Integrated ecological modelling for decision support in the integrated urban water system modelling of the Drava river (Varazdin, Croatia)

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Abstract: Legal physical-chemical emission limits are traditionally used for assessing the effectiveness of urban sanitation infrastructure. However, the receiving water's ecological aspects are disregarded with this conventional approach. European legislation (i.e. Water Framework Directive-WFD) now has an integrated approach of river management, which considers the concept of ecological status. Furthermore, the WFD urges the adoption of a combined analysis of emission limits values and physical-chemical and ecological aspects of the receiving waters and encourage the availability and use of decision support tools for water management such as simulation models. Croatia has signed agreements to join the European Union (EU) and thus taken up the obligation to coordinate its legislation with EU standards, such as the implementation of the WFD for its investments in the construction and upgrading of WWTPs. Thus, Croatia needs a simulation tool that allows assessing the impact of WWTPs discharges on the water quality of rivers, considering physical–chemical and ecological aspects. During the last decade the water quality of the Drava river in Croatia has been affected by an increased demand of electricity production and its misuse as receiving aquatic ecosystem of controlled and uncontrolled discharges of wastes from agricultural, urban or industrial activities. This paper presents an integration of wastewater treatment, river water quality and quantity and ecological assessment models to study the effect of upgrading a WWTP in the city of Varazdin and its ecological effects for the receiving river, the Drava river. The paper explains the integrated modelling framework and provides some illustrations of its application. Three scenarios for pollution control in the study area were evaluated with the integrated model. The scenario assessment showed that the upgrading of the WWTP, with Nitrogen and Phosphorous removal, is not enough to reach good ecological water quality in this river, therefore, other point and diffuse pollution sources should be controlled in the area. The integrated modelling framework is flexible enough to be used in conjunction with different approaches/models and can be applied to any river basin. More data should be collected and more variables should be included in an optimization of these models.

Keywords: Integrated ecological river modelling, decision support in river management

1   INTRODUCTION

Traditionally, the assessment of investments in sanitation infrastructure of urban wastewater systems has been done considering the fulfilling of legal physical chemical emission limits, but omitting the ecological state of the receiving waters (Devesa et al., 2009). However, during the last decade, the European legislation (Water Framework Directive, WFD, 2000/60/CE) changed the conventional practice by introducing the integrated approach in the river management, considering the concept of ecological status. The ecological status is defined in terms of the quality of the biological community and the hydro-morphological and physical–chemical characteristics. The WFD focuses on the impacts of pressures on river biota which in turn could be used to assess river quality. The WFD requires that all European member states assess all their surface waters based on a number of biological elements, including macroinvertebrates. Furthermore, the WFD promotes a combined approach of the emission limits values and the recipient quality standards and encourage the availability and use of decision support tools for water management (Devesa et al., 2009). Holguin et al. (2010) and Pauwels et al. (2010) previously have shown that there is high potential of integrating water quality and ecological assessment models to evaluate the potential impacts of the foreseen water quality management plans.

During the last decade Croatia has invested into the construction of sewage systems and municipal wastewater treatment plants (WWTPs), according to the circumstances of post-war and transition processes its economy has been undergoing. Significant investments in the construction of new WWTPs and in the upgrading of existing WWTPs (secondary and tertiary treatment) are planned in the coming years. Croatia has signed agreements to join the European Union (EU) and thus taken up the obligation to coordinate its legislation with EU standards. For the welfare of its citizens and future generations, but also for tourism and food production, the most important economical activities, Croatia needs to achieve, at least the same level of quality for rivers, sea water and the same standard of urban sewerage infrastructure as those in the EU. The major environmental concerns in Croatia related to water is the insufficient level of treatment of municipal and industrial wastewater. Meeting the criteria for utility infrastructure quality in cities and communities is, at the same time, one of the prerequisites for admission to the EU. This especially refers to infrastructures used for environmental protection such as collection and treatment of wastewater. Thus, Croatia needs a decision support tool that allows assessing and simulate the impact of WWTPs discharges on the water quality of rivers, considering physical–chemical and ecological aspects.

