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Modelling the ecological impact of discharged urban waters upon receiving aquatic ecosystems. A tropical lowland river case study: city Cali and the Cauca river in Colombia

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Abstract: The Cauca river is one of most severe cases of pollution for domestic and industrial wastewater discharges in Colombia, principally when it crosses the industrial cities of Cali and Yumbo. The rapid urbanization and major economic development in the Cauca river´s geographical valley has led to dramatic degradation of the environment and increased health risks due to inefficient processing of the increased pollutant load effluents and solid wastes. The city of Cali which is the main urbanization center, with more than two million inhabitants and limitations of the treatment of its wastewaters, discharged in the year 2005, 75 tons of BOD_5 per day. These discharges of wastewater are producing an increasing deterioration of the water quality of the Cauca river. This pollution problem is critical after the river crosses the city of Cali, especially during dry season (low flows), when pollution can reach values of 7.5 mg/l of BOD_5 and concentrations of Dissolved Oxygen (DO) near to zero (0) mg/l. Low DO levels affect the ecosystem equilibrium and the functioning and survival of biological communities. For this reason, the main objective of this research was to contribute to the integrated water quality management of the Cauca river, developing a mathematical model to investigate the ecological quality of this river under actual conditions as well as after different restoration actions. The approach followed was to build habitat suitability models (statistical models) that allow predicting the presence and the abundance of macroinvertebrates in this river under different conditions. An integration of these ecological models with the hydrodynamic and physical-chemical water quality model MIKE11 was performed. The integrated ecological model allows to model and assess the ecological impact of wastewater discharges into the Cauca river and to calculate the needed reductions in discharges of organic matter to meet biological quality criteria in this river.

***Keywords**:* Integrated ecological modelling; habitat suitability models

1. INTRODUCTION

One of the worldwide problems that affect the quality of water resources, has been their use such as receiving aquatic ecosystems of controlled or uncontrolled discharges of wastes from agricultural, urban or industrial activities. These discharges can potentially affect human health and aquatic life, limit water uses, affect riverine ecology and cause loss of amenity. Furthermore, scarcity and misuse of fresh water pose a serious and growing threat to sustainable development and protection of the environment. These problems will intensify unless effective and concerted actions are taken. Challenges remain widespread and reflect severe problems in the management of water resources in many parts of the world. The optimal balance between the different stakeholder activities needs a very deep insight in the integrated water management. In this context, models can show the limitations of the self-cleaning capacity of water resources. Indeed, water quality modelling is an effective tool to investigate the ecological situation of surface water resources. Nevertheless, until now ecological models have rarely been used to support river management and water policy.

The biotic component of an aquatic ecosystem can be considered as an 'integrating-information-yielding unit' for assessment of its quality. Biological communities also integrate the effects of mixed types of stress and in certain cases already respond before analytical detection allows for, [De Pauw and Hawkes, 1993]. Among the biological communities, the macroinvertebrates are by far the most frequently used group for bioindication in standard water management, because they are ubiquitous and abundant throughout the whole river system and they play an essential role in the functioning of the river continuum food web, [Goethals, 2005; Giller and Malmqvist, 1998].

The Cauca river is one of most severe cases of contamination for domestic and industrial wastewater discharges in Colombia. The main urbanization center and source of pollution that affects this river is the city of Cali, with more than two million inhabitants and limitations of the treatment of its wastewaters. This city discharged during the year 2005 around 75 tons of BOD_5 per day, which is around 38% of the total of wastewater discharged load of BOD_5 per day in the Valle del Cauca department. The sewer system of Cali has limitations in the operation and only 40% of the total flow of the wastewaters generated by the city is treated by primary treatment. The rest of the wastewater generated by the city does not receive any type of treatment and it is discharged to the Cauca river. These discharges of wastewater are producing an increasing deterioration of the water quality of the Cauca river. This pollution problem is critical after the river crosses the city of Cali, especially during dry season (low flows), when pollution can reach values of 7.5 mg/l of BOD_5, concentrations of Dissolved Oxygen (DO) near to zero (0) mg/l, values of Faecal and Total Coliforms in the order of $2{,}4x10^8$ NMP/100ml and critical values for some heavy metals [CVC and Univalle, 2004a; EMCALI and Univalle, 2006].

