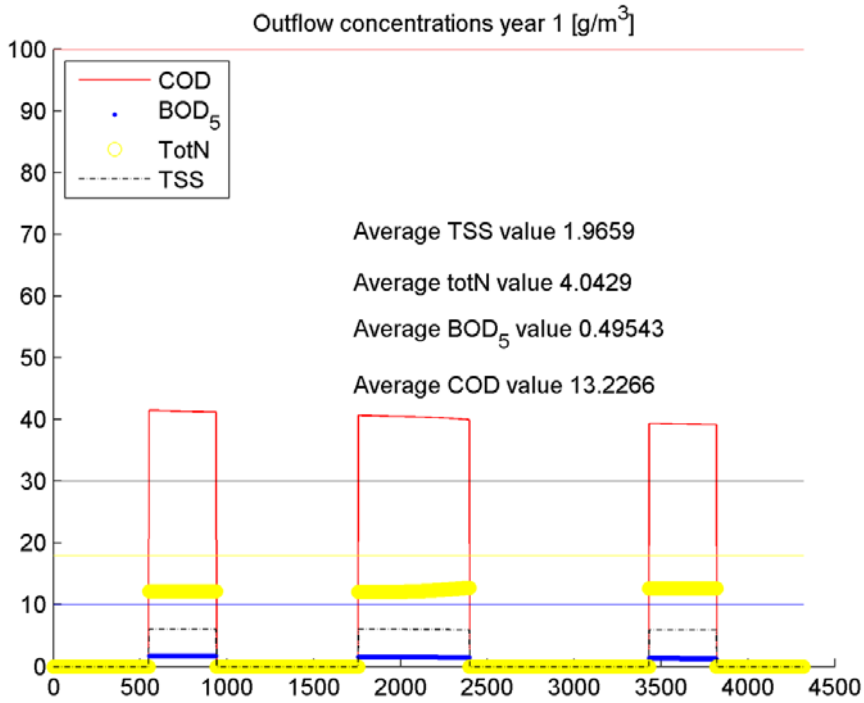

Figure 6-28. Simulated outflow concentrations after 1 year of urban growth: medium housing density (60 houses/ha).

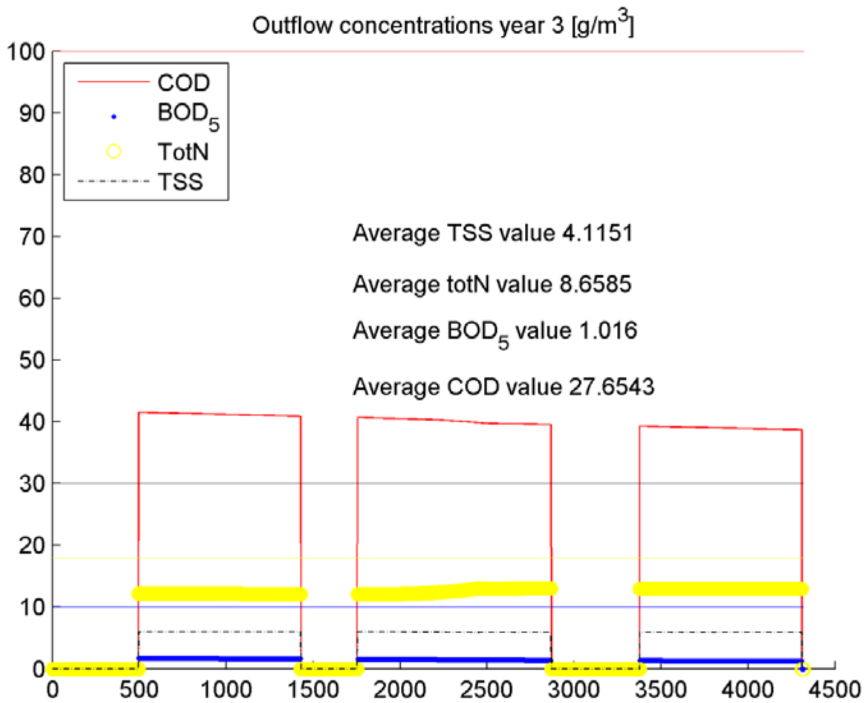

Figure 6-29. Simulated outflow concentrations after 3 years of urban growth: medium housing density (60 houses/ha).

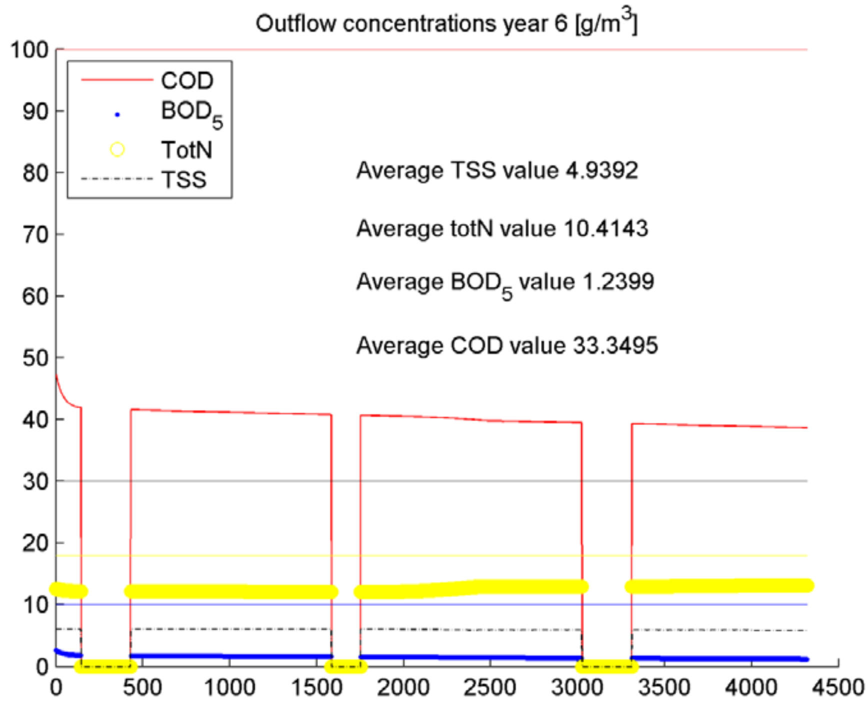

Figure 6-30. Simulated outflow concentrations after 6 years of urban growth: medium housing density (60 houses/ha).

Figures from 6-31 to 6-36 shows the overflow discharge and its concentrations of TSS, COD, BOD_5 and TotN, with maximum housing density of 60 households per ha, considering the 1-year, 3-year, 6-years period of urban expansion.

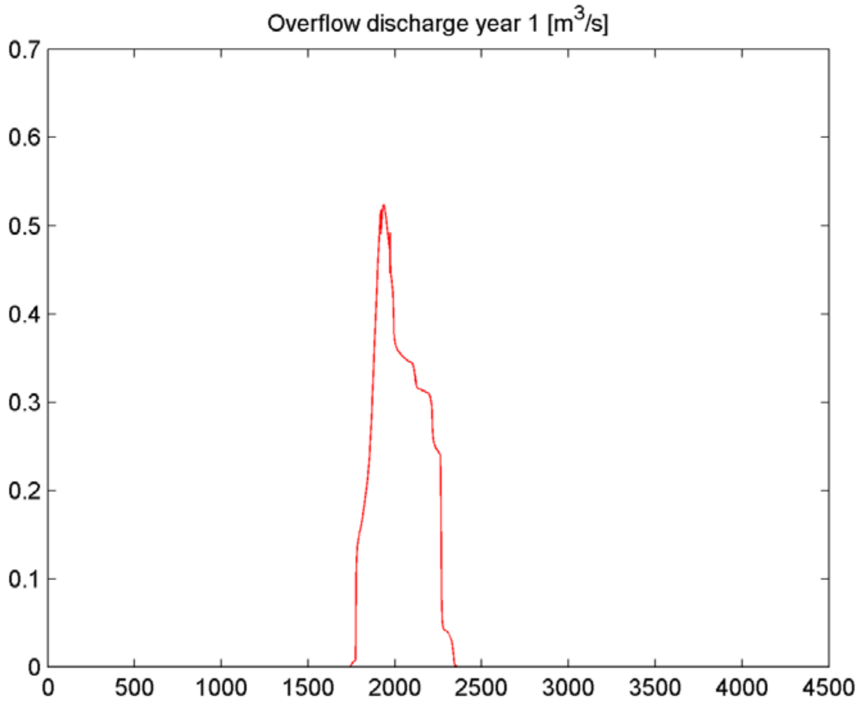

Figure 6-31. Simulated overflow discharge after 1 year of urban growth: medium housing density (60 houses/ha).

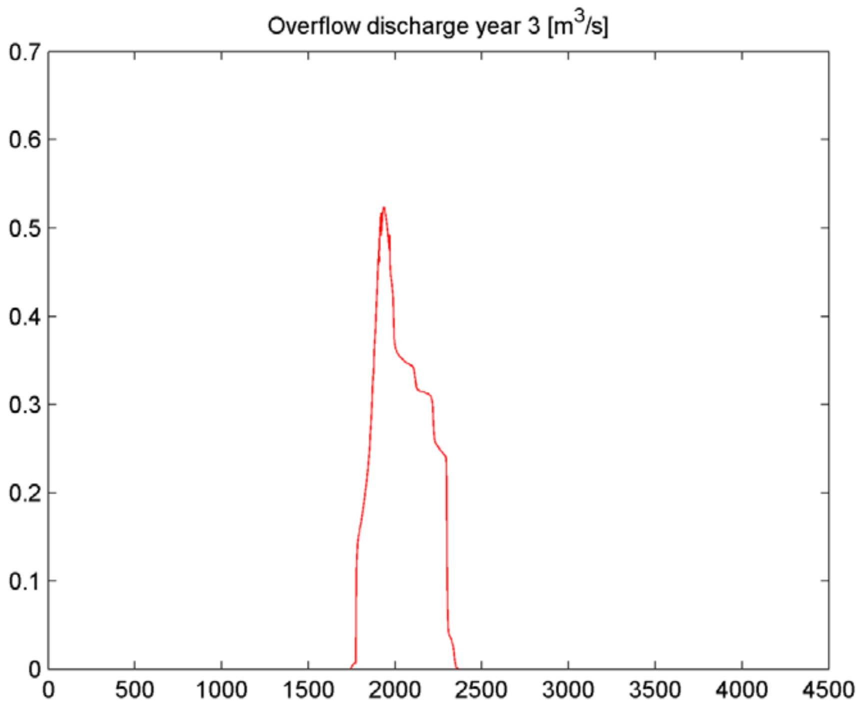

Figure 6-32. Simulated overflow discharge after 3 years of urban growth: medium housing density (60 houses/ha).

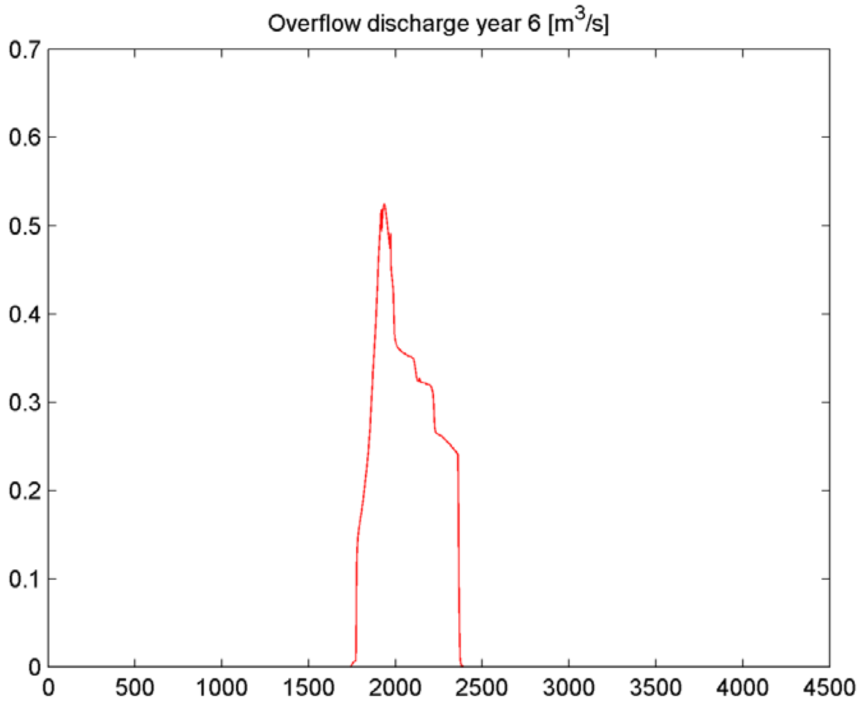

Figure 6-33. Simulated overflow discharge after 6 years of urban growth: medium housing density (60 houses/ha).

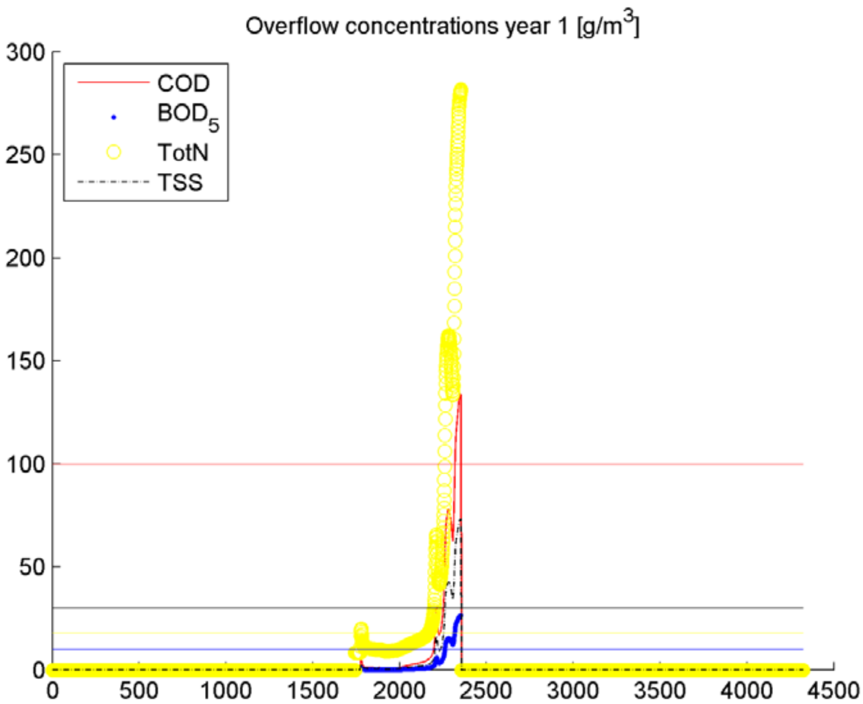

Figure 6-34. Simulated overflow concentrations after 1 year of urban growth: medium housing density (60 houses/ha).