In 2010, Croatia and Belgium (the Flemish region) developed a cooperation project called Water Treatment Optimization with Ecological Criteria (WATROPEC), in the north-east part of Croatia. In this project we included a wide perspective for the assessment of investments in sanitation infrastructure, considering physical–chemical and ecological characteristics of the receiving aquatic ecosystem (as requested by the WFD). This paper presents the application of an integrated ecological modelling framework, developed for an urban water system constituted by the WWTP of the city of Varzdin and the Drava river. The integrated framework allows assessing the effect of upgrading the existing WWTP and its impact on the receiving river, considering physical–chemical and ecological water quality. The modelling framework has four sub-models: WWTP, river water quantity and quality and, ecological assessment models. The WWTP and the river water quantity and quality were modeled with the WEST software (www.mikebydhi.com) (Vanhooren et al., 2003). WEST is a modelling and simulation platform for different processes such as wastewater, rivers, fermentation, etc. (see e.g. Benedetti et al. (2007) for WWTP and river models integration). For the ecological assessment models, the approach followed was to use classification trees (Breiman et al., 1984). Using the integrated ecological river assessment modelling framework, three scenarios for pollution control were run and evaluated. Furthermore, the computer simulations also allow the optimization of the WWTP itself, eventually resulting in power savings and increased performance efficiency.

2 MATERIALS AND METHODS

2.1 Data collection

2.1.1 *Study area and data collection*

The Drava river rises in Italy at an altitude of 1192 m.a.s.l., and flows about 730 km through Austria, Slovenia, Croatia and Hungary. This study focuses on the Drava river stretch located in the north-east part of Croatia, in the Varazdin county (Fig 1.) The system consists of two lakes (Cakovec and Dubrava) each one connected by both a channel build to divert water for the hydroelectric power plant (drainage channels) and the river after a dam (Fig. 1). Additionally, there are four small perimetrical channels along these lakes which collect the filtered water which is not retained by the impermeable walls of these reservoirs. The dams make possible to regulate the proportion of flow in the channel and river. In addition to electricity production, the system of dams ensures flood control, provision of irrigation water and maintenance of a minimum instream flow at the Drava river.
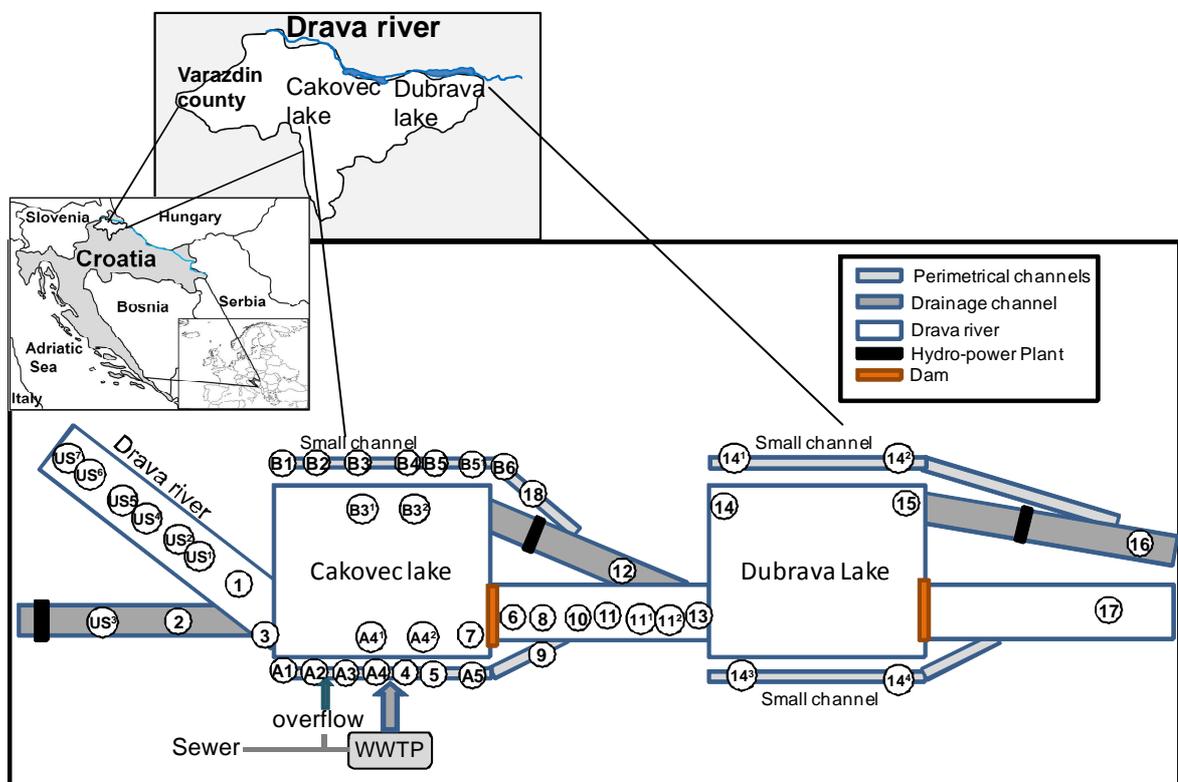