The mathematical modelling approach has been used to support the generation of policy, plans and projects for the water quality improvement of the Cauca river and the control of wastewater discharges since 1972. During this process, limitations in the knowledge of software and also in the information required in terms of water quantity and quality have been faced. During the last decade (1997-2007) in the framework of the Cauca River Modelling Project (PMC), the water quality model software MIKE11 was used to simulate the hydrodynamic and water quality of the river. This modelling approach allowed a very deep insight of the processes that occur in the river under dynamic conditions, such as temporary variations of flows and polluting loads. However, this approach just considered physical-chemical parameters, therefore biological components of the aquatic ecosystem were not taken into account. For this reason, in order to have a robust, reliable and effective tool to support river management and water policy in the Cauca river, it is necessary to develop and to apply an ecological modelling approach that integrates the hydrodynamic and physical-chemical water quality model MIKE11, with an ecological water quality model developed for this river, which allows to investigate the ecological quality of the Cauca river under actual conditions as well as after different restoration actions.

2. MATERIALS AND METHODS

2.1 Study area

The Cauca river is the second most important river in Colombia and the main hydric resource of the Colombian southwest. The Cauca river geographical valley, situated in the high basin, is especially important for the country's development and economy. A significant part of the south-western manufacturing industry, the paper production industry, the sugar cane agricultural industry and part of the coffee zone are located in this area. This study focuses on the stretch of the Cauca river which is situated in the geographical valley, which extends from the station La Balsa until Anacaro (Figure 1) with a total length of 389 km. The most important water quality problems can be found in this zone, especially in the stretch close to the city of Cali.

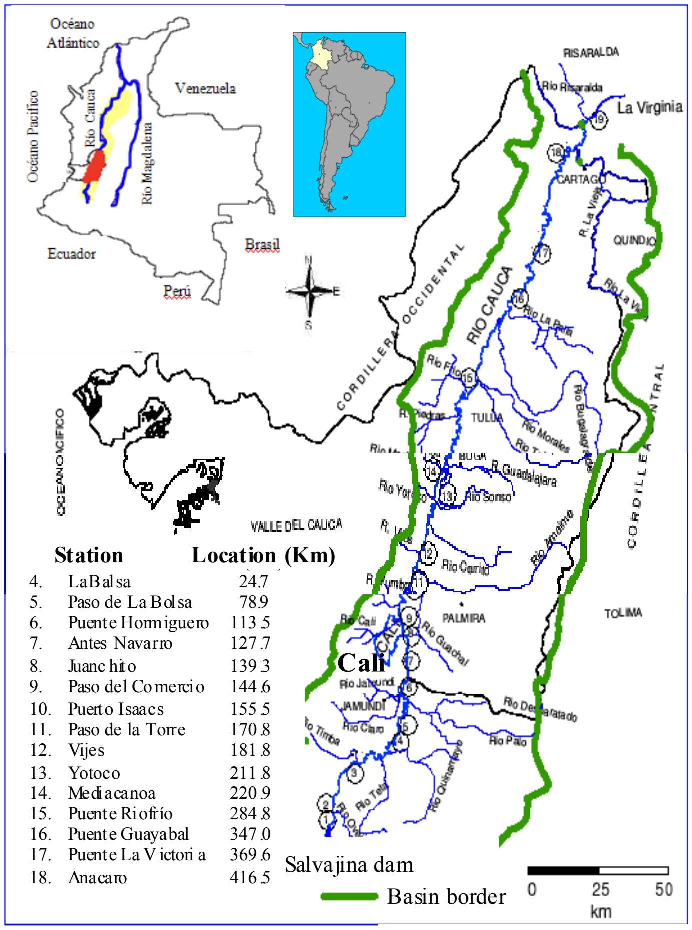

Figure 1. Drainage basin of the C Source: CVC and Univalle, 2007b

The Cauca river flows for 445 km in its geographical valley and descends from a height of 1000 meters (Salvagina dam) to 900 meters above sea level. This stretch of the river has an average width of 105 meters and it can fluctuate between 80 meters in the high part of its course (Salvajina dam– La Balsa) to 150 meters in the low part (Anacaro – La Virginia). The depth can vary between 3.5 and 8.0 m. The longitudinal profile of the river shows a concave shape with a hydraulic slope which oscillates between $7x10^{-4}$ m/m and $1.5x10^{-4}$ m/m [CVC and Univalle, 2007b].

