Environmental Modelling & Software 48 (2013) 27–36

Contents lists available at SciVerse ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Development and application of an integrated ecological modelling framework to analyze the impact of wastewater discharges on the ecological water quality of rivers

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ARTICLE INFO

Article history:
Received 28 September 2012
Received in revised form
27 May 2013
Accepted 16 June 2013
Available online 6 July 2013

Keywords:
Integrated ecological modelling
Habitat suitability models
MIKE 11
Multi-model inference
Information-theoretic approach

ABSTRACT

Modelling is an effective tool to investigate the ecological state of water resources. In developing countries, the impact of sanitation infrastructures (e.g. wastewater treatment plants) is typically assessed considering the achievement of legal physicochemical quality standards, but ignoring the ecological water quality (EWQ) of the receiving river. In this paper, we developed a generic integrated ecological modelling framework quantifying the impact of wastewater discharges on the EWQ of the Cauca river (Colombia). The framework is flexible enough to be used in conjunction with different approaches/models and integrates a hydraulic and physicochemical water quality model with aquatic ecological models. Two types of ecological models were developed, habitat suitability models for selected macroinvertebrate groups and ecological assessment models based on a macroinvertebrate biotic index. Four pollution control scenarios were tested. It was found that the foreseen investments in sanitation infrastructure will lead to modest improvements of the EWQ, with an increase lower than six units of the ecological index BMWP-Colombia. Advanced investments, such as the collection and treatment of all wastewater produced by the cities of Cali, Yumbo and Palmira and upgrading of the treatment systems should be considered to achieve a good EWQ. The results show that the integration of ecological models in hydraulic and physicochemical water quality models (e.g. MIKE 11) has an added value for decision support in river management and water policy. The integration of models is a key aspect for the success in environmental decision making. The main limitation of this approach is the availability of physicochemical, hydraulic and biological data that are collected simultaneously. Therefore, a change in the river monitoring strategy towards collection of data which include simultaneous measurements of these variables is required.

1. Introduction

The traditional management of sanitation infrastructure of urban wastewater systems aims at fulfilling the legal physicochemical quality standards, usually without taking into account the ecological state of the receiving waters. European legislation (Water Framework Directive (WFD), 2000/60/CE) changed the conventional practice by introducing the integrated approach in river management, considering the concept of ecological status. This status is specified in terms of the quality of the structure and functioning of aquatic ecosystems, considering ecological, hydromorphological and physicochemical quality elements. Moreover, the WFD promotes a combined water management of the legal emission limit values and the recipient quality standards and encourages the use of decision support tools such as water quality models. In the United States the importance of ecological assessments of receiving waters is postulated in the Clean Water Act of 1972 (CWA) and the Water Quality Act of 1987 (USEPA, 2011). During the last two decades, it has been emphasized that biomonitoring of surface waters is a complement tool for water quality assessment (USEPA, 2011). In developing countries, such as Colombia, a prioritization of investments in sanitation infrastructure is necessary due to the limitation of available financial resources and the increasing deterioration of the water quality.

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http://dx.doi.org/10.1016/j.envsoft.2013.06.004

Therefore, in these countries, the development and application of integrated ecological modelling tools to support river management and water policy are necessary.

During the last decade, the integration of hydro-morphological, physicochemical and ecological models for decision support in river management started gaining interest (Mouton et al., 2009; Vaughan et al., 2009; Hughes and Louw, 2010; Boets et al., 2013). From an ecological point of view, benthic macroinvertebrates have been chosen as ecological indicators because they are expected to respond to both physicochemical and hydro-morphological pressures, and can act as a link between primary producers and higher organisms (De Pauw and Hawkes, 1993; De Pauw et al., 2006). Recently, researchers emphasized on the integration of hydraulic/hydrodynamic models with habitat suitability index (HSI) curves for macroinvertebrates (e.g. Bockelmann et al., 2004; Tomsic et al., 2007). This HSI approach considers hydro-morphological pressures (e.g. changes in water depth, water velocity, type of substrate), but omits the impact of physicochemical pressures (i.e. physicochemical pollution). More recently, Mouton et al. (2009) considered the impact of these two types of pressures on the ecological river quality, with an application of the Water Framework Directive Explorer (WFD-Explorer) toolbox. The WFD-Explorer includes a one-dimensional hydraulic model linked to a mass balance module that allowed them to predict the ecological water quality (EWQ) based on ecological expert knowledge rules. However, this toolbox simplifies water quality processes as a retention factor. Moreover, it operates at the coarse river basin scale level; whereas the impact of physical habitat changes on river biology occurs at smaller scale levels, such as mesoscale or microscale level (Mouton et al., 2009). Additionally, its knowledge rules were developed based on empirical data of Dutch and Flemish lowland streams, therefore, the transferability of these rules to other ecoregions in the world is limited (Randin et al., 2006; Fitzpatrick et al., 2007).