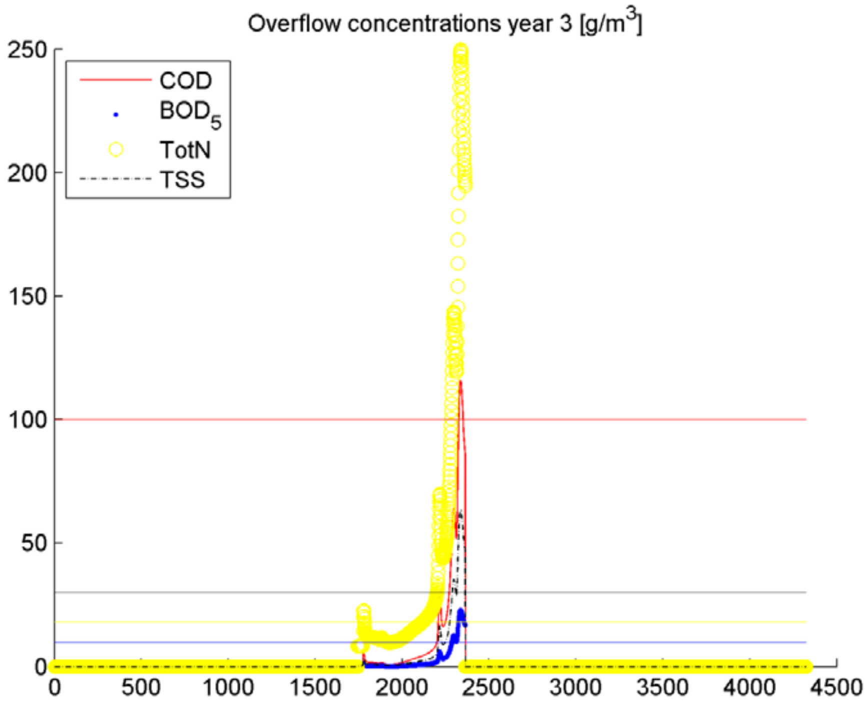

Figure 6-35. Simulated overflow concentrations after 3 year of urban growth: medium housing density (60 houses/ha).

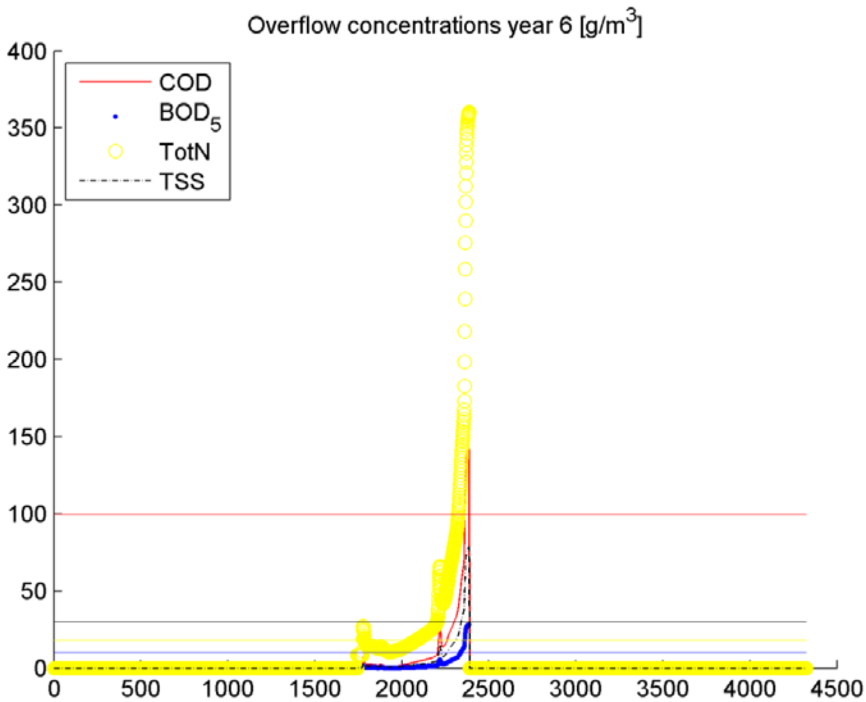

Figure 6-36. Simulated overflow concentrations after 6 year of urban growth: medium housing density (60 houses/ha).

Finally a third set of images, Figures from 6-37 to 6-42, show the 95th percentile values of inflow and overflow to the difference in housing density, considering 40, 60 and 80 households per ha.

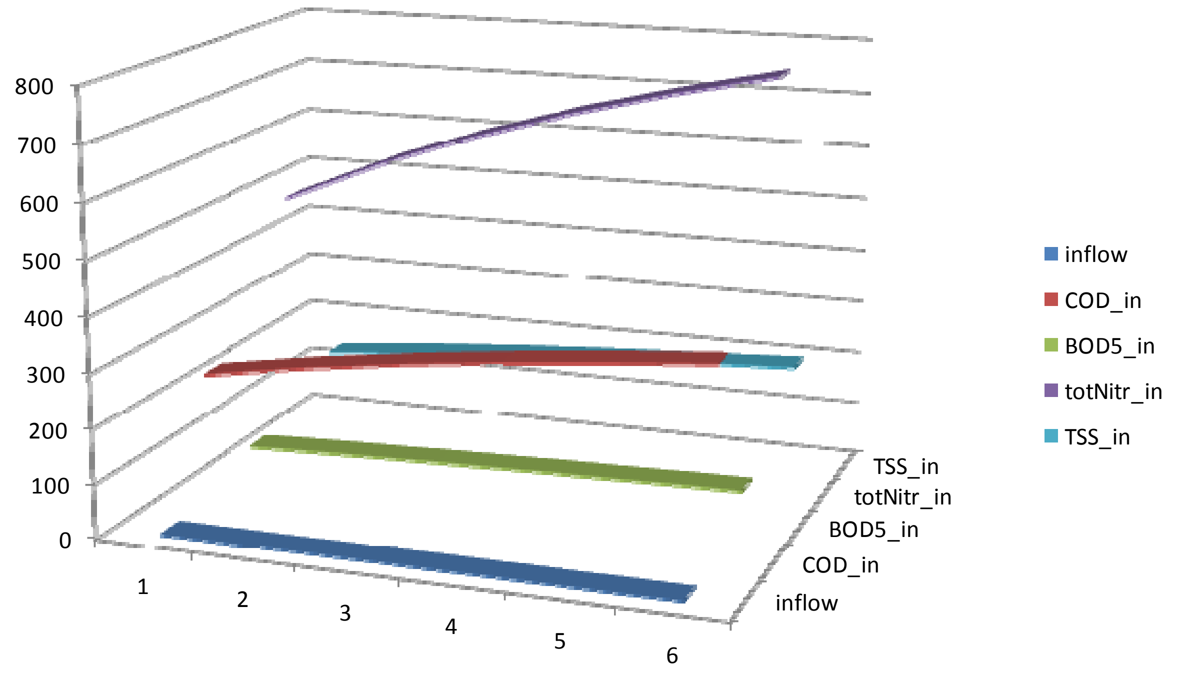

Figure 6-37. 95th Percentile of WWTP inflow to 40 households per ha.

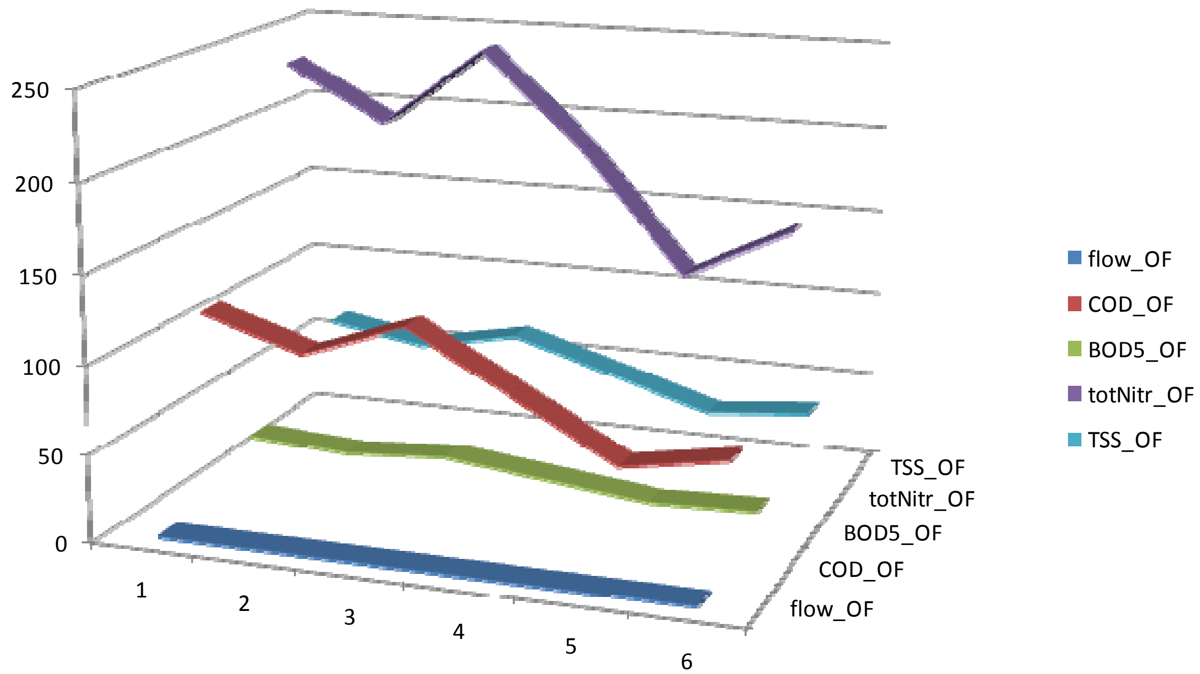

Figure 6-38. 95th Percentile of overflow to 40 households per ha.

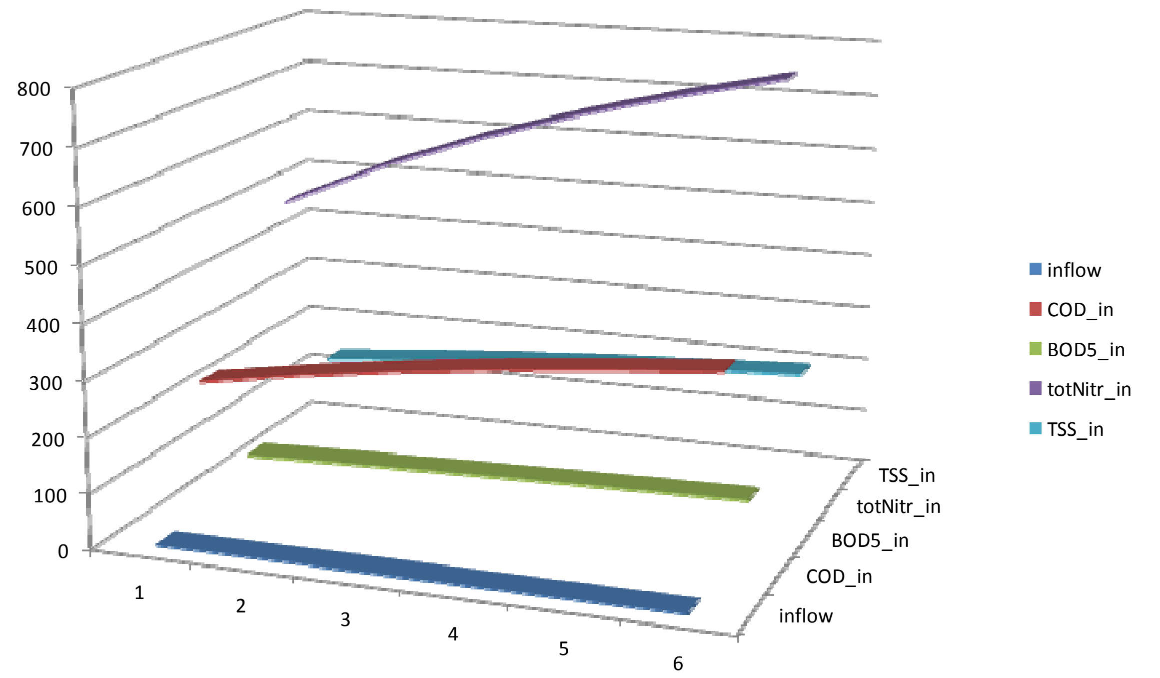

Figure 6-39. 95th Percentile of WWTP inflow to 60 households per ha.

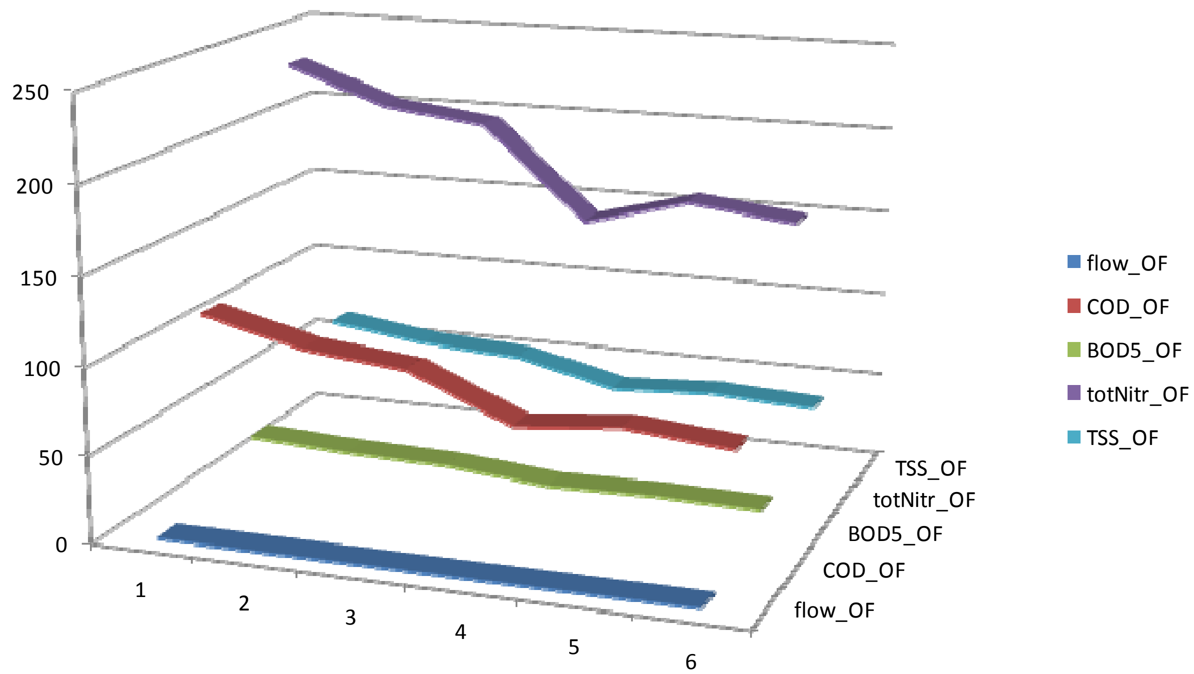

Figure 6-40. 95th Percentile of overflow to 60 households per ha.

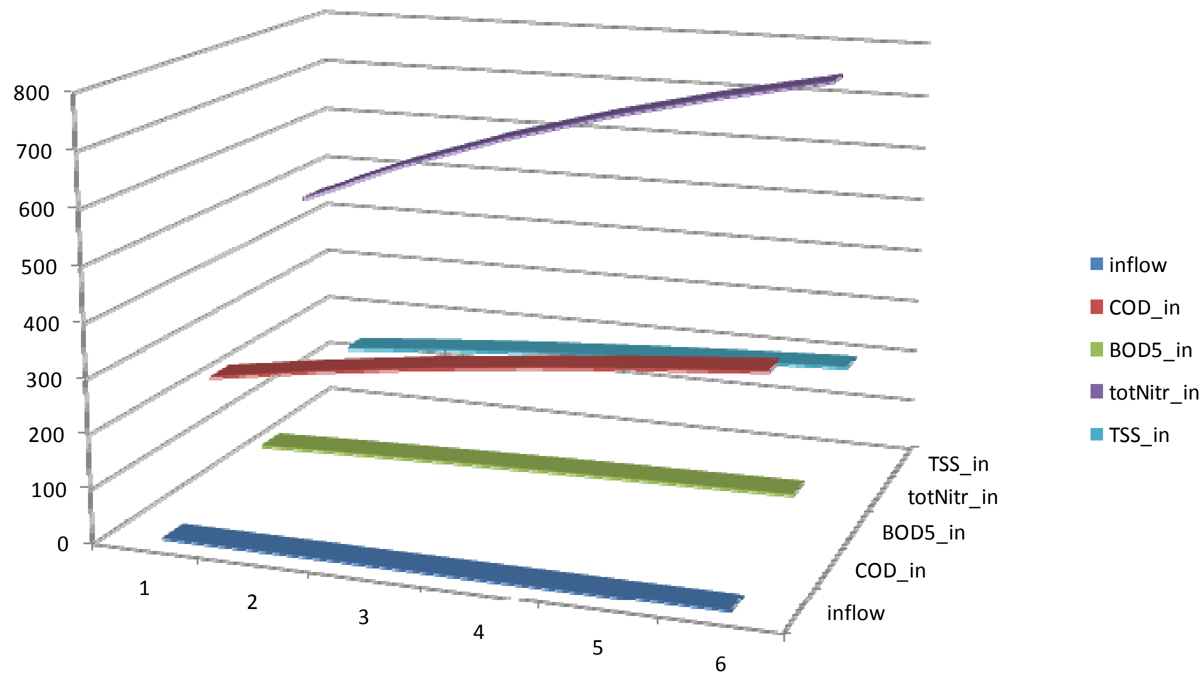

Figure 6-41. 95th Percentile of WWTP inflow to 80 households per ha.