2.2 Data and information collection to develop and validate models

The database used in this research corresponds to the information collected and analyzed during the years 1997-2007 by the environmental authority in the Cauca river´s geographical valley called CVC and the Cauca River Modeling Project (PMC), [CVC-Univalle, 2004b and CVC-Univalle, 2007a and 2007b]. The database used for the implementation of the ecological models for predicting macroinvertebrates in the Cauca river was selected considering the simultaneousness of biological, physical-chemical and hydraulic measurements in the sample stations. This information corresponds to the years 1997 (high flow conditions), 2001 and 2004 (low flow conditions).

Benthic macroinvertebrates were collected in the Cauca river considering the type of substrate: stone substrate, sand substrate, mud substrate, trunks and floating vegetation substrate. Samples were collected in the middle and at the borders of the transversal section. Thus all type of macroinvertebrate habitats were considered during the monitoring. After samples were collected in each zone and substrate, they were preserved, labelled and transported to CVC's environmental laboratory where finally an identification and classification of macroinvertebrates, mainly at the taxonomic level of genus (phylum, class, order, family and genus) was carried out [CVC-Univalle, 2004b]. Simultaneously with the biological monitoring, water samples were taken for the analysis of physical-chemical parameters. These water samples were preserved at 4°C and transported to the CVC's environmental laboratory for the analysis. The hydraulic information reported by the sample stations during the monitoring campaigns was mainly provided by CVC from hydrometric stations. When this information was not available interpolations with the hydrodynamic model (MIKE11) were performed.

2.3 Water quality modelling software used in the catchment of the Cauca river

Hydrodynamic and physical-chemical water quality models: In the framework of the Cauca River Modelling Project (PMC), a physical-chemical water quality and hydrodynamic model (MIKE11) was implemented for the Cauca river. This model was calibrated and verified for dynamic flow conditions and reproduces in acceptable form the values of DO, BOD_5, temperature, flow, depth and velocity in the monitoring stations of the Cauca river, considering hourly fluctuations. [CVC-Univalle, 2007a and 2007b]. The model is conformed by 62 cross sections, 2 external boundaries (La Balsa and La Virginia), 96 internal boundaries which include 27 rivers and streams, 9 municipal wastewater discharges, 12 industrial wastewater discharges and 37 water extraction sites. Each internal boundary was represented like a lateral extraction or discharge. Water quality modelling was carried out in Level 1 of MIKE11, which includes temperature, BOD_5, and DO as state variables. In the framework of the PMC project two monitoring campaigns with calibration and verification purposes for the water quality model were carried out during the months of August of 2003 and February of 2005. These campaigns had a duration of respectively five (5) and four (4) days, a monitoring period between 12 and 24 hours per day, with a measuring frequency between 30 and 60 minutes for field parameters (flow, DO, temperature, conductivity and pH) and between six (6) and eight (8) hours for laboratory parameters (BOD_5, COD, TSS).

***Ecological models for predicting macroinvertebrates in the Cauca river*:** When performing ecological modelling two approaches can be followed which are mechanistic and data driven modelling. In the case of the Cauca river the water quality model MIKE11 allows to calculate water quality variables such as temperature, BOD_5, and DO. However, there is a lack of information about processes associated with particulate organic matter and nutrients. This lack of information limits the use of ecological mechanistic models (i.e. food-webs) for the Cauca river, for that reason data driven models such as habitat suitability models (e.g. statistical models) for predicting macroinvertebrates were implemented in this research. These models can be used as a first approach for modelling composition of macroinvertebrate communities, and they can be useful for this more detailed type of calculations, where direct relations between a set of predictor variables (physical-chemical and hydraulic) and biological species are calculated, without incorporating feedback loops. The approach followed was to build statistical models called Generalized Linear Models (GLMs) (parametrical method, that provides users with a conventional mathematical function), which are mathematical extensions of linear models for non-linearity and non-constant variance structures in the data. GLMs are better suited for analyzing ecological relationships, which can be poorly represented by classical Gaussian distributions.

