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Development of an integrated framework for assessing the impact of urban planning on water quality

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Abstract: Recently, environmental concerns have gained increasing attention in the urban planning process. This paper aims to address the effects of urban planning on the surrounding water quality by developing an integrated modelling framework. This framework provides a conceptual and quantitative tool to quantify the impacts of urbanisation patterns on water systems, including urban drainage, wastewater treatment plant, and receiving rivers. The development of the framework (known as SSDIM), including individual components and their interactions, is described in this paper, and its functionality is demonstrated by a semi-hypothetical case study. The results show the effects of different planning strategies on receiving water quality, and also show that the framework is a flexible and useful tool for town planners and water specialists, to explore sustainable paths in the urban planning process.

Keywords: Impact assessment; Integrated modelling; Sewer system; Urban planning; Water quality

1. INTRODUCTION

Urban development has grown significantly both in the developing and developed countries in recent years in response to demographic changes and economic growth. For example, the UK government [2007] has recently pledged to build 3 million new homes by 2020, many of which will be in the already densely populated south-east. The development of housing and its associated infrastructure is one of the main driving factors for changes in land cover to urban land uses, which have long been recognised as a principal contributing factor to many environmental problems, including water pollution, air pollution, aquatic environmental deterioration, flooding and many others. Particularly, development of a new housing area can severely affect water flow and water quality of urban water systems in several aspects [Butler and Davies, 2004], including the increased pollutant loadings from intensified human activities and the runoff generated from impervious areas during rain events. These will impose increasing pressure on existing wastewater infrastructure, and increase the likelihood and risk of combined sewer overflows (CSO) in a combined sewer system.

These environmental impacts from urban land use changes have gained increasing attention in the urban planning process, along with many other concerns in the regional, political, social-economic and cultural aspects. Urban planning is a complex decision making process, and its overall effects are not always obvious, and might only be revealed with the aid of specific simulation models. Integrated assessment and modelling is a promising tool for providing good guidance in such complex realms [Jakeman and Letcher, 2003]. This paper describes the development of an integrated framework that provides a conceptual and quantitative tool to investigate qualitatively and, ultimately, quantify the short- and long-
term impacts of urban planning on ambient water quality. The functionality of this framework is demonstrated by a semi-hypothetical case study, in which the impacts of three planning scenarios are analysed and compared in terms of the river dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonium concentrations and river flow.

2. DEVELOPMENT OF THE FRAMEWORK

The framework acts 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.

The framework consists of four key subsystems, including land use, urban drainage/ sewer, wastewater treatment plant, and river systems. It was implemented in the SIMULINK® environment, which allows a system dynamics modelling of the different processes in various components and the interactions between them. Figure 1 shows the information-flow diagram of the framework, and each of the components is described below.

![Figure 1. The information flow diagram of the integrated framework (SSDIM).](image)

2.1 Land use change model

The land use change model represents the land planning process and is used to simulate the urban growth over a given planning horizon. This model is a cellular automata-based model, in which the development state of each cell is determined in terms of its own state and the states of its nearby neighbours at the previous time step, according to some transition rule. 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.

Table 1 shows the parameters used in the land use model. 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 is transformed and linked to the node-based sewer network in the spatial aggregation model according to the geographic information of the catchment and the topology of the newly designed/expanded network. The new network branch was defined a priori in this paper, and an automatic procedure for expanding automatically the network in the implementing process will be investigated at a later stage. For the sake of simplicity, a uniform square grid was used to represent land parcels.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of grids</td>
<td>The total number of grids for the new housing area</td>
</tr>
<tr>
<td>Grid resolution</td>
<td>The size of the grids used</td>
</tr>
<tr>
<td>The initial land use type</td>
<td>The land use types of each cell at the initial time</td>
</tr>
<tr>
<td>The existing houses</td>
<td>The number of houses of each cell at the initial time</td>
</tr>
<tr>
<td>Land use class</td>
<td>The land classes of each cell specifying the priority for development</td>
</tr>
<tr>
<td>The maximum housing density</td>
<td>The maximum number of houses per ha specified for each cell</td>
</tr>
<tr>
<td>The development pattern</td>
<td>The transition rules specified for the new development</td>
</tr>
<tr>
<td>Housing parameters</td>
<td>The house type, occupancy, and landtaken</td>
</tr>
</tbody>
</table>

Table 1. The land use model parameters.
2.2 Urban drainage and river models

These two components are used to simulate the various water quantity and quality processes in the river and sewer system, which expands to the new urbanised areas for wastewater discharges. The EPA Storm Water Management Model (SWMM) [Huber and Dickinson, 1998] was chosen because of its robustness and popularity.

Complex biochemical processes can occur while pollutants are transported in the sewer networks, which have a significant effect on the urban water system. A water quality model [Lijklema et al., 1996] was chosen here to model the river system, which mainly focuses on the oxygen balance in the river. The organic matter was modelled in two fractions, i.e., slowly and readily biodegradable. This has an advantage in modelling the effect of CSO discharges and treatment plant effluents that might contain very different organic matter in terms of biodegradability [Schütze, 1998]. This model also considered DO and ammonium.