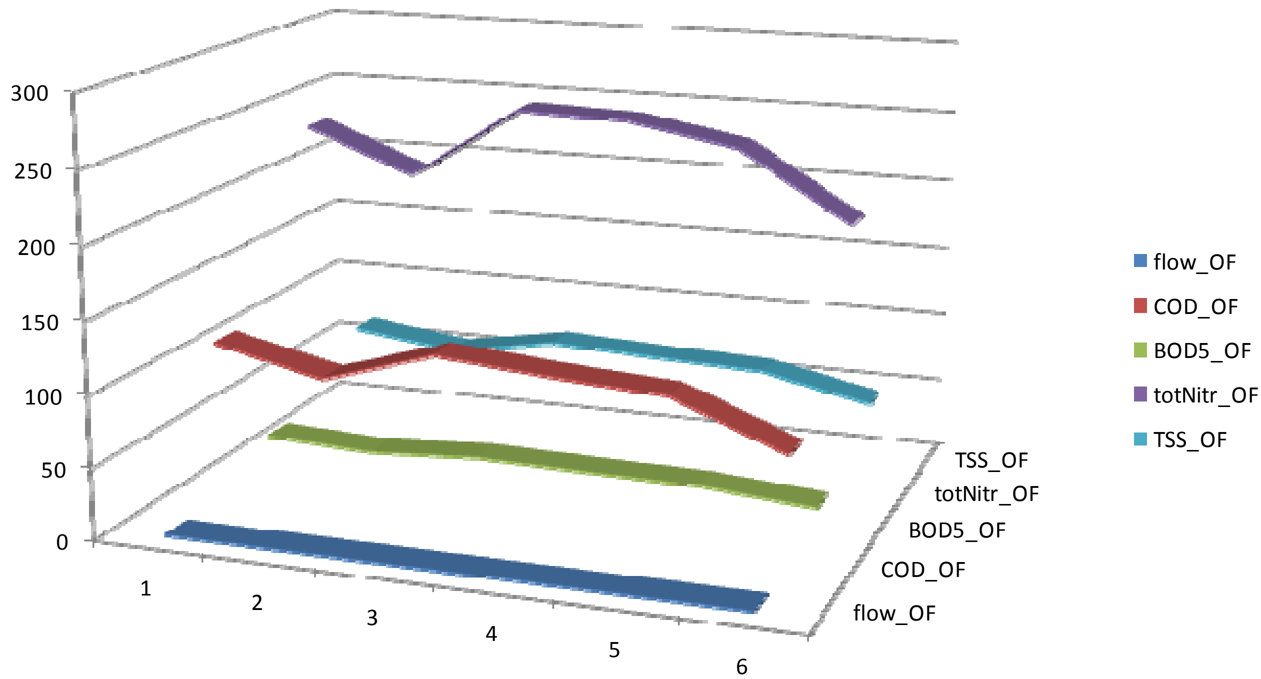

Figure 6-42. 95th Percentile of overflow to 80 households per ha.

It is noteworthy that Figures 6-38, 6-40 and 6-42 show significant differences among the three sub scenarios, when the overflow values are investigated. While a low household density seems to show a decreasing trend of the 95th percentile valued of pollutant concentrations, the further two cases, medium and high density, show a substantially stable or at most slightly decreasing trend of pollutant concentrations. This may be interpreted as a dilution effect related to slightly different shapes of the hydrographs, in fact the low density assumption imply a lower percentage of new impervious area. This may also imply an higher rate of hydrologic losses, and then of drained water. Therefore this can be a fictitious benefit, since the pollutants are roughly discharged into the soil rather than drained. However, the uncertainty related to Scenario 1 sub options does not allow to depute the motivations of such behaviour just to a single cause.

Looking at Figures 6-37, 6-39 and 6-41, it is noteworthy that the 95th percentiles are quite similar among the sub scenarios and always increasing. This means that different density options on a single expansion area do not seem to bias the inflow to the treatment plant.

The following Figures, from 6-43 to 6-78, shows the results obtained from the case study concern the **Scenario 2**, where the new areas are connected to the existing network at the nodes N17, N61, N143, N259, N283. These Figures shows the difference among potential scenario due variable year period of urban expansion, when the household density's is assumed fixed (60 households per ha).

Figures from 6-43 to 6-48 shows the situation of the inflow, outflow (Out1) and overflow (Out6) discharge and the concentration profiles of TSS, COD, BOD5 and TotN, in the 1-year period of urban expansion.

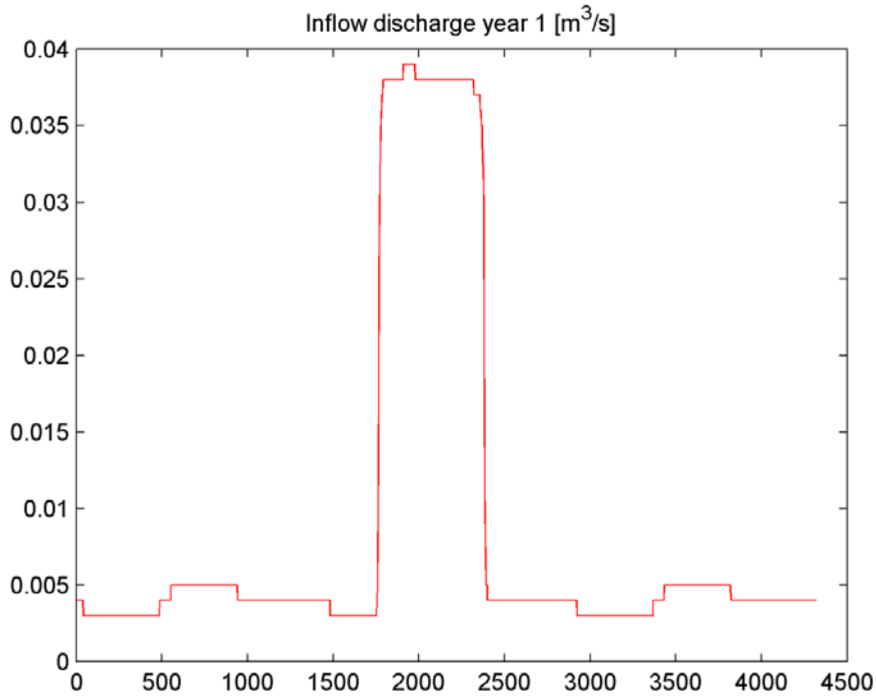

Figure 6-43. Simulated inflow discharge after 1 year of urban growth.

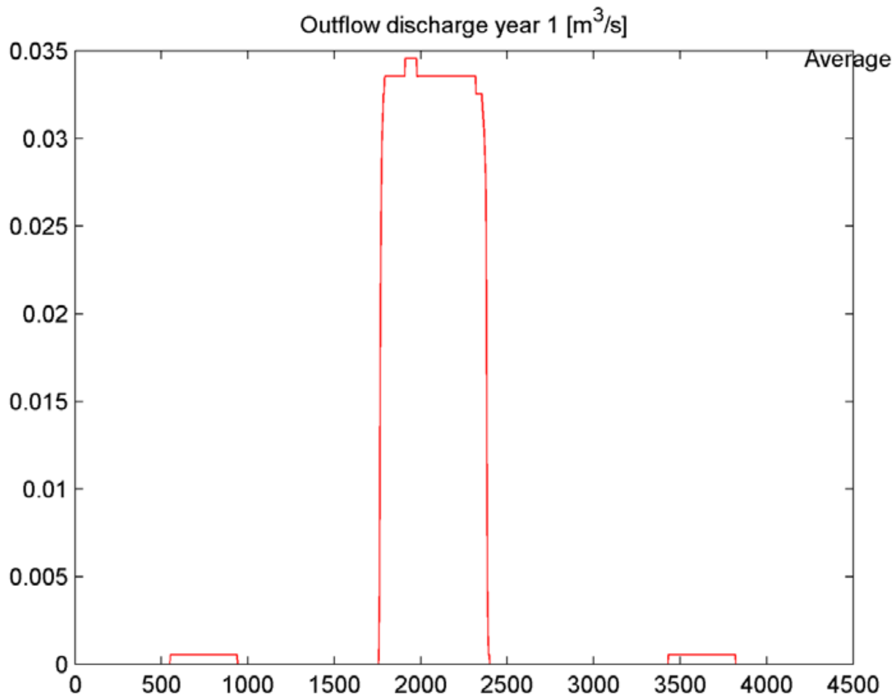

Figure 6-44. Simulated outflow discharge after 1 year of urban growth.

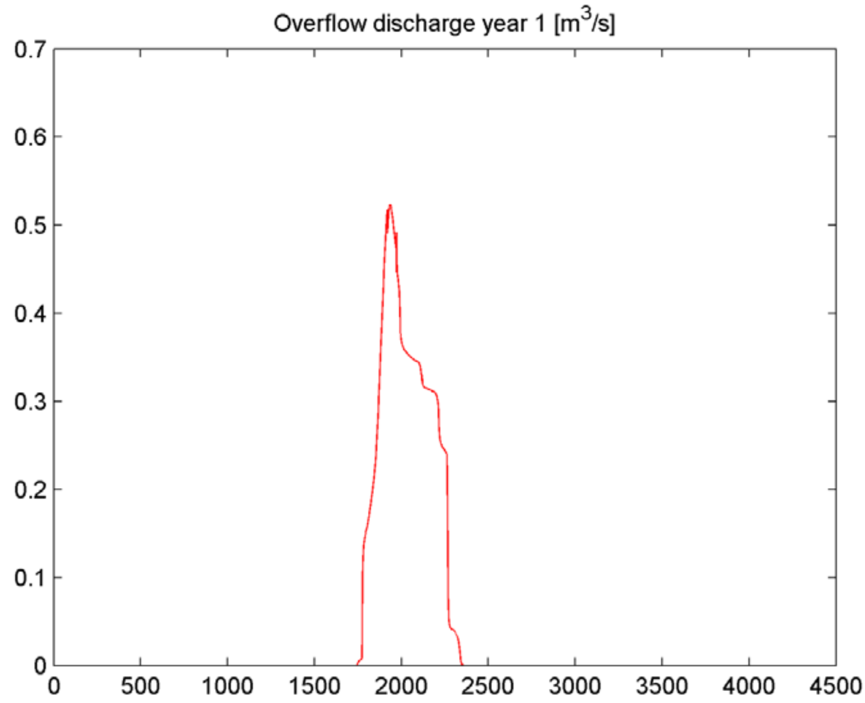

Figure 6-45. Simulated overflow discharge after 1 year of urban growth.

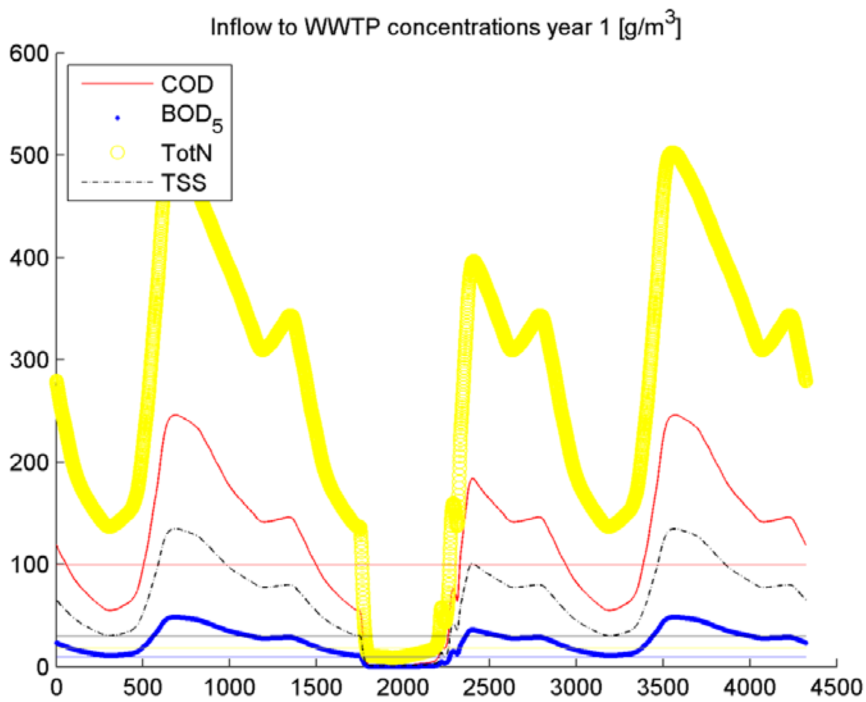

Figure 6-46. Simulated inflow concentrations after 1 year of urban growth.

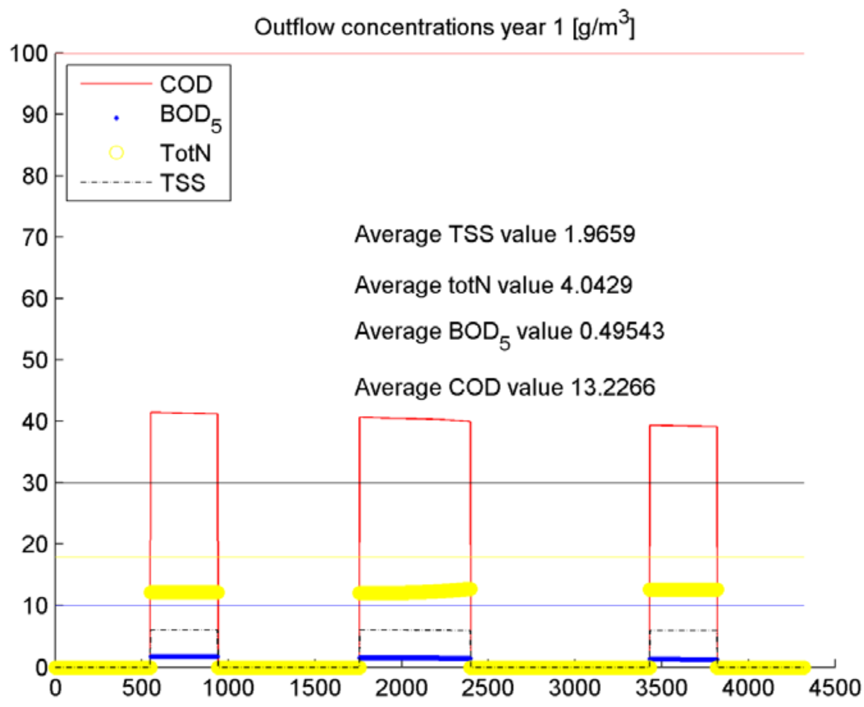

Figure 6-47. Simulated outflow concentrations after 1 year of urban growth.