Logistic regression (i.e. GLM with logit link function and binomial error distribution) is the most frequently used modelling approach of the GLM techniques, for predicting the probability of species occurrence [Manel *et al.*, 2000; Pearce and Ferrier, 2000; Ahmadi-Nedushan, 2006], because a single record of presence or absence of the target species can be considered to be a binomial trial with a sample size of 1. This method has become a favourite tool in habitat modelling when the species information is given as presence/absence data, because this information is comparatively easy to collect in the field, even when the zero data set has to be created afterwards by a different sampling strategy. The model estimates the probability of a positive response occurring given a set of explanatory environmental variables (e.g. depth, velocity, DO, substrate, cover). Based on the presence-absence data, a response curve of a species describes the probability of the species being present, *p*, as a function of environmental variables. The response variable is transformed by the logit link function, which transforms bounded probabilities (between 0 and 1) to unbounded values [Ahmadi-Nedushan, 2006].

In order to select the best multiple logistic regression model (MLRM) for predicting the probability of macroinvertebrate species occurrence in the Cauca river the Akaike's information criterion (AIC) was used. Logistic models were fitted using the maximum likelihood method [McCullagh & Nelder, 1989] with backwards elimination to select the final predictor variables. The step function, implemented in the statistical software XLSTAT version 2009 used in this research provides a procedure for this purpose using the AIC; this is a penalized version of the likelihood function in which the best model is given by the lowest AIC value. Additionally, the Receiver Operating Characteristics-ROC curve was used to evaluate the performance of the MLRM by means of the area under the curve (AUC) and to compare several models together. The AUC, which ranges form zero (0) to one (1), corresponds to the probability such that a positive event has a higher probability given to it by the model than a negative event [Hosmer and Lemeshow, 2000].

For modelling abundance of macroinvertebrates (numbers of organisms) at new sites and/or future times at the Cauca river, quasi-Poisson regression (other modelling approach based on GLM techniques) was used. Often, data of organisms come in the form of counts, and in ecological modelling the idea is to relate these counts to environmental conditions. Count data in ecology are often ''overdispersed'' (i.e. for any data set or model the variance exceeds the mean) which is a limitation for Poisson regression. A common way to deal with overdispersion for counts is to use a GLM framework [McCullagh and Nelder, 1989], where the most common approach is the quasi-Poisson regression, because it is widely available in software and it generalizes easily to the regression case [Ver Hoef, and Boveng, 2007]. The regression constants in the QPRM models were estimated by means of the maximum quasi-likelihood method using the statistical software S-PLUS version 6.1. In order to select the explanatory variables in the QPRM, changes in goodness of fit statistics were used to evaluate the contribution of subsets of explanatory variables to a particular model. The deviance (i.e. how much variation is left), defined to be twice the difference between the maximum attainable log likelihood and the log likelihood of the model under consideration, was used as a measure of goodness of fit.

3. RESULTS AND DISCUSSION

Mathematical models are widely applied in science. The application of models in ecology is almost compulsory if we want to understand the function of such a complex system as an ecosystem [Jorgensen and Bendoricchio, 2001]. However, the knowledge of ecological processes in ecosystems and the information available for a very deep insight of these processes have been much less developed and accessible compared with other science fields such as hydrodynamic or hydro-morphologic and physical-chemical processes. This situation is occurring in the Cauca's river context, where the CVC has many hydrometric stations with hourly database, a few automated measurement stations for continuous water quality monitoring and historical information mainly based on discrete monitoring campaigns, with time intervals of months, however biological information for river quality assessment has been hardly recollected during few years. Therefore, the development of mathematical models for predicting biological communities (the aim of this research) together with the study of biological indicator species are complementary tools for river quality assessment and contribute to the integrated water quality management of this river.