2.3 Wastewater treatment plant component

This component is used to simulate the biological processes in the municipal activated sludge wastewater treatment plant, and is based on the Benchmark Simulation Model No. 1 [Copp, 2002]. 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 modelled as a non-reactive 10-layer process using a double exponential settling velocity model developed by Takács et al. [1991]. As shown in Figure 2, 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.

![Figure 2. Schematic representation of the benchmark plant.](image)

2.4 Model interactions

In this framework, the components of the framework were run at different time steps to allow for an accurate enough description of the processes involved. In general, the time step of land use change model was set to one year; the urban drainage and treatment plant models are simulated at a much smaller step (for example, 5 or 30 mins). The underlying assumption for the different time steps is that the urban wastewater system can be simulated for a rain events based period, within each annual time step for land use change model. This enables the effective representation of system dynamics arising from rain events. One of the important characteristics in a combined sewer system is the CSO discharges, which is generated when the inflow exceeds the maximum treatment plant influent. These discharges are directly discharged into receiving rivers, and could have a significant impact on river water quality.

System interactions also exist between the pollutants considered in the sewer system, treatment plant and river, and these are usually modelled using different pollutant variables. In the urban drainage system, 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. In the ASM1 model, there are 8 processes incorporating 13 different components, which are classified into soluble components and particulate components. In the river, the pollutants considered are readily and slowly biodegradable BOD, ammonium and DO. A factor-based conversion method is used here to convert different pollutants [Schütze, 1998].

Outcomes from urban drainage, wastewater treatment plant and river system will be used to provide urban planners with feedbacks with the view of identifying alternative and more sustainable development patterns. These feedbacks may include the occurrence of sewer flooding, treatment plant effluent compliance, and river water quality exceeding a predetermined threshold.

3. SET UP OF A CASE STUDY

The functionality of this framework is demonstrated by a semi-hypothetical case study, consisting of a real combined sewer system in UK, a hypothetical treatment plant and river system. The network has 346 manholes, 7 Weirs and 2 outfalls. The treatment plant influent is controlled by a weir, and the flow exceeding the maximum influent is directly discharged into the receiving river. The hypothetical treatment plant was adjusted according to the capacity of the sewer system. The river considered is about 40 km in length, and it was equally divided into 40 reaches for simulation. A constant upstream inflow with constant pollutant concentrations was assumed for this river in order to clearly illustrate the impact of a rainfall event with a 10-year return period. The CSO overflows are discharged into the river at Reach 2 and treatment plant effluent at Reach 8.

An area of 100 ha was identified for possible future residential development, and a grid cell size of 100 m × 100 m was used in the land use model for population distribution. Three planning scenarios assessed in this paper were defined below:

Scenario I (normal increase): the population increase by 10,000 in 20 years, and the maximum housing density is set to 40 households per ha.

Scenario II (low density increase): the population increase by 20,000 in 20 years, and the maximum housing density is set to 40 households per ha.

Scenario III (high density increase): the population increase by 20,000 in 20 years, and the maximum housing density is set to 60 households per ha.

In the three scenarios, the population increase was assumed to be equally distributed over each year, for instance, in the base case scenario, 10,000/20 = 500 persons are distributed to the new development each year. These urban planning scenarios were evaluated in terms of a set of water quality indicators including the DO, BOD5 and ammonium concentrations at Reach 11, i.e., 3 km downstream of the treatment plant effluent and 9 km downstream of the CSO discharges in the receiving river. Reach 11 was chosen because it is the most critical location in terms of the chosen water quality indicators.

4. RESULTS AND DISCUSSION

4.1 The impact of Scenario I

Figure 3 shows the effects of the base case scenario on river water quality for three selected years, i.e., Years 1, 10 and 20. The river water quality in terms of DO, BOD5, and ammonium has deteriorated continuously with the population increase in the new development, while the river water flow increases steadily over time. The increased river 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 in the receiving water quality.
4.2 Comparison of the scenarios

Figure 4 shows the comparative results of the three scenarios at the end of the planning period, i.e., Year 20. Compared with the base case scenario, it is clearly shown that the river 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 receiving water quality. However, increasing the housing density has a positive impact on river 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.
5. CONCLUSIONS

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. The impact of urban planning on the surrounding environment is not always obvious and difficult to assess, particularly for the long term impact, and it usually needs specific computer simulation models to support in the process.

In this paper, an integrated modelling framework was developed to assess the effects of alternative urbanisation patterns on the surrounding water quality. This framework provides a conceptual and quantitative tool to quantify the impacts of urban land use changes on urban water systems, including urban drainage, wastewater treatment plant, and receiving rivers. To demonstrate the functionality of this framework, a semi-hypothetical case study was set up and three planning scenarios were evaluated for a new housing area. The comparative results show that the population growth rate has obvious effects on receiving water quality. However, these effects can be reduced to some extent when the housing density is raised to a higher level. 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.

ACKNOWLEDGEMENTS

The study is partly funded by UK EPSRC grant no GR/S86846/01 and is also part of the Integrative Systems and the Boundary Problem (ISBP) project (www.tigress.ac/isbp), supported by the European Union’s Framework 6 Programme New and Emerging Science and Technology Pathfinder initiative.

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