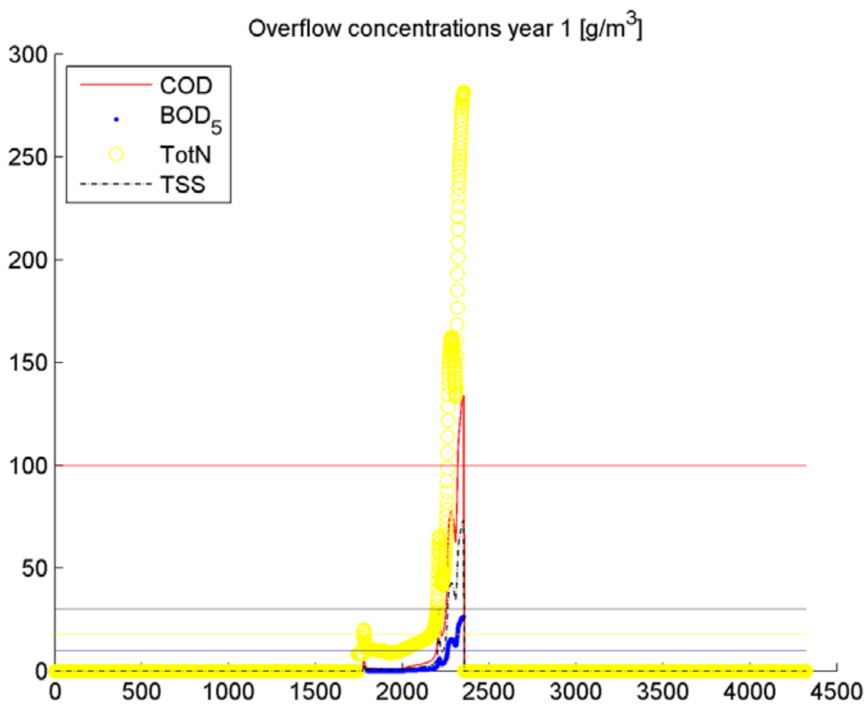

Figure 6-48. Simulated overflow concentrations after 1 year of urban growth.

Figures from 6-49 to 6-54 shows the situation of the inflow, outflow (Out1) and overflow (Out6) discharge and the concentration profiles of TSS, COD, BOD5 and TotN, in the 2-years period of urban expansion.

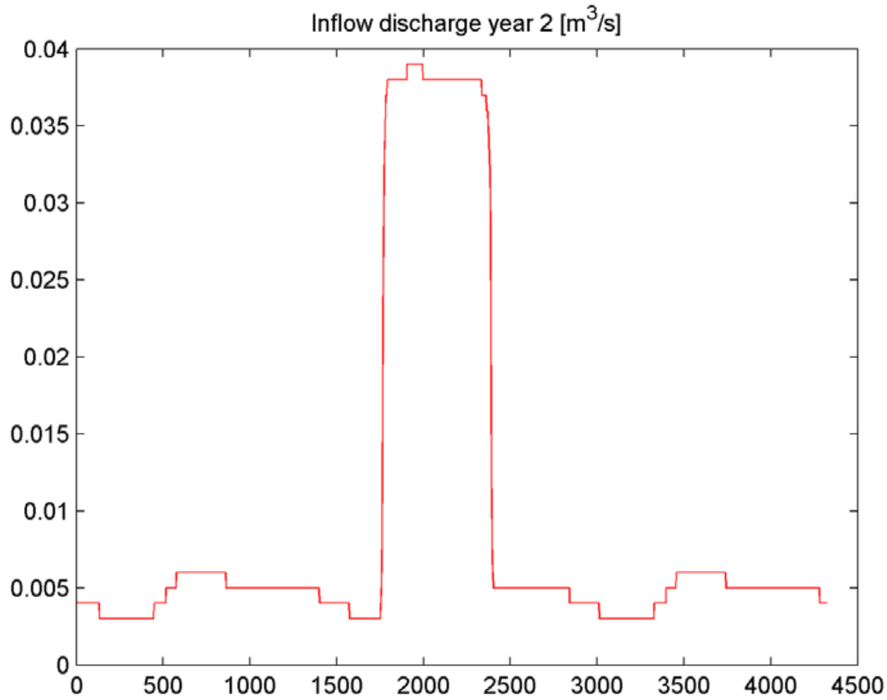

Figure 6-49. Simulated inflow discharge after 2 years of urban growth.

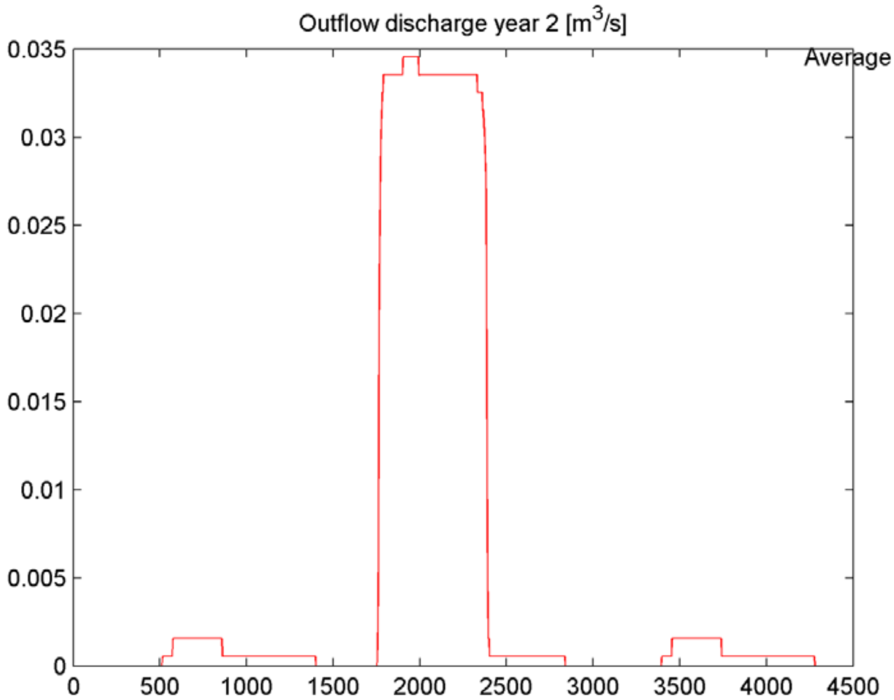

Figure 6-50. Simulated outflow discharge after 2 years of urban growth.

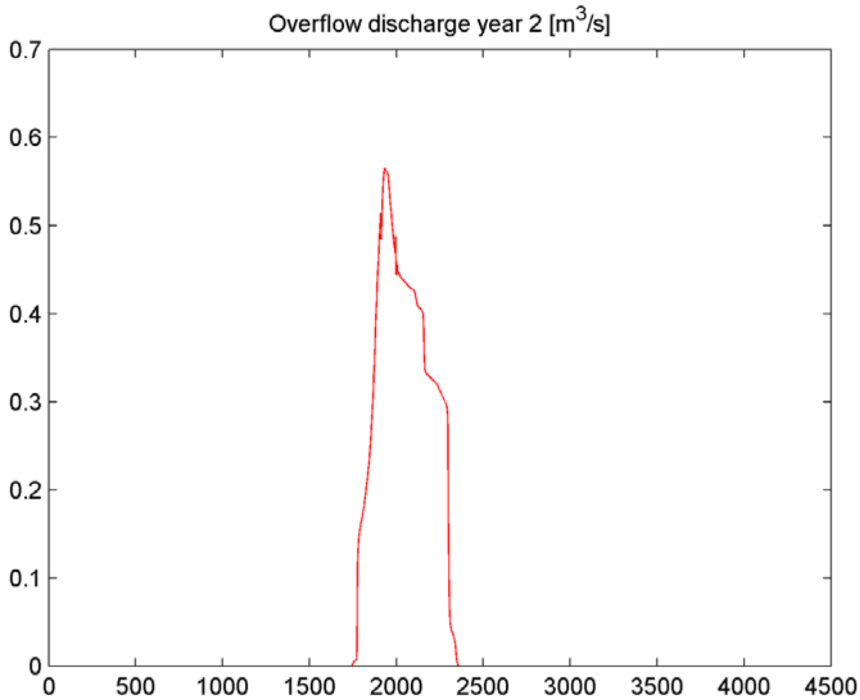

Figure 6-51. Simulated overflow discharge after 2 years of urban growth.

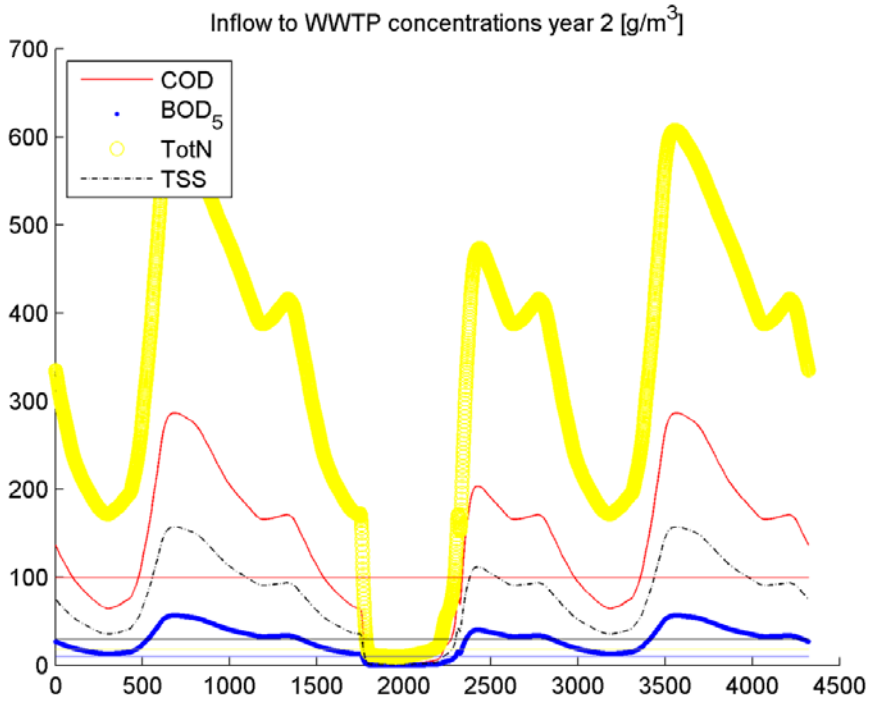

Figure 6-52. Simulated inflow concentrations after 2 years of urban growth.

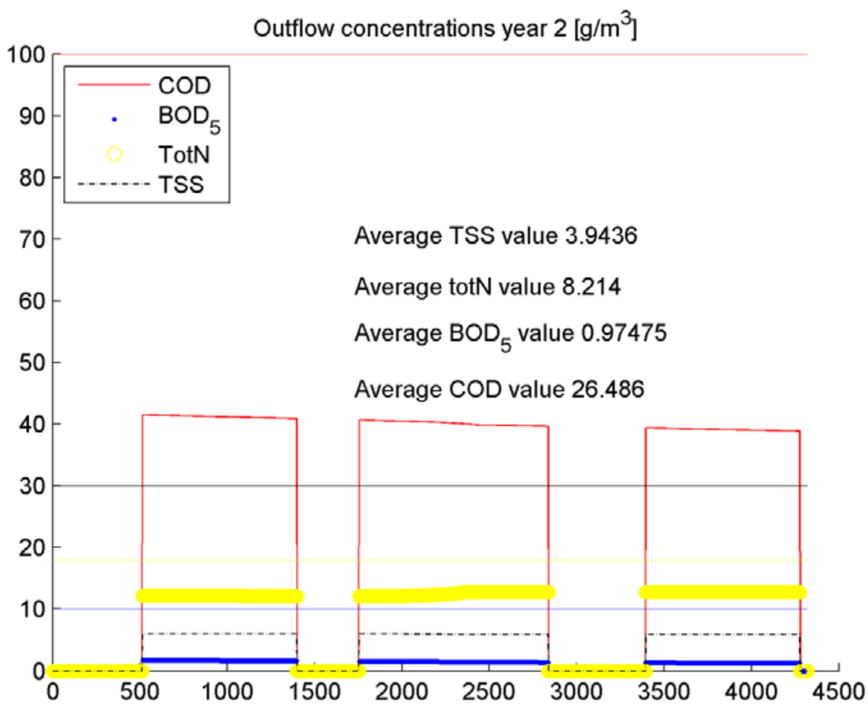

Figure 6-53. Simulated outflow concentrations after 2 years of urban growth.

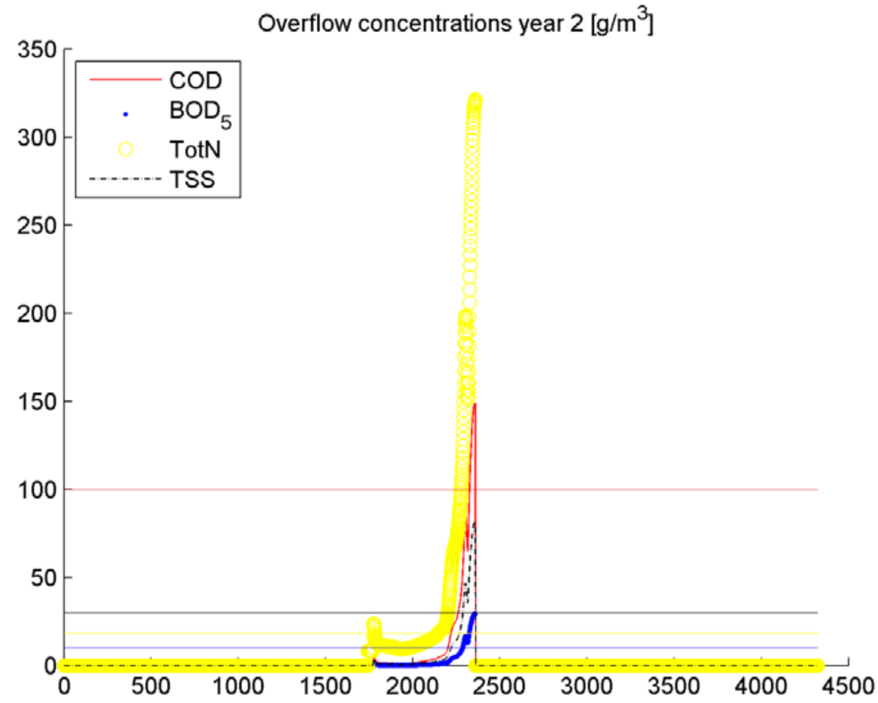

Figure 6-54. Simulated overflow concentrations after 2 years of urban growth.

Figures from 6-55 to 6-60 shows the situation of the inflow, outflow (Out1) and overflow (Out6) discharge and the concentration profiles of TSS, COD, BOD5 and TotN, in the 3-years period of urban expansion.

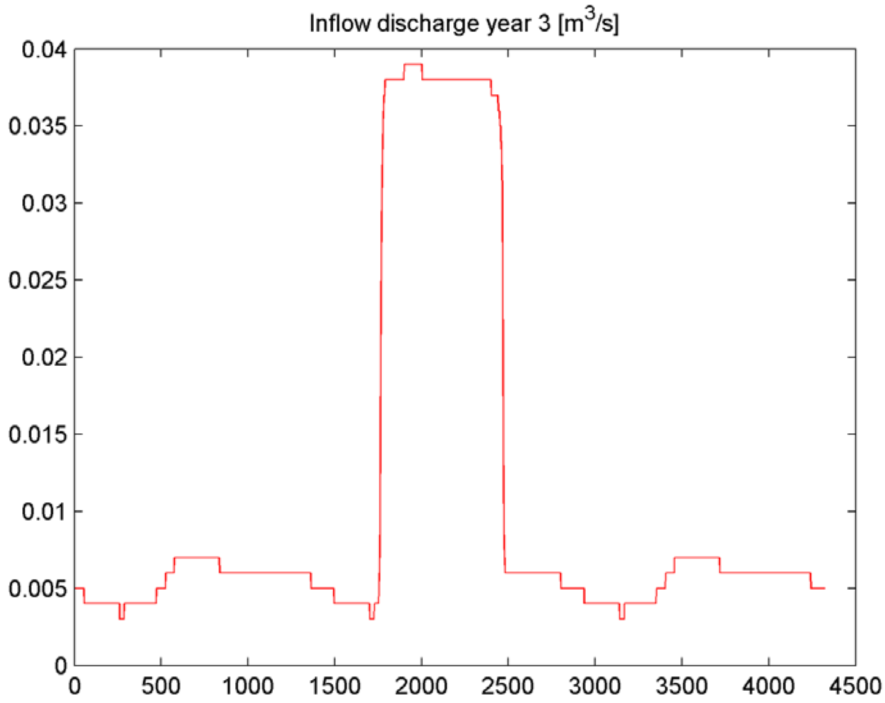

Figure 6-55. Simulated inflow discharge after 3 years of urban growth.