Taken into consideration the aim of this research, which is to build predict models for macroinvertebrates communities present in this river under different conditions by means of an integration with the MIKE11 model, the ecological statistical models proposed in this research included during its calculation a data set of explanatory variables which could be calculated using the model MIKE11 (i.e. temperature, BOD_5, DO, flow, depth and velocity). An important consideration for all types of models is which and how many explanatory variables should be included in the model. If there are too few variables, the model will not be able to explain much of the variation. On the other hand, if there are too many variables, then the model will be too specific for the current data set [NIVA, 2007].

A total of three (3) macroinvertebrate predictive models at the taxonomic level of Order, were selected for constructing the ecological models. Ephemeroptera and Trichoptera Orders (pollution sensitive benthos, which belongs to Phylum Arthropoda and Class Insect) as biological indicators for good water quality conditions and Haplotaxida Order (pollution tolerant benthos, which belongs to Phylum Annelida and Class Oligochaeta) as biological indicator for polluted water with high organic matter content. At this taxonomic level these models could be considered too coarse in their predictive ability, however, considering the limitations regarding the database and the financial resources available for biological assessment at the CVC, these models can be thought as a first approach for ecological modelling at the Cauca river, that can be improved afterwards with more detailed data.

The results of the ecological modelling showed that the best MLRM for Ephemeroptera included DO, flow and depth as environmental predictor variables, the best MLRM for Trichoptera included the variables BOD_5, velocity, flow and depth and the best MLRM for Haplotaxida included BOD_5 and velocity as predictor variables. The assessment of the MLRMs reliability showed that the models for Ephemeroptera (AUC=1), Trichoptera (AUC=1), and Haplotaxida (AUC=0.926) correctly discriminates between occupied (presence) and unoccupied (absence) sites in the dataset. On the other hand, the best QPRM for Ephemeroptera included DO, velocity, flow and temperature as environmental predictor variables, the best QPRM for Trichoptera included the variables DO, depth, flow and temperature and the best QPRM for Haplotaxida included DO, depth and flow as predictor variables. Regarding the predictive validation procedure for QPRMs, it was found that in general the models reproduce with good precision the tendencies and the maximum and minimum values of the abundance data for each macroinvertebrate (i.e. Ephemeroptera, Trichoptera and Haplotaxida) with high coefficient of determination (R^2) values ($0.866 < R^2 < 0.998$). An example of the results obtained for the QPRM considering the complete database can be seen in the Figure 2. The same kind of models and graphs were developed for the database divided according to high flow and low flow conditions.

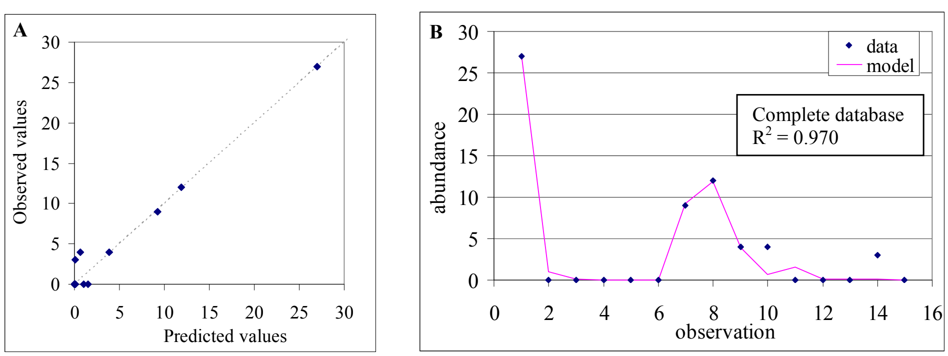

Figure 2. Results of the QPRM for predicting abundance of Ephemeroptera in the Cauca river

The results obtained in this research showed that flow velocity was the variable most important in four (4) of the six (6) ecological models developed in this research, followed by the depth in two (2) models and DO in one (1) model. Additionally, in five (5) of the six (6) predictive models the DO and the BOD_5 as indicators of organic pollution, were the first or the second most important variables. These results are in accordance with the literature, which reports that other factors than water quality are also important determinants of benthic communities. Of these the related factors of current velocity and nature of the substratum are overriding ones determining the nature of the community, especially in relation to invertebrates [Goethals, 2005]. Since these factors differ along the river in different zones, different communities become established at different sites with the same water quality [Giller and Malmqvist, 1998].