Figure 1 Location of the Drava river in the Varazdin County in Croatia and sketch of the studied system with the sampling sites

Three physical-chemical and biological monitoring campaigns were made during the months of April and October of 2010 (by the WATROPEC project) and September of 2011 (by the authors), in a total of 60 sampling locations in the Drava river. The sampling campaigns performed at this river were needed to collect information regarding the hydraulic and chemical conditions, physical habitats as well as macroinvertebrates communities. The information collected allowed the calibration and verification of the river water quantity and quality models, with two different datasets (two campaigns in 2010). Additionally, the biological monitoring allowed the calculation of the Multimetric Macroinvertebrate Index Flanders (MMIF, Gabriels et al., 2010) which assesses the ecological water quality as: bad (0-0.3), poor (0.3-0.5), moderate (0.5-0.7), good (0.7-0.9) and high (0.9-1.0). For the WWTP, average historical data (October of 2009) reported for the WWTP influent and effluent was collected.

2.1.2 *Coupling of data and data-set pre-processing*

The unprocessed database encompassed 106 records of 13 predictor variables (physical-chemical parameters measured) and one response variable reported for the 60 sampling locations (MMIF index). In order to enable the coupling of the ecological assessment model with the water quality model, a database was built including only six water quality variables modelled by WEST (i.e. dissolved oxygen-DO, Chemical Oxygen Demand-COD, Biological Oxygen Demand-BOD$_5$, Nitrate, Phosphate and Ammonium) and the biological information. These variables were selected considering that the integrated ecological modelling framework will be used to evaluate the effect of upgrading the WWTP to tertiary treatment (which implicates carbon and nutrient removal). Concerning the data-set pre-processing for the ecological model, we applied a data exploration focusing on 3 aspects: (1) removal of outliers, (2) evaluation of the collinearity and (3) relationships between the response variable (i.e. MMIF index) and the explanatory variables (i.e. physical-chemical variables). The sampling stations at the Drava river have mainly bad, poor and moderate ecological quality, only few have a good quality. Therefore, a coupled dataset was stratified to a dataset with about 7 MMIF values of each quality class. This yielded a dataset with 28 records (MMIF value and corresponding values for the predicting abiotic variables).