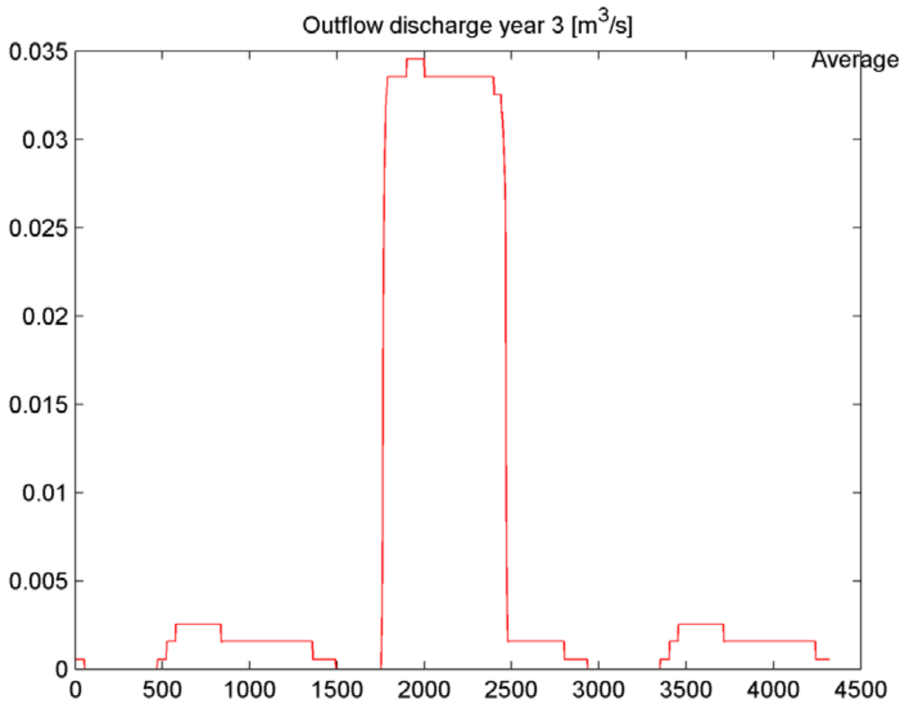

Figure 6-56. Simulated outflow discharge after 3 years of urban growth.

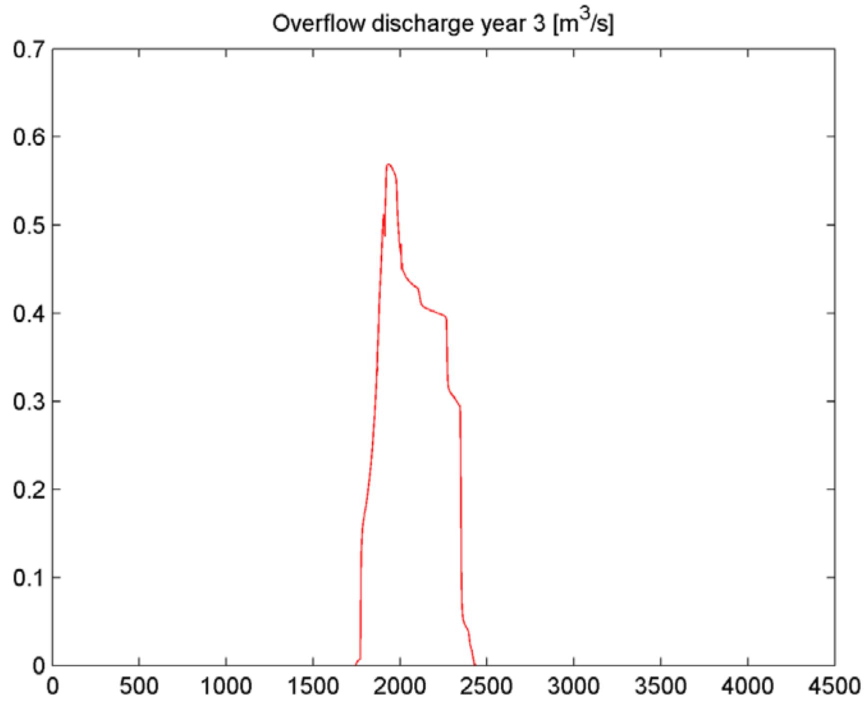

Figure 6-57. Simulated overflow discharge after 3 years of urban growth.

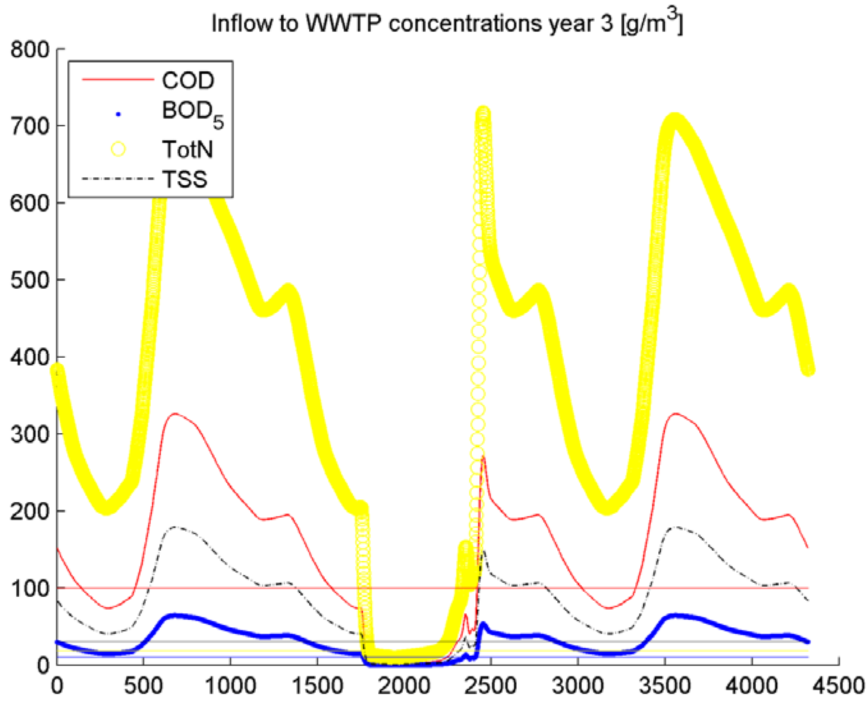

Figure 6-58. Simulated inflow concentrations after 3 years of urban growth.

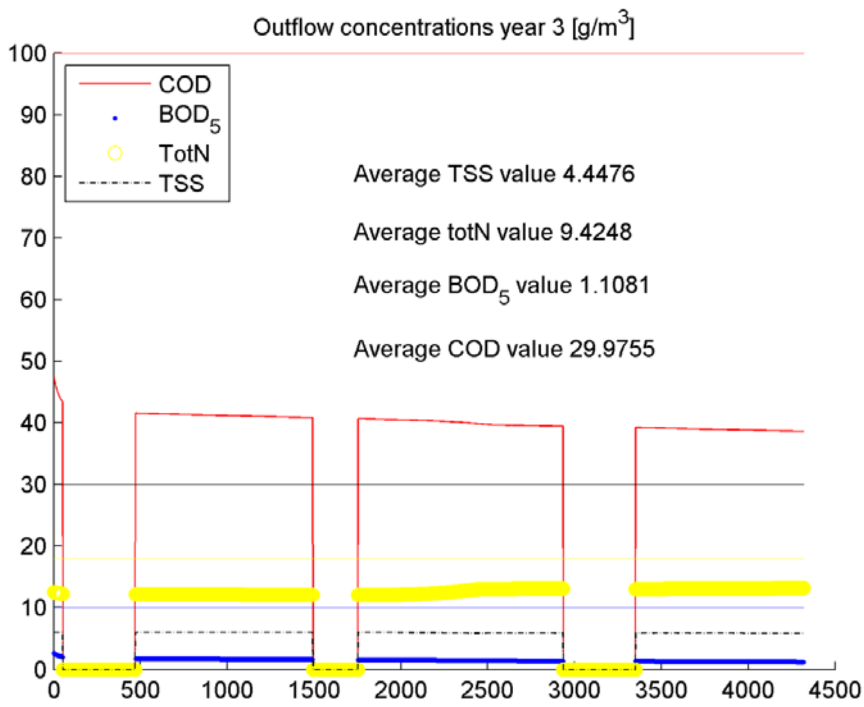

Figure 6-59. Simulated outflow concentrations after 3 years of urban growth.

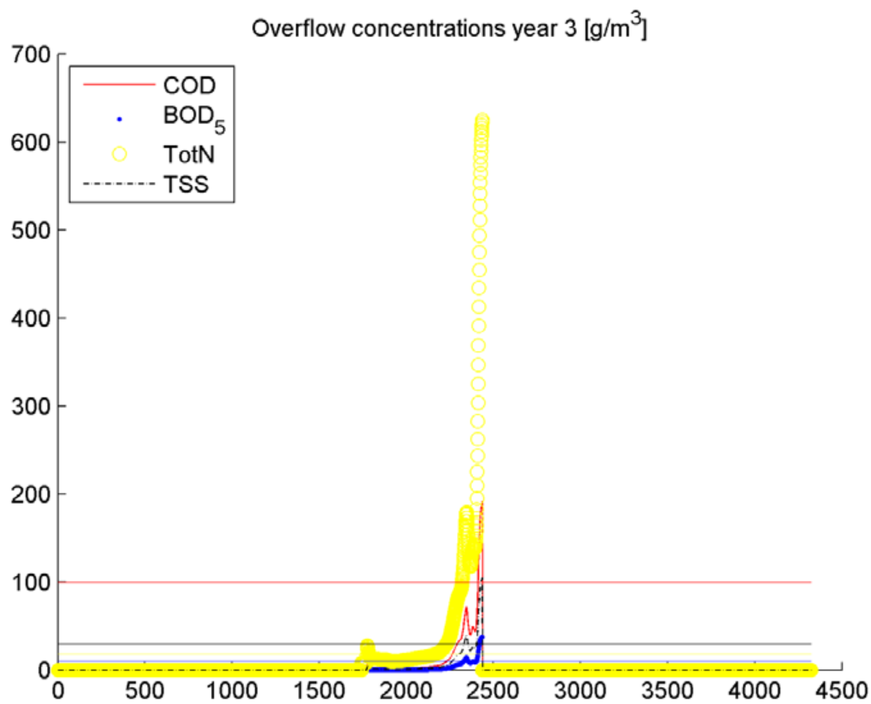

Figure 6-60. Simulated overflow concentrations after 3 years of urban growth.

Figures from 6-61 to 6-66 shows the situation of the inflow, outflow (Out1) and overflow (Out6) discharge and the concentration profiles of TSS, COD, BOD5 and TotN, in the 4-years period of urban expansion.

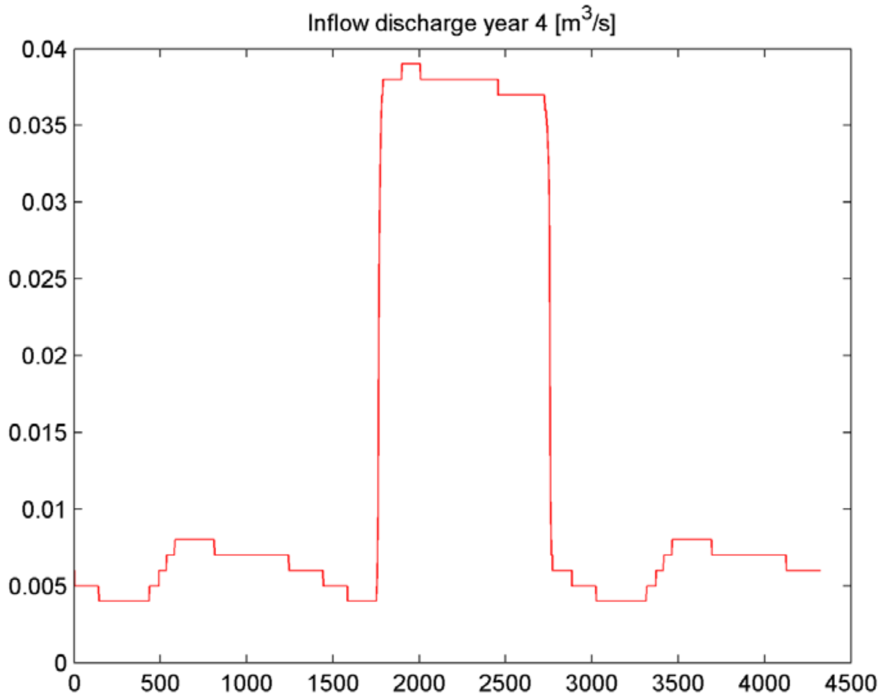

Figure 6-61. Simulated inflow discharge after 4 years of urban growth.

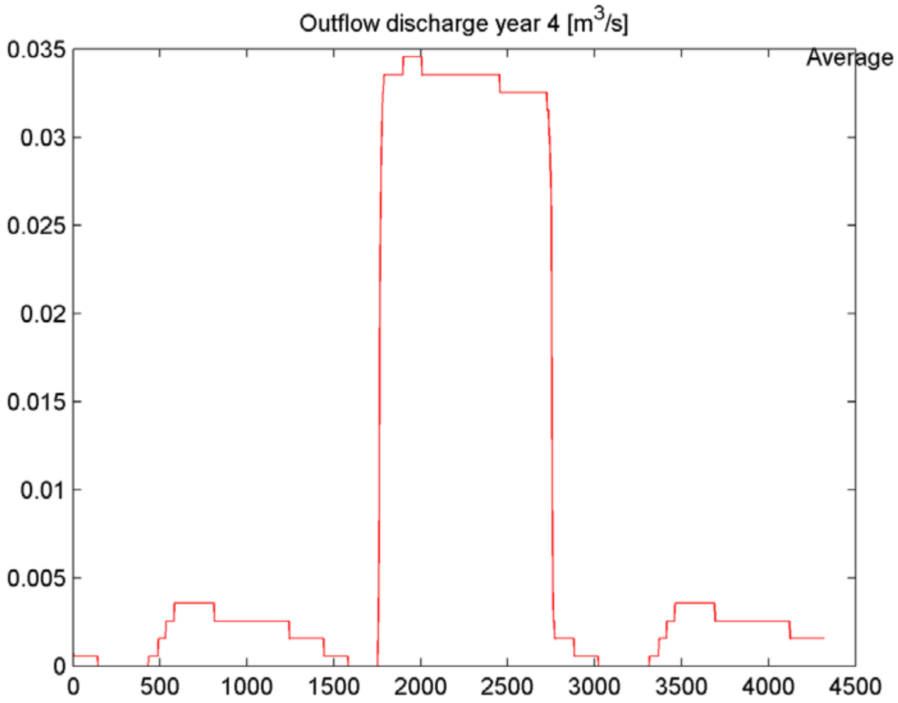

Figure 6-62. Simulated outflow discharge after 4 years of urban growth.