Considering the limitations of the HSI and WFD-Explorer approaches, there is a need for an integrated approach that allows us to assess simultaneously the impact of hydro-morphological pressures and physicochemical pollution on the ecological river water quality. This approach should include a detailed physical habitat and water quality model linked to ecological models based on specific characteristics of the studied river. In this research, a generic integrated ecological modelling framework for decision support in river management was proposed (Fig. 1), tested and validated on a case study of a lowland river basin in Colombia (Cauca river). The framework integrates a river water quantity and quality model with two types of ecological models, habitat suitability and ecological assessment models. This integrative framework was used to assess the ecological benefit of investments in sanitation infrastructure in the Cauca river by considering four pollution control scenarios and coupling the water quality model (MIKE 11 model; DHI, 1999) with EWQ models.

The Environmental Authority in the Cauca Region (CVC) has been using a mathematical modelling approach since 1972 to support water management and to improve the water quality of the Cauca river. During the last decade (1997–2007), in the framework of the Cauca River Modelling Project (CRMP), the MIKE 11 model (DHI, 1999) was used to simulate the hydrodynamics and water quality of the river (CVC and Univalle, 2007). This modelling approach allowed getting insight into the processes that occur in the river under dynamic conditions, such as temporary variations of flows and polluting loads. However, the EWQ of the receiving river should be incorporated in this assessment, in order to guarantee the preservation of habitats and species, stop degradation and restore water quality.

2. Materials and methods

2.1. Study area

The Cauca river is the second most important river in Colombia and the main hydrologic resource of southwest Colombia. The Cauca river's valley is especially important for the country's development and economy (CVC and Univalle, 2007). A significant part of the south-western manufacturing industry, the paper and sugar cane industry as well as part of the coffee producing zone are located along the river. The rapid urbanization and major economic development in the Cauca river's valley, has led to dramatic degradation of the environment. There is an increasing deterioration of the water quality of this river due to wastewater discharges from domestic and industrial activities. This study focuses on the river stretch from the station Paso de La Balsa (abscissa 27.4 km and elevation of 965 metres above sea level-m.a.s.l) to the station Anacaro (abscissa 416.5 km and 805 m.a.s.l) (Fig. 2) with a total length of 389.1 km. Multiple water quality problems can be found in this zone, especially in the dry season, downstream from the cities of Cali, Yumbo and Palmira (main industrial cities in the region). Under low flow conditions the Biological Oxygen Demand (BOD_5) and Faecal Coliforms can rise up to 7.5 mg/L and $2.4^* 10^8$ MPN/100 mL, respectively, whereas the Dissolved Oxygen (DO) concentration can drop near to 0 mg/L. The city of Cali, with more than two million inhabitants, is the main source of pollution as 60% of all wastewater does not receive any type of treatment and is directly discharged into the Cauca river (CVC and Univalle, 2007).

2.2. Data collection and dataset pre-processing

The dataset used in this research corresponds to the information collected in a 10 year period (1996–2005) by the CVC and the CRMP Project in the Cauca river (CVC and Univalle, 2007). Two types of datasets were used, the first one for the implementation of the MIKE 11 model and the second one for building the ecological models. Two monitoring campaigns with calibration and verification purposes for the MIKE 11 model were carried out during the years 2003 and 2005 considering hourly measurements during low and high flow conditions.

For the ecological models, a dataset was developed which included simultaneous measurements (based on sampling location and time) of physicochemical data, hydraulic data and biological information. The biological information

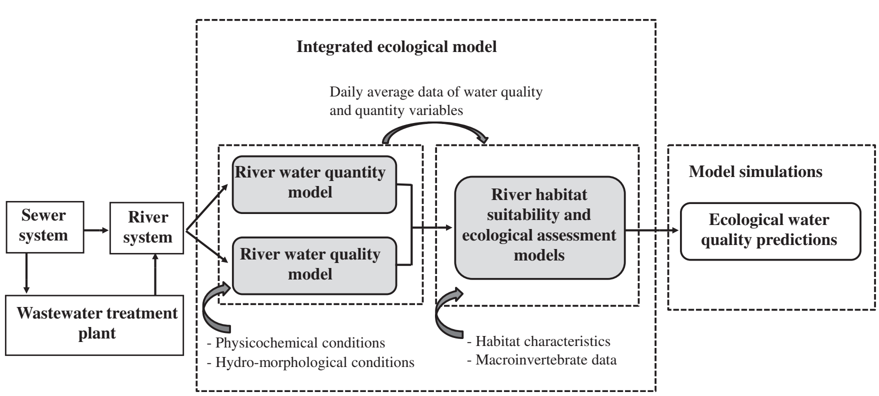

Fig. 1. Overview of the proposed integrated ecological modelling framework for decision support in river management. The three basic components of the framework are found in grey boxes.