2.2   Model building, validation and implementation

The implemented integrated ecological river assessment (IERA) modelling framework has four basic sub-models (Fig. 2): first, a WWTP model; second, a river water quantity model; third, a river water quality model and; fourth, an ecological assessment model based on macroinvertebrates. The first, second and third sub-models were implemented in WEST platform. For the fourth sub-model, a classification tree (CT) for the prediction of the MMIF index was considered.
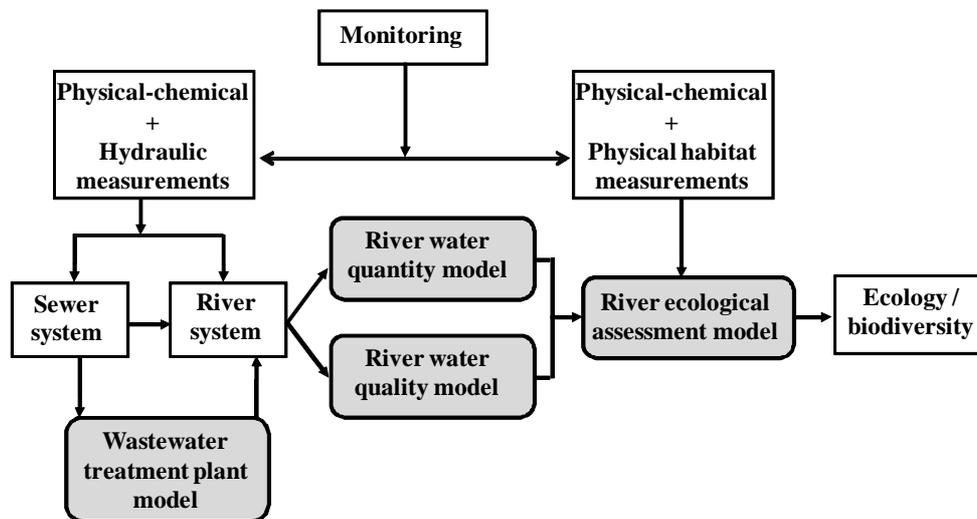

Figure 2 Overview of the integrated ecological river assessment (IERA) modelling framework. The four basic components of the framework are found in grey boxes.

Once the IERA model is implemented with the four sub-models, it can be used to simulate scenarios of the upgrading of the WWTP considering ecological criteria of the receiving river. The CT model developed can be used to make predictions about the dependant variable (i.e. MMIF index) based on other independent values (i.e. physical-chemical variables) than the values that were used to build the model. Therefore, the simulation results of physical-chemical variables of the river model in the scenarios were used as input variables for the CT to estimate the MMIF index at each sampling site. Daily average data of these input variables, in all sampling points of the system modelled, were considered as input for the CT in the scenarios.

2.2.1 *WWTP model and river water quantity and quality model*

The WWTP was modelled using an adaptation of the Activated Sludge Model No. 2d (ASM2d, Henze et al., 2000), to allow different decay rates under different environmental conditions (Gernaey and Jørgensen, 2004). In the second and third sub-models, water quality processes were modelled with the River Water Quality Model No.1 (RWQM1, Reichert et al., 2001) and hydraulics by following a 'tanks in series' approach (Benedetti et al., 2007). Details about the implementation of the WEST platform in the Drava river are described by VARKOM et al. (2010).

2.2.2 *Ecological river assessment model*

For the fourth sub-model of the integrated modelling framework, a machine learning technique called classification tree (CT, Breiman et al., 1984) was implemented. In CT the construction and the structure of the model allows the user to understand how each input variable contributes to the structure of the tree and to identify associations and general trends in the data. By implementing independent physical-chemical input variables and following the hierarchical structure of the tree, these tests lead to the associated predicted MMIF class. The CT was built in the Waikato Environment for Knowledge Analysis (WEKA software) using the J48 algorithm, a re-implementation of the C4.5 algorithm (Hall et al., 2009). For the settings of the CT, a pruning confidence factor (PCF) of 0.25 and binary splits were applied. For the validation of the CT, we implemented a leave-one-out cross-validation procedure. This procedure is recommended in cases of small sample sizes (Pearson et al., 2007). With this procedure is possible to use all the information available during the model building. To assess model performances of the CT we evaluated two criteria: Cohen's kappa coefficient (K, Cohen, 1960) and the area under the receiver-operating-characteristic (ROC) curve called AUC. In order to reach a satisfactory model performance K should be at least 0.4 and AUC should be higher than 0.7 (Manel et al., 2001). Gabriels et al. (2007) suggest ranks of model performance for K values in a freshwater ecological context, whereas Hosmer & Lemeshow (2000) and Pearce & Ferrier (2000) suggest ranks for AUC that give an idea of the discrimination capacity of the model.

2.3   Simulation of restoration options

A total of three scenarios generated by simulations with WEST were evaluated. These scenarios were: 1) current situation, 2) upgrading of WWTP with Nitrogen (N) and Phosphorous (P) removal and; 3) upstream treatment and upgrading of WWTP with N and P removal.