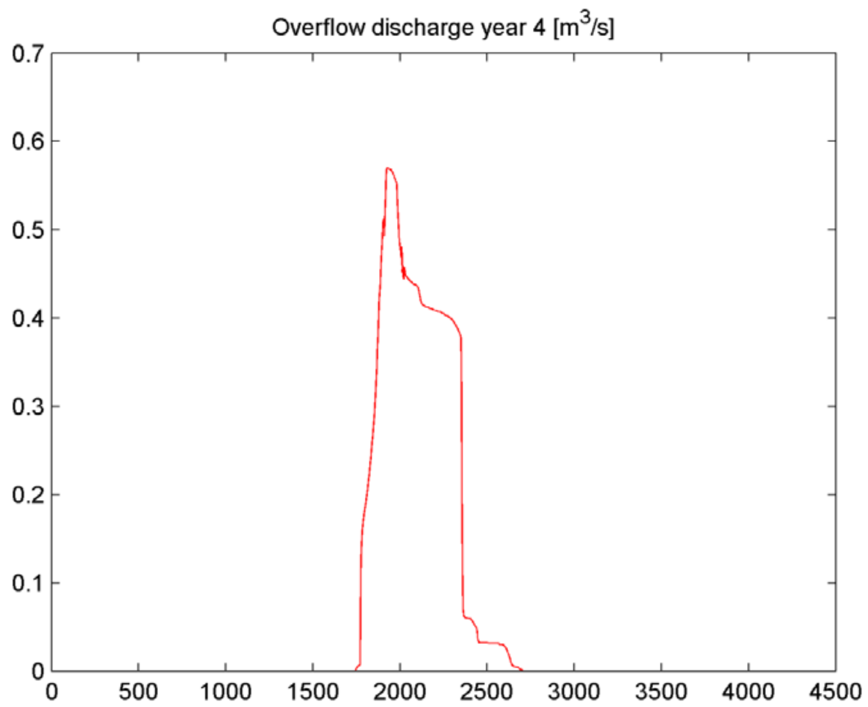

Figure 6-63. Simulated overflow discharge after 4 years of urban growth.

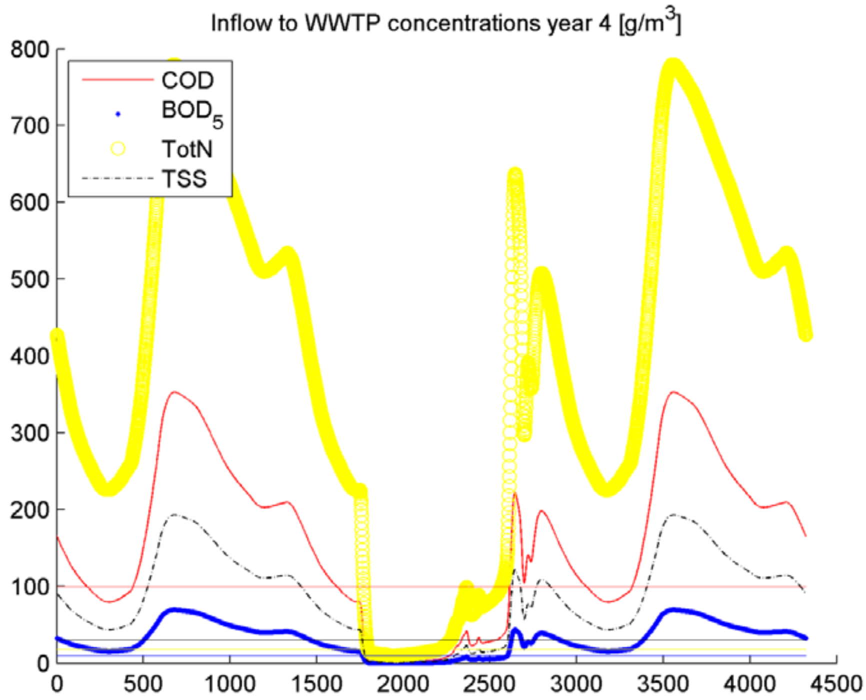

Figure 6-64. Simulated inflow concentrations after 4 years of urban growth.

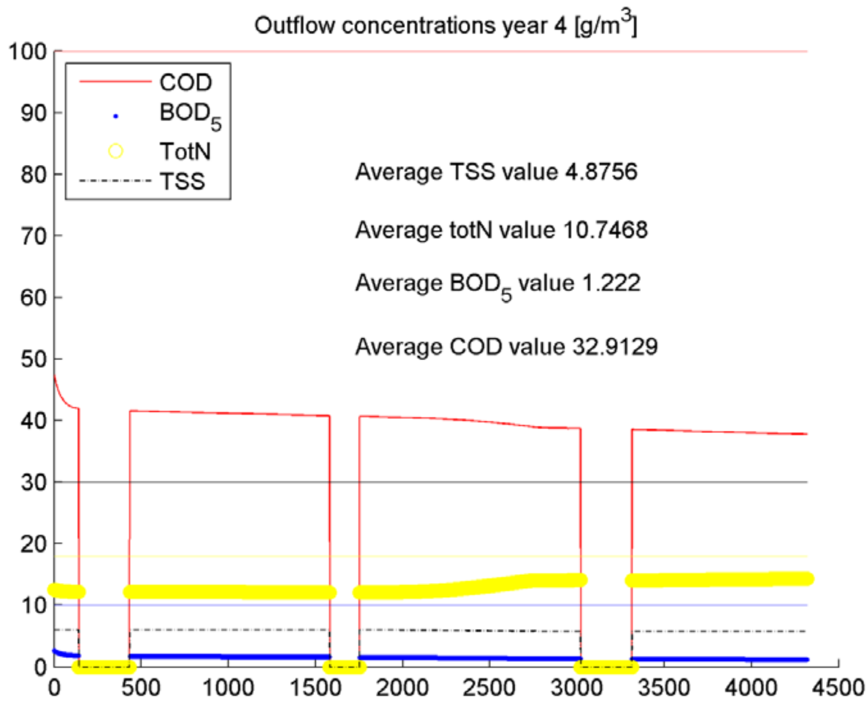

Figure 6-65. Simulated outflow concentrations after 4 years of urban growth.

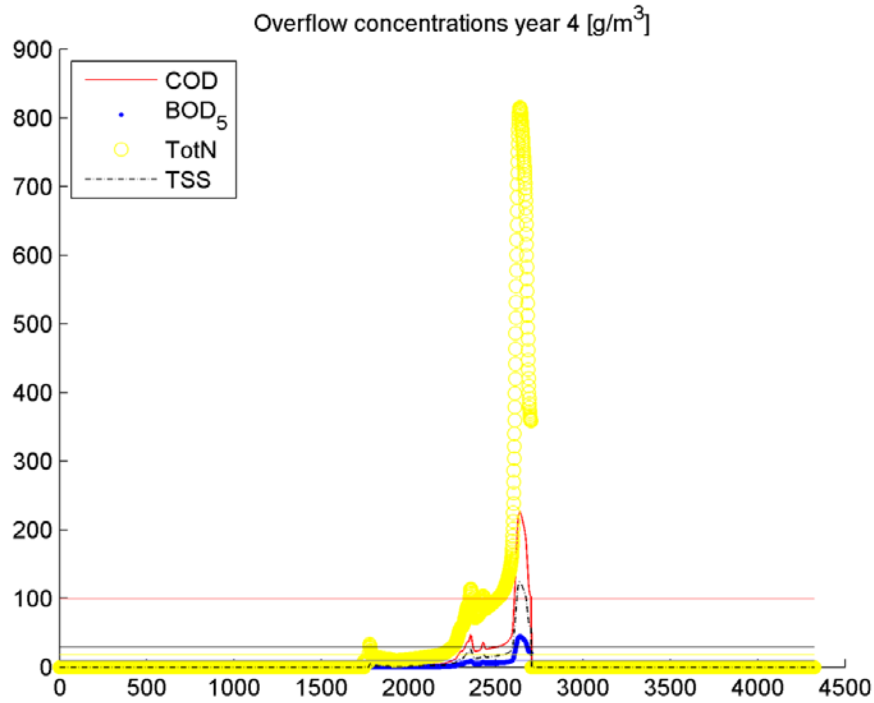

Figure 6-66. Simulated overflow concentrations after 4 years of urban growth.

Figures from 6-67 to 6-72 shows the situation of the inflow, outflow (Out1) and overflow (Out6) discharge and the concentration profiles of TSS, COD, BOD5 and TotN, in the 5-years period of urban expansion.

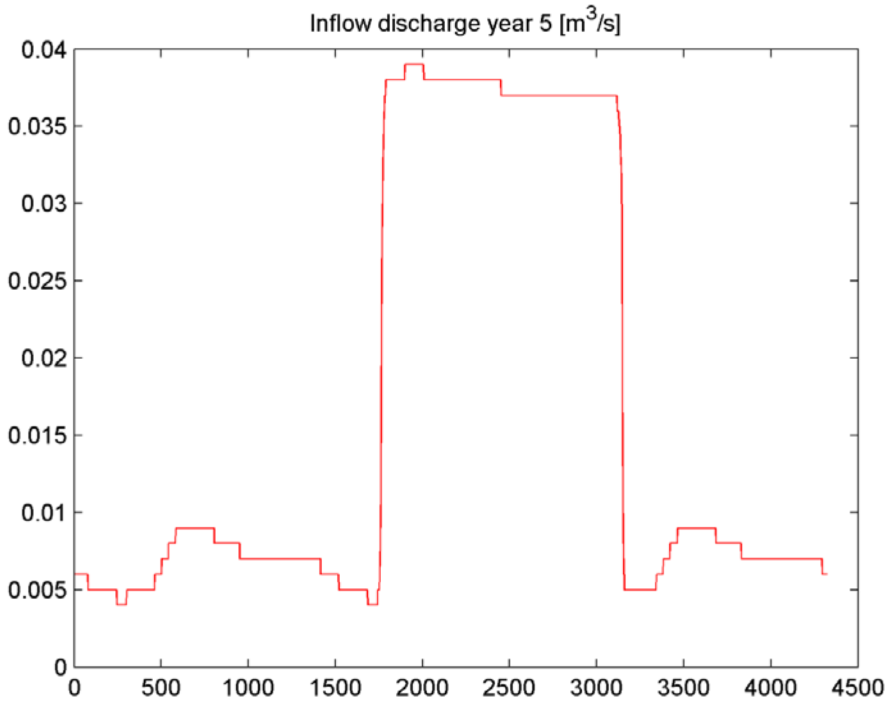

Figure 6-67. Simulated inflow discharge after 5 years of urban growth.

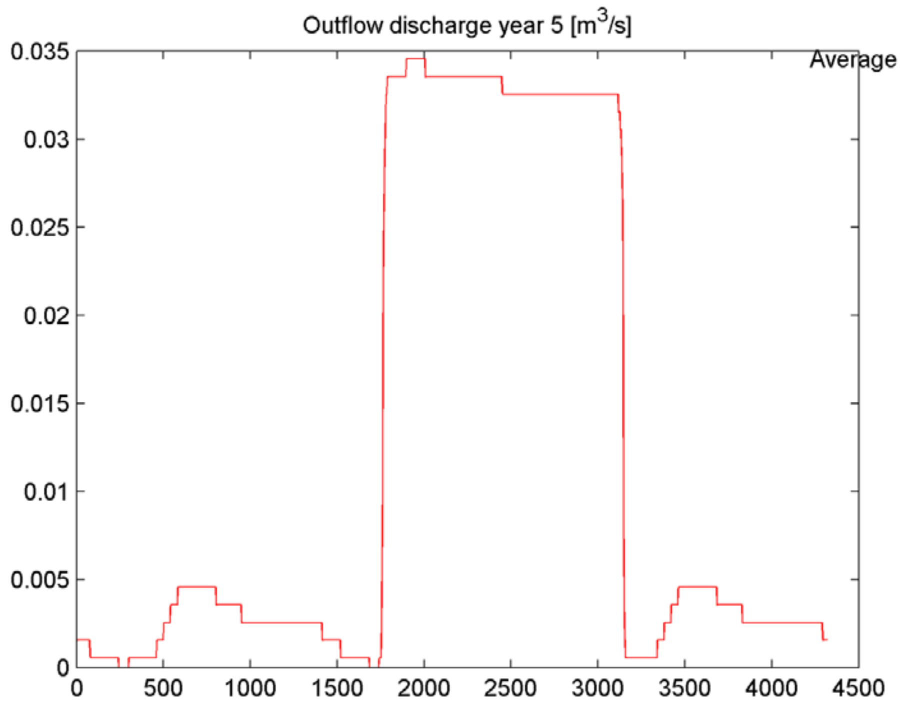

Figure 6-68. Simulated outflow discharge after 5 years of urban growth.

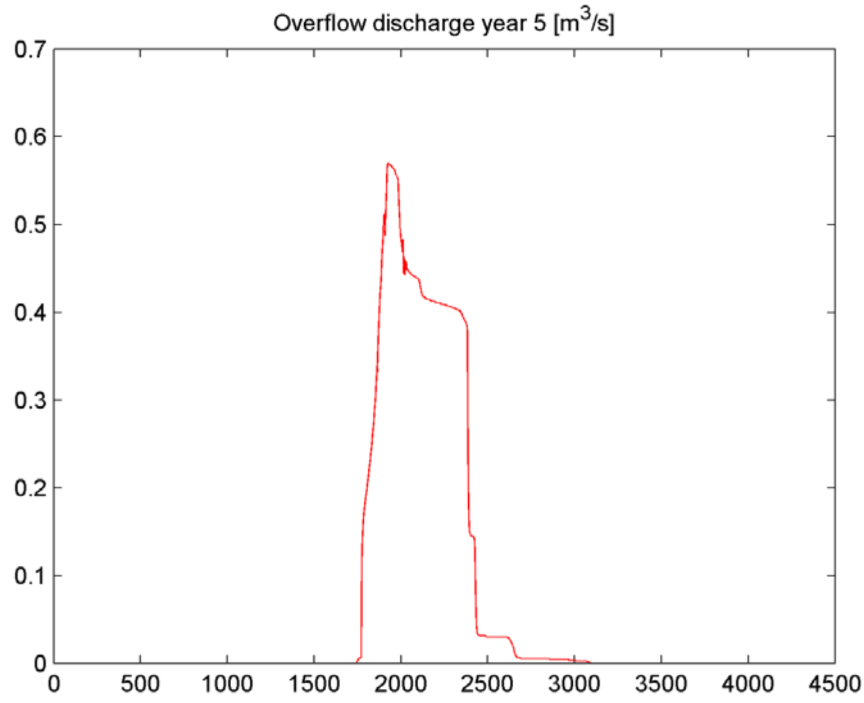

Figure 6-69. Simulated overflow discharge after 5 years of urban growth.

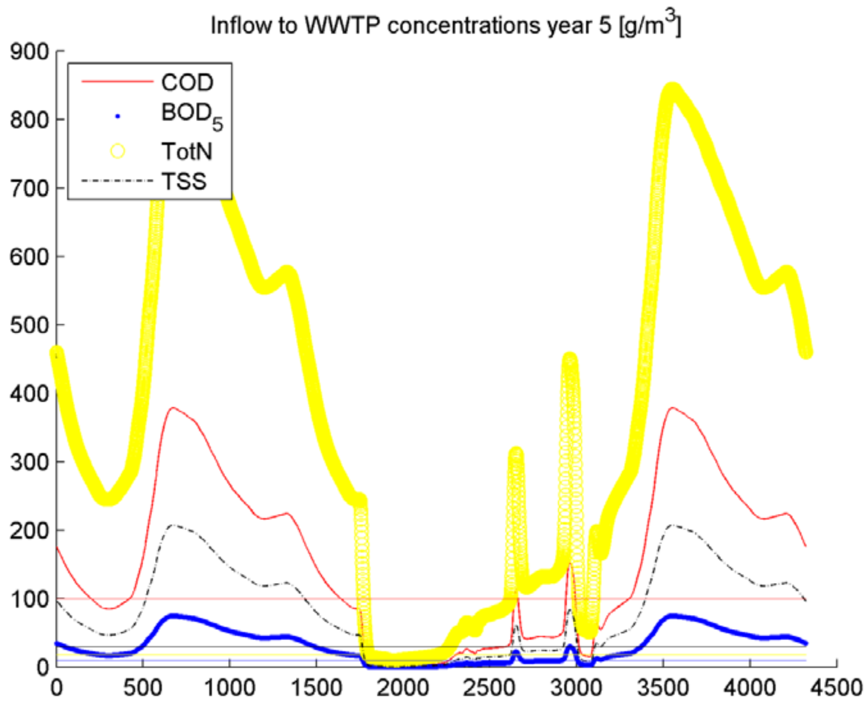

Figure 6-70. Simulated inflow concentrations after 5 years of urban growth.