Using the model MIKE11 implemented in the framework of the PMC Project, and the ecological models developed in this research for predicting the (likelihood of) occurrence and the abundance of macroinvertebrates in the Cauca river, some applications were carried out that allowed to study the effects in the water quality of the river generated by the plans and actions for the pollution control proposed by the environmental authorities, the municipalities and the industries in the Cauca river´s geographical valley. The scenarios considered were: reference situation scenario (year 2005); very optimist scenario (year 2015), very pessimistic scenario (year 2015); and the scenario of water quality objectives proposed by the environmental authority (CVC) (year 2015). Profiles of average concentrations of DO, BOD_5, temperature and flow at the Cauca river, were made for each scenario considering the results obtained with the physicochemical and hydrodynamic model MIKE11. In general, those scenarios showed that in spite of the reduction of the total organic matter load discharged into the Cauca river's basin considered (even in the very optimist scenario), the DO concentrations in the station Paso de La Torre (the most critical zone in terms of pollution, just after the city of Cali) never reach values higher than 2.6 mg/l. Additionally, these DO values are still lower than the minimum standard value established by the Colombian Decree 1594/84 for different uses of the water resource, which means, smaller than 70% of the DO saturation concentration (5.2 mg/l for this river).

The application of the integrated ecological modelling of the Cauca river showed that the MLRMs and QPRMs predicted well the ecological impact of the scenarios for pollution control in the Cauca river's basin. Thus, in the scenario with the highest pollution reduction an improvement of the water quality of the Cauca river is achieved, which is represented with the presence and/or an increase of the number of pollution sensitive benthos (i.e. Ephemeroptera and Trichoptera) and the absence and/or a decrease of the number of pollution tolerant benthos (i.e. Haplotaxida). On the other hand, if the worst pollution condition scenario is considered a deterioration of the water quality is obtained, which is represented with the absence and/or a decrease of the number of pollution sensitive benthos and the presence and/or an increase of the number of pollution tolerant benthos. Finally, if the scenario of water quality objectives proposed by the CVC is considered, which is an intermediate scenario in terms of pollution reduction, a water quality improvement is achieved in some stations, but there are other stations that still show water quality deterioration (between Puente Hormiguero and Juanchito). This indicates that the pollution reduction proposed by the CVC in this scenario is not enough for increasing significantly the number of pollution sensitive benthos or for decreasing the number of pollution tolerant benthos, and therefore a good biological water quality is not reached in this river.

4. CONCLUSIONS AND RECOMMENDATIONS

The statistical models proposed in this research, allow predicting the occurrence and the abundance of macroinvertebrates for the Cauca river under different hydraulic and physical-chemical water quality conditions. This research demonstrated the high potential of the integration of hydrodynamic and physical-chemical water quality models with ecological models, in helping to get insight in aquatic ecosystems, for finding what is necessary to improve in the integrated water management and policy development. The integrated ecological model proposed in this research is a powerful operational tool, which allows to model and to assess the ecological impact of wastewater discharges into the Cauca river and can help to calculate the needed reductions in wastewater discharges of organic matter to meet biological quality criteria in this river.

Today river quality assessment is mainly based on discrete monitoring campaigns, with time intervals of several hours, weeks, months or even years. For the study of highly dynamical processes such sampling schemes are often insufficient to make a reliable assessment of the river status. In those cases, the application of automated measurement stations for continuous water quality monitoring together with the study of biological indicator species are complementary tools for river quality assessment. Having relatively long life cycles and being confined for most part of their life to one locality on the river bed, aquatic macroinvertebrates act as continuous monitors, integrating water quality over a longer period of time (weeks, months, years). Biological indicator species are unique environmental indicators as they offer a signal of the biological condition in a watershed.

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