3   RESULTS AND DISCUSSION

3.1   Ecological model building, validation and implementation

The evaluation of the collinearity in the explanatory variables measured in the river showed that only COD and BOD_5 had moderate correlation (Pearson correlation=0.6). Thus, for the ecological model building we selected COD because it had higher correlation with the response variable (MMIF index). Our data exploration analysis showed that DO had the highest correlation with the MMIF (Pearson correlation=0.67).

In general, two approaches can be followed when performing (ecological) modelling: mechanistic and data-driven modelling. The first approach mathematically synthesizes available knowledge into a predictive framework, while the latter consists more of a data-driven process. Which approach will be preferable in a specific case depends on the aim of the research, the knowledge of the ecological processes and state variables in the system, the required properties

of the model and the data set available. The application of ecological mechanistic models (i.e. food-webs) has been mainly focused on lentic ecosystems (lakes, ponds, reservoirs and wetlands) and the prediction of phytoplankton, zooplankton, macrophytes and fish communities. However, examples of the application of mechanistic models for predicting macroinvertebrates in lotic ecosystems (rivers and streams) are rather limited and hardly described in literature. Data-driven modelling, including computational intelligence and machine-learning methods, are therefore more suitable for predicting macroinvertebrates (Goethals, 2005) and biological indices associated to them (Everaert et al, 2010). These methods can be used to build models for complementing or replacing physically based models (i.e. mechanistic models). Machine-learning methods, such as classification trees, are used to determine the relationship between a system's inputs and outputs using a training data set that is representative of all the behavior found in the system. Thus, CT allow having an ecological model in which direct relations between a set of predictor variables is calculated, without incorporating feedback loops.

The resulting CT shows that low COD concentrations ($\leq$12 mg/l) are essential to reach a good ecological quality (Fig. 3). Additionally, DO and Nitrate are the key parameters that determine bad, poor or moderate ecological quality. DO concentrations equal or lower than 4 mg/l cause a bad quality, whereas DO values higher than 4 mg/l and Nitrate concentrations equal or lower than 0.59 produce a moderate quality. Moreover, if Nitrate is higher than 0.59 there are two options, in the first one, DO values higher than 5.5 mg/l cause a poor quality, whereas in the second, DO values between 4 mg/l and 5.5 mg/l provoke a moderate quality. The CT is ecologically relevant. The first rule states that in order to assure good ecological quality, the concentration of COD should be equal or lower than 12 mg/l (Fig. 3). Chapman (1996) reported that COD values lower than 20 mg/ indicate surface waters with very low pollution levels. Additionally, the second rule states that in order to avoid bad ecological quality, the concentration of DO should be higher than 4 mg/l (Fig. 3). Concentrations below 5 mg/l may adversely affect the functioning and survival of biological communities and below 2 mg/l may lead to the death of most fish (Chapman, 1996). The CT developed was satisfactory, and showed a moderate predictive performance (K=0.52) and reasonable discrimination capacity (AUC=0.71).
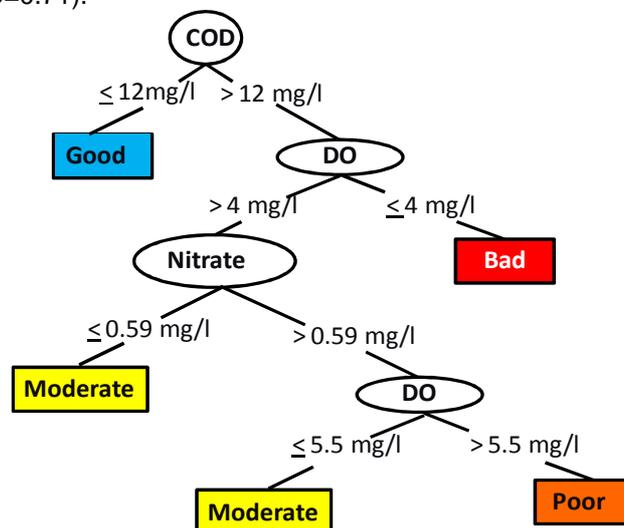