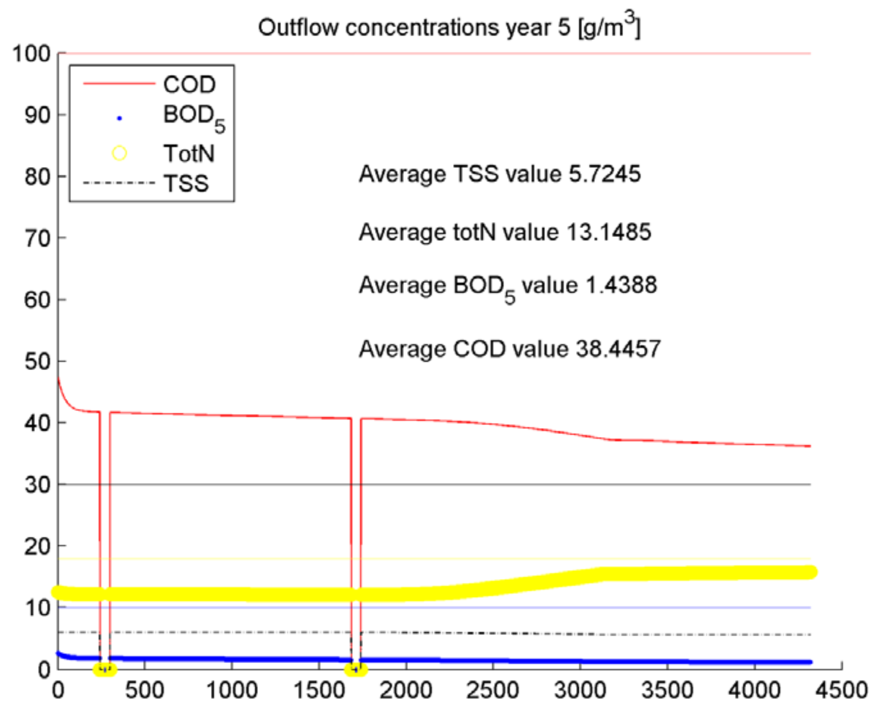

Figure 6-71. Simulated outflow concentrations after 5 years of urban growth.

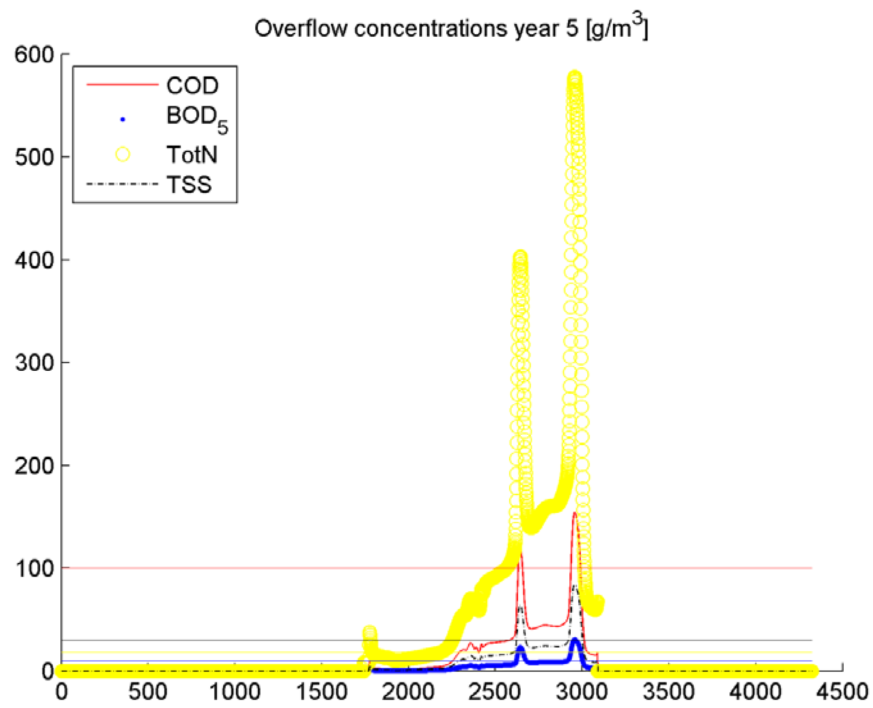

Figure 6-72. Simulated overflow concentrations after 5 years of urban growth.

Figures from 6-73 to 6-78 shows the situation of the inflow, outflow (Out1) and overflow (Out6) discharge and the concentration profiles of TSS, COD, BOD5 and TotN, in the 6-years period of urban expansion.

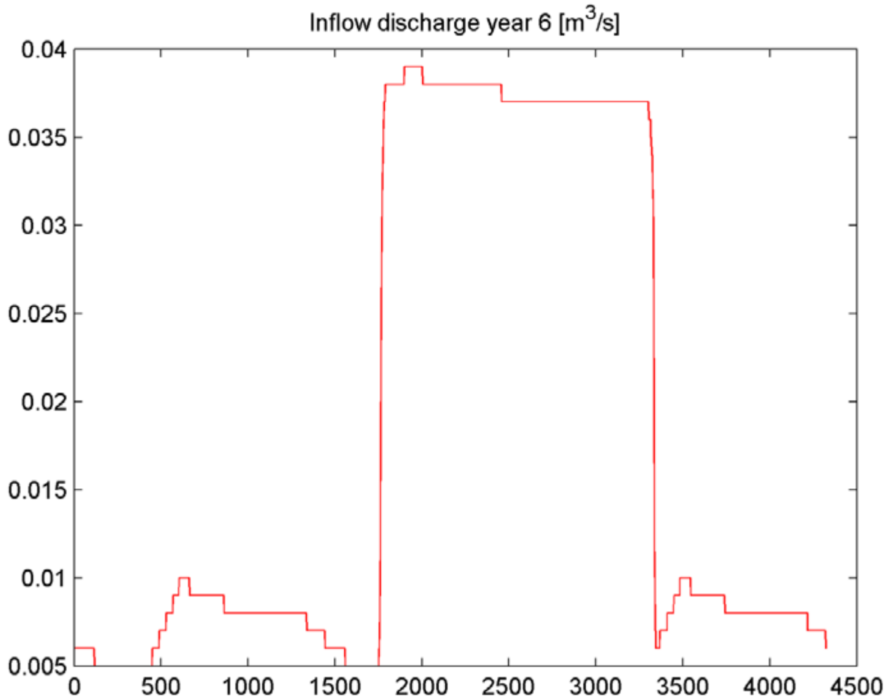

Figure 6-73. Simulated inflow discharge after 6 years of urban growth.

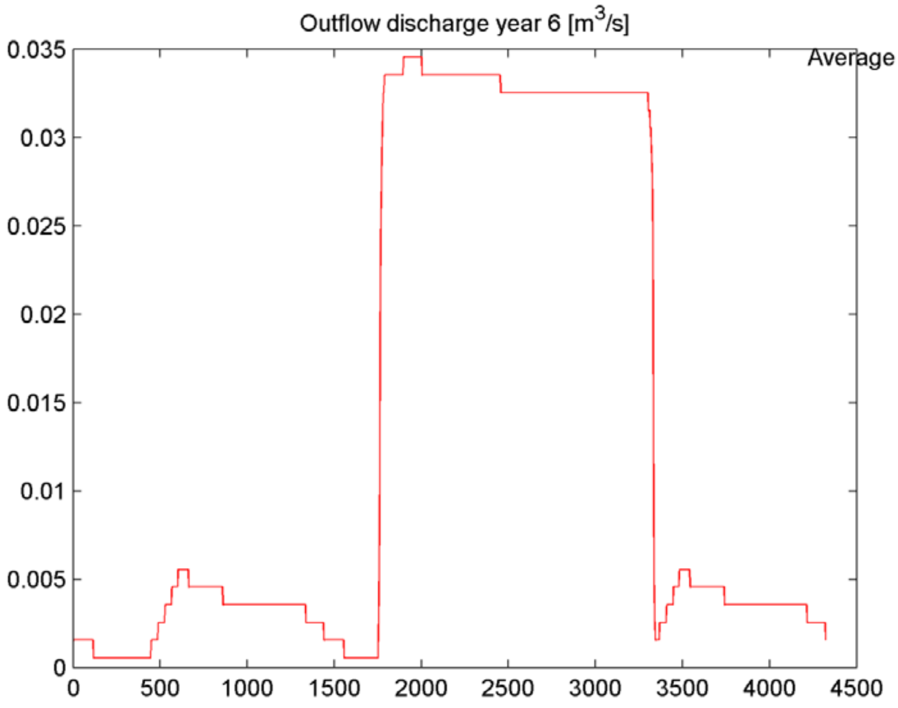

Figure 6-74. Simulated outflow discharge after 6 years of urban growth.

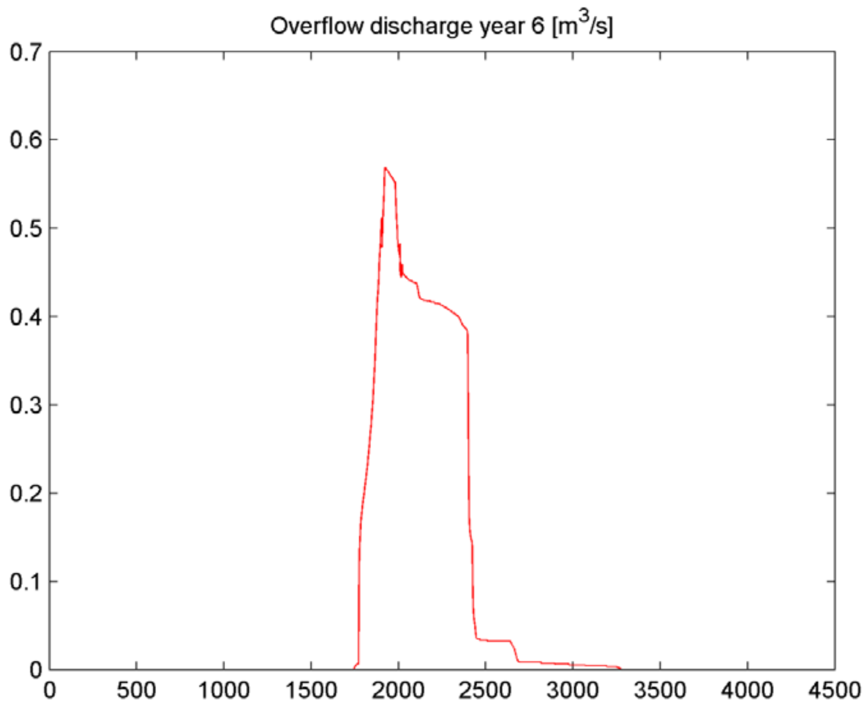

Figure 6-75. Simulated overflow discharge after 6 years of urban growth.

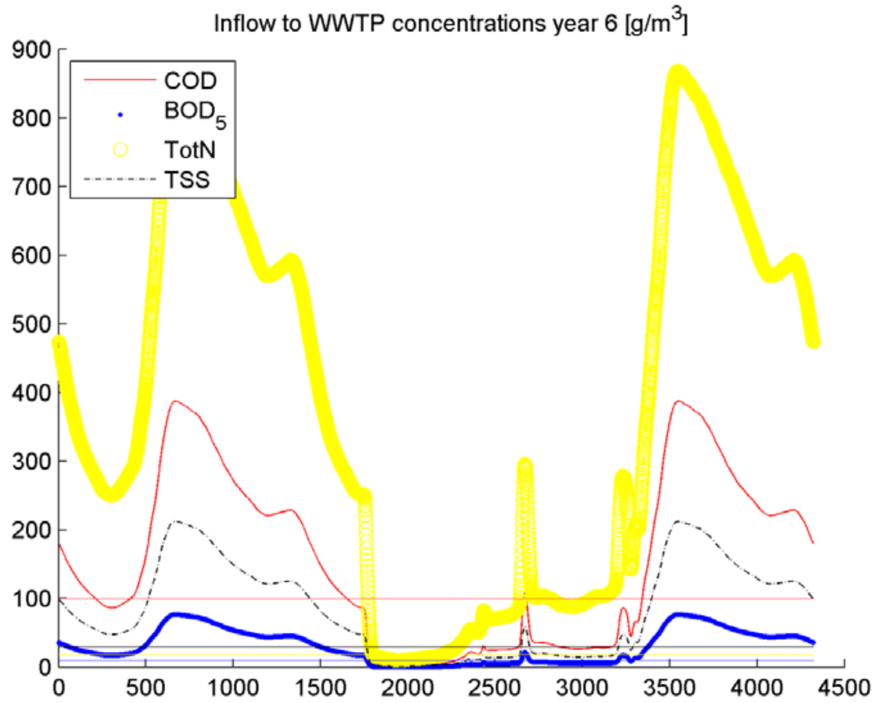

Figure 6-76. Simulated inflow concentrations after 6 years of urban growth.

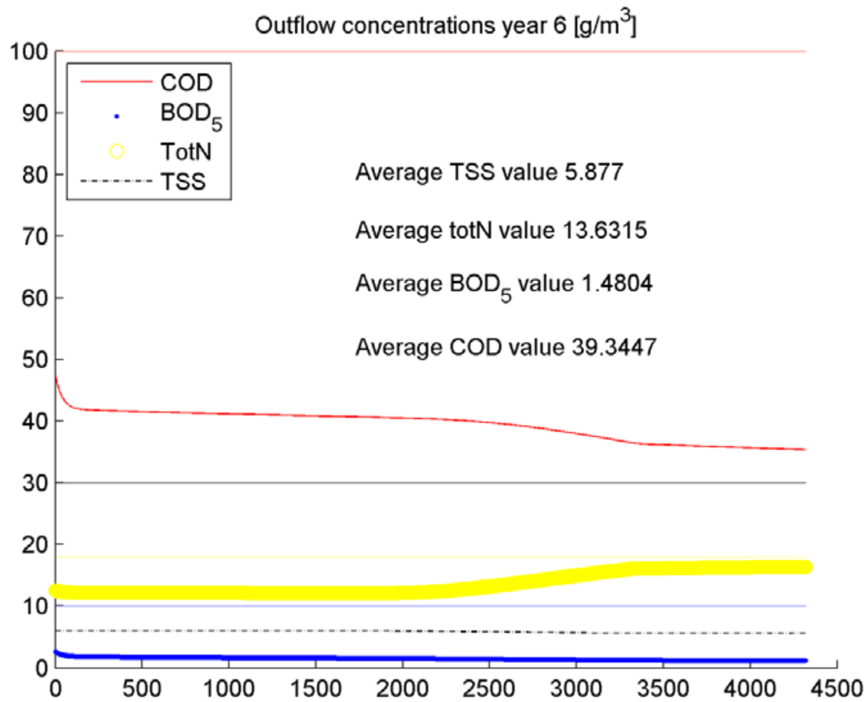

Figure 6-77. Simulated outflow concentrations after 6 years of urban growth.

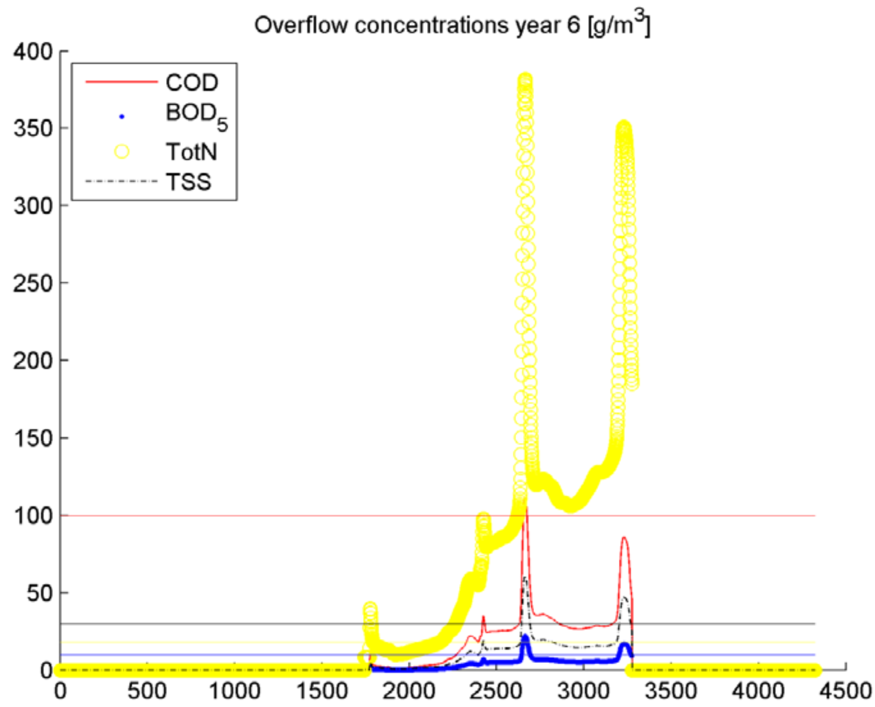

Figure 6-78. Simulated overflow concentrations after 6 years of urban growth.

Scenario 2 clearly shows that the diffused urbanization has a different impact both on the wastewater treatment inflow and to the overflow.

Over the years, three peaks can be clearly observed and a generally higher system discharge, in particular due to the runoff is observed. This also implies higher concentrations of the pollutant indicators, as well as potential crisis scenarios for the wastewater treatment.

Total nitrogen is the indicator which appears highly affected by the new urbanization; it is envisaged that its concentration is very close to the limit assumed by Communitarian rules, however never exceeding this upper bound. The remaining pollutant indicators show high values, but apparently never too close to the upper bounds. The highest values of all the indicators are in particular observed during years 5 and 6, which represent the latest two years of the expansion scenario. Moreover, looking at the flows, it is envisaged that the discharged are consistently higher than for Scenario 1. Indeed, the equalization tank of the wastewater treatment plant gradually stops its function, whereas for years 5 and 6 it experienced a constant inflow to the treatments, see Figures 6-71 and 6-77.

It is also noteworthy to investigate the overflow, which is a critical point under a potential contamination viewpoint. Looking at Figures 6-72 and 6-78, the total nitrogen exceed 2 times the upper bound recommended by the UE rules, while a third peak is very close to that bound. Moreover, COD exceeds one time its upper limit, while a second peak is very close to the upper value. It is also concerning the time windows during which the pollutant values exceed or remain closer to the upper values.

While Scenario 1, whatever the household density is, shows high peaks which are quite impulsive, Scenario 2 shows wide periods during which the concentrations remain high. This means that the volumes of polluted water discharged into the receiving water body are high, and of course, harshly impacting with the biologic and chemical equilibrium of the water body. It is also envisaged that the higher quota of drained runoff does not seem to provide high dilution effects, thus the first flush yields anyway a striking impact on the system.

Finally, Figures from 6-79 to 6-80 show the 95th percentile values of inflow and overflow.

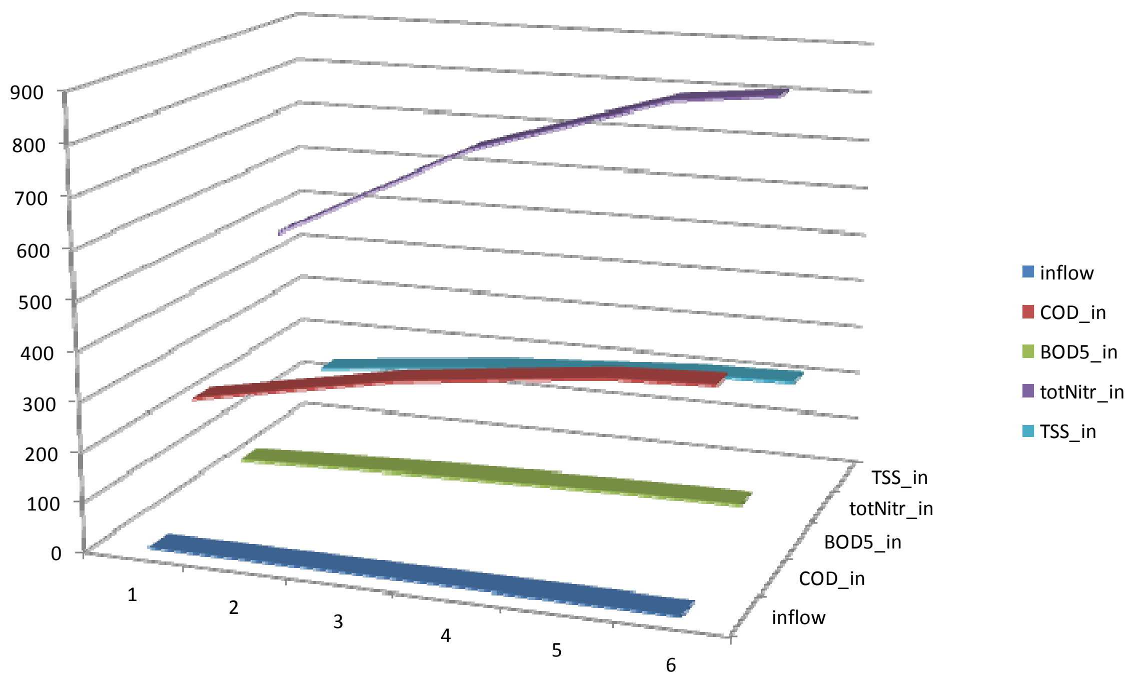

Figure 6-79. 95th Percentile of WWTP inflow.

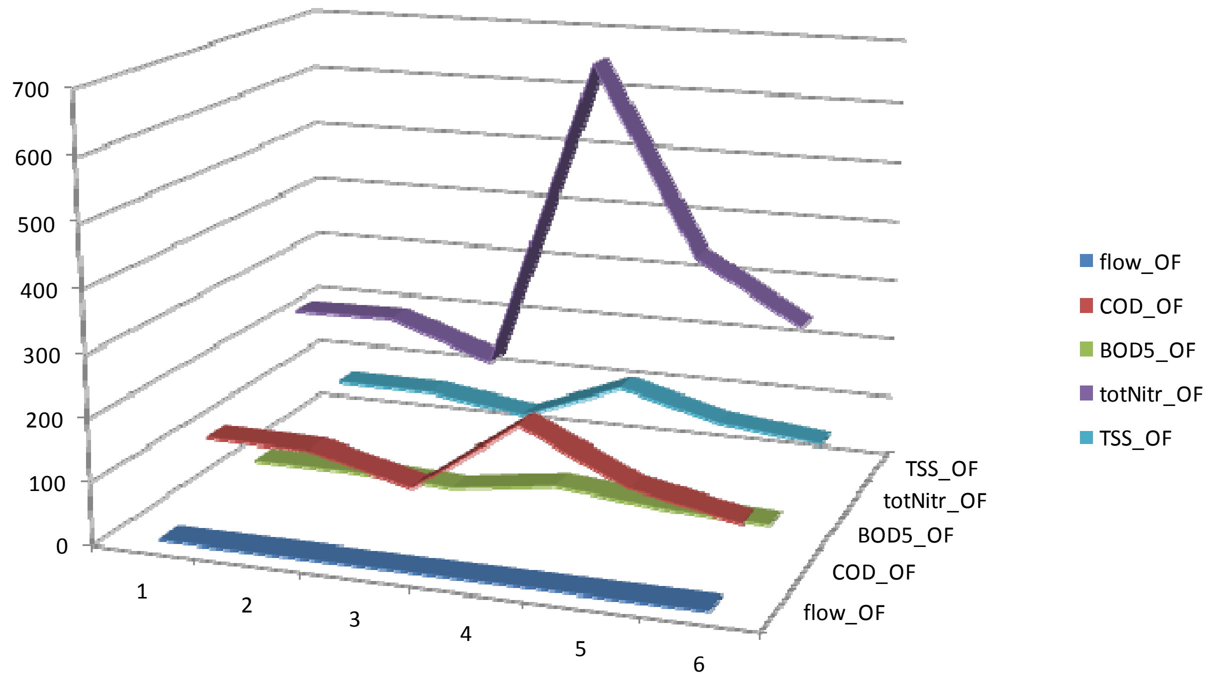

Figure 6-80. 95th Percentile of overflow.

Figures 6-79 and 6-80 show the evolution in the order for the inflow to the treatment and for the overflow the 95th percentiles of pollutant indicators. This analysis clearly shows that there is an increase of concentration, which is generally higher than for Scenario 1, whatever household density is assumed. This proves again that a diffused urbanization may imply pollution effects which are worse to be managed than in Scenario 1. Moreover, from a planning viewpoint, a diffuse urban growth is also more complicate to be managed, since it claims multiple infrastructural needs which shall be provided to multiple suburban zones. It is also notorious the effect of the dilution over the overflow discharge. Indeed, year 4 shows a sort of breakpoint, whereas the following years have lower pollutant concentration, this may be related to a lover mass of pollutant inside a higher volume of water.

Finally, it is worth to be emphasized that Scenario 2 does not necessarily imply just nefarious effects, since the investigated hypothesis relates to an almost fully exploitation of new areas, whereas this does not commonly yields. However, the purpose of this study is to show the influence of different urbanization options on wastewater infrastructures as well as on the water environment, and this is a clear outcome of the presented results.

7 CONCLUSIONS

7.1 A SHORT SUMMARY

The work presented in this Thesis starts from the introduction to the complex relationship between proposed housing development and wastewater pollution incident control and through a general introduction to the most used approaches to contend with problem of planning. In the literal review to this Thesis (see Chapter 2) several techniques and their application to the integration of complex problem and a legal background have been presented. The focus was then moved to the description and the integration of the three models: land use change model, urban drainage model and wastewater treatment plant model. Although the framework developed has been studied, improved and applied to a real world environmental problem, some potentialities of the developed framework arise in the results concerning with the proposed case study.

The following objectives have been accomplished in this Thesis:

- Development and integration of a modeling framework for assessing the impact of an urban infrastructure for the collection and treatment plant, and on receiving waters.
- Applying the framework to a specific case study.
- Analysis of feasibility and impact of specific development plans for urban ecosystem hydraulic and water infrastructure for a small urban centre.
- Identification of key parameters in determining the potential impacts and their mitigation.
- Differences among alternatively feasible planning options in terms of impact on the wastewater infrastructures and aquatic environment.

On the basis of what is presented, and based on the obtained results, it can be concluded that the developed methodology represents an innovative approach, as ever faced in literature, and with potential advantage for further development and applicability.

7.2 CONTRIBUTIONS OF THE PRESENT WORK

During the present work of Thesis the following contributions has been introduced:

- The identification of the model components which can simulate single events concurring to the description of the complex system.
- The integration of the single components into a common framework.
- The motivation, the rational and implementation details of a modeling framework, which is an effort to bridge the gap of integrated models for decision making in urban planning.
- The stochastic system dynamics integrative model has been tested on cases study from different planning scenarios to evaluate for new housing areas against the quality of the wastewater drained by a sewer system and treated by a wastewater treatment plant.

These work contributions have led up to a new general approach to environmental modelling, based on the analysis of multiple aspects involved in model construction, as described in Chapter 6.

7.3 WORK CONCLUSIONS

The impact of urban planning on the surrounding environment is not always obvious, particularly for the long term impact and it usually needs specific computer simulation models to support the process. Hence, urban land use planning is a crucial task that has large impact on our lives. It drives economic development, affects social structures, shapes the urban landscape and modifies the environment. However, the long term impact of urban planning on the surrounding environment is not always obvious, and this case study shows how specific computer simulation models provide a useful support.

Overall, the results of the case study analysed show that the population growth rate, despite generating higher pollutant loads and flows, does not severely compromise the performance of the sewage system nor of the treatment plant. The feedbacks gathered through this simulation provide important operational and planning considerations that should complement the information available to planners and authorities to better assess consequences and identify alternatives to urban expansion plans.

In this Thesis, an integrated modeling framework was developed to assess the effects of alternative urbanization patterns on the surrounding water quality. Even if the presented base structure of the case study is quite simple, the framework provides a conceptual and quantitative tool to quantify the impacts of urban land use changes on urban water systems, including urban drainage and wastewater treatment plant.

As shown by results, the focus is not to find a potential crisis of the system, even if accidentally met, but to show how the framework works and which kind of information it is possible to gather. This kind of approach could be complementary to a minimization of the impacts pollutants on water, when different scenarios of urban development and population growth are analyzed. This could produce feedbacks which can help urban planner to plan the expansion of towns evaluating the costs of the urban growth on the existing infrastructures.

To demonstrate the functionality of this framework, a case study was set up and two main planning scenarios, comprising a set of sub-cases, were evaluated for new house dwellings. The results show that the population growth rate has obvious effects on water quality. However, these effects do not completely compromise the functionality of the sewage system and of the treatment plants. An interesting effect seems to be caused by the rainfall event, but in this case the feedback could be the construction of a storage tank which limits the peak inflow to the treatment plant. Moreover, the two main scenarios, concentrated and diffused urban expansion, show different consequences both of the wastewater infrastructures and on the discharge into the receiving water body. In particular, Scenario 2 highlights some critical consequences, whereas it produces higher pollutant concentrations for longer periods than Scenario 1. In addition, the presence of a larger and widespread paved area implies higher drained runoff percentage and consequently higher first flush drainage than Scenario 1. This increase the overflow discharge, which means a higher untreated water quota which is directly discharged into the receiving water body. It is also shown that the distribution of the links of new drains to the existing network modify the shape of the hydrograph wave and therefore the inflow to the wastewater treatment plant. This implies a modification of the routine of the plant, and in particular that it is almost exploited to the maximum of its potential. Therefore the risk of out of order or biological tilts is quite probable.

These results therefore show that a concentrated urban expansion is a guessable option despite the diffused urbanization. However, this is not definitive, since the investigated diffused urbanization tents to exploit this option almost to its limit, while commonly this does not happen, at least on the assumed time window, 6 years.

Finally, the results emphasize that the adoption of alternative urban plans can severely bias the infrastructures and the quality of the environment. This work proves that not only the number of people affects the infrastructures and the pollutant, but also how they spatially distribute, given a particular existing urban scenario and environmental morphology. Therefore, the computer aided simulation of scenarios, based on stochastic evolution of population, is a necessary tool for planners and for the sustainable, both environmentally and economically, development of urban areas.

7.4 FUTURE WORK RECOMMENDATIONS

The application of the developed framework in order to control the impact of new edification areas on the existent watercourse has brought to the following conclusions:

- A further development of presented framework to become a practical tool supporting communication and decision making amongst the parties involved in urban planning. Moreover, it shall be amended in order to provide more flexibility for tuning the model components to represent the features of specific application areas and for integrating new model components to represent other application specific processes.
- The developed framework will be integrated and applied also to water distribution system infrastructures.
- Such strategy applied to different planning assumptions may suggest effective mitigation options for sustainable land use planners to reduce the impact of new developments and thus achieve a better water environment.
- It is guessed that such methodology becomes a standard in planning new sustainable settlements both with respect to the environment than to existing infrastructures.

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