Figure 3 Classification tree for predicting the MMIF index. See the importance of the low COD concentrations ($\leq$ 12 mg/l) required for good ecological water quality

3.2 Analysis of the IERA modelling approach

In order to make predictions of the MMIF index in the scenarios with the IERA model, we used the simulation results of physical-chemical variables of the river model (i.e. WEST model) in the scenarios, as input variables for the CT. At each sampling location we run the CT with the daily average data generated by WEST

model and we predicted the MMIF value at each sampling site at each scenario. We consider that using daily average data is a valid approach, because aquatic macroinvertebrates have relatively long life cycles and are confined for most part of their life to one locality on the river bed, therefore, they act as continuous monitors of the water flowing over them and integrate environmental conditions over longer periods of time (weeks, months, years) (Goethals, 2005). De Pauw and Hawkes (1993) pointed out that the biotic component of an aquatic ecosystem can be considered as the 'memory' of the ecosystem, integrating a wide range of ecological effects over time, while chemical analyses only provide information on the chemical water composition at the moment of sampling.

3.3   Implementation of different restoration options

The implementation of different restoration options at the Drava river basin yielded three main results. First, there is a need for an integrated modelling approach that considers ecological aspects in the water management of this river. Such comprehensive evaluation would not be possible by looking at each individual component of the system separately. Second, any change in the WWTP effluent quality has an important effect only to the water quality in the small stream in which it is discharging and marginally in the first section of the Drava river after the junction with the small stream (Table 1 and Fig 1.). In all other sections of the river downstream the WWTP the effect of its effluent changes is practically negligible, due to the large dilution and long residence time effects. Third, in order to improve the ecological quality from bad to good in this small stream and the river (Table 1), it is necessary to upgrade the WWTP with N and P removal and the treatment of other point (e.g. the overflow of the WWTP, see Fig 1) and diffuse pollution sources (i.e. scenario 3). Additionally, if an increase in the minimum in-stream flow ('environmental water requirement') after the dams is considered, a higher dilution capacity and a higher self-cleaning capability could be obtained at the Drava river.

Table 1 Ecological water quality estimated for the simulations of the different scenarios

Section downstream of the WWTP discharge in the small channel (A5)			Section downstream of the WWTP discharge in the Drava river - Section 10		
		MMIF			**MMIF**
Scenario		**Class**	**Scenario**		**Class**
1	Current situation	Bad	1	Current situation	Bad
2	N and P removal	Poor	2	N and P removal	Poor
3	Upstream treatment + N and P removal	Good	3	Upstream treatment + N and P removal	Good

4   CONCLUSIONS AND RECOMMENDATIONS

In this case study we showed that the water quality management of the Drava river needs an integrated modelling approach that considers ecological aspects. Such comprehensive evaluation would not be possible by looking at each individual component of the system separately (i.e. sewer system, WWTP and receiving river). This integrated ecological river assessment (IERA) model can help to calculate the needed reductions in wastewater discharges of organic matter to meet biological quality criteria in this river. The scenario assessment showed that in order to reach good ecological water quality in this river, it is necessary an upgrading of the WWTP with Nitrogen and Phosphorous removal, together with the treatment of other point and diffuse pollution sources (including the overflow of the WWTP).

We recommend the use of this type of decision support tools for water management, because the assessment of the effectiveness of sanitation infrastructure, such as WWTPs, should include both, the fulfilling of legal physical-chemical emission limits and the ecological state of the receiving waters. Additionally, the IERA modelling framework is flexible enough to be used in conjunction with different approaches/models and can be applied to any river basin.

To improve the ecological models, more data should be collected, especially in surface waters characterized by a good ecological quality (i.e. to increase the stratified dataset) and more variables need to be monitored (in particular hydraulic and hydro-morphological characteristics). Additionally, by including new ecological models based on hydraulic and hydro-morphological characteristics, would be possible to simulate scenarios that consider simultaneously the impact of flow variations after the dams and the upgrading of the WWTP on the river ecosystem.

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