Application Of A Decision Support System For The Sustainable Planning Of Rio Pojuca Basin (Bahia, Brazil) Water Resources

V. Torretta[1], M.Raboni[1] and G.Urbini[1]
[1]Dipartimento di Scienza e Alta Tecnologia – Università dell'Insubria, Varese, 21100, Italy.
massimo.raboni@uninsubria.it

Abstract
The paper presents the structure and the application of a Decision Support System (DSS) to Pojuca River watershed placed in the Northeast Region of Brazil (Bahia State).
It is composed of surface-water quality models (total phosphorus, BOD, dissolved oxygen concentration and thermo-tolerant coliform bacteria pollution). A model evaluates the riverine microhabitat applying autochthonous fish species habitat suitability indexes (water depth, velocity, substrate and dissolved oxygen) valuated by local ichthyologists. Surface-water quality and microhabitat models are based on a hydrologic and hydraulic model. Models have been calibrated and validated using discharge and water quality measurements collected during a 1.5-year period of monitoring. Output data are available on a spreadsheet and ready to be spatially analyzed in a GIS software.
We show how DSS can help the decision-making process to achieve the sustainable development of the basin, considering population growth, economic activities, climate change, management of sewage and wastewater treatment systems. The DSS is also applied to a challenging scenario: the building of an in series reservoir for supplying the Capital (Salvador) of drinking water.
The experience has been characterized also by a large involvement of local specialists, with the aim to emphasize the existing qualifications and to consider local culture.

Keywords Decision Support System, DSS, habitat suitability index, modelling, river basin management plan, water quality.

Introduction

Governance of river basins requires complex decision making regarding regulation, population distribution, land use and resources availability. The territorial planning systems allow designing interventions able to mitigate the effects of human activity on the environment.
Decision makers need to balance the needs of various actors, such as industry and the public; they must (a) have a multi-hazard approach, (b) take into account the spatial dimension of the problem and (c) know the vulnerability of the considered territory. Therefore, they must have appropriate decision support tools that facilitate the required integration of information.
In general terms a DSS is a specific class of computerized information systems which assist people in making decisions based on data that are gathered from a wide range of sources. DSS applications are not single information resources, such as a database, a model or a program that graphically represents results and figures, but the combination of integrated resources working together. The structure and the design of a DSS can vary according to skill and aptitude of the decision-makers and the needs of the decision-making process (Di Mauro and Nordvik, 2010).
Many DSS tools have been developed in recent years for river basin management (Lautenbach *et al.*, 2009) but problems still remain; in particular they are complex to use by non-experienced people, such as the most part of stakeholders. For the authors this is a gap for the complete involvement of stakeholders into the decision-making process. Moreover, DSS tools need to be as flexible as possible in order to verify stakeholders' suggestions.
Pojuca River is about 200 km long and flows from West to East through the region of Reconcavo Norte, State of Bahia, Brazil; it flows into the Atlantic Ocean near the well known tourist resort of Praia Do Forte. The basin (area: 4,771 km²) is subjected to wide urban and economic growth: the population density in 2010 is about 272 inh/km^2 (Collivignarelli *et al.*, 2012). During the last decade a significant and sprawl increase of industrial activities in parallel with traditional

agricultural practices has been occurred along Pojuca River; meanwhile eco-sustainable tourism is developing along the oceanic shore near estuary, which is also a protected sea turtles egg-laying site (DASS-UFBA, 2008).

In the last few years the first effects of water course pollution appeared with some negative consequences on turtles community; moreover, a project to build an in-series reservoir ("Itapecirica Lake") near river mouth in order to supply Salvador da Bahia Metropolitan Area, capital city of Bahia State, with drinking water exists (DASS-UFBA, 2008).

In 2006 a two-year Italo-Brazilian International cooperation project with the purpose to realize a sustainable River Basin Management Plan (RBMP) of Pojuca started. It was aimed at protecting the surface-water quality and riverine ecosystem without compromising social and economic growth of the whole basin.

In order to choose the best RBMP guidelines, different scenarios of the social and economic basin development (the so-called "Pressures", according to OECD Pressure-State-Response framework already used in Bahia State; *CRA*, 2002) have been necessary to foresee.

The paper presents the main characteristics and some possible applications of RP-DSS, a DSS based on a simple, robust and solid dynamic modelling suite developed during the Italo-Brazilian cooperation project able to simulate surface-water qualitative-quantitative aspects and evaluate riverine micro-habitat of Pojuca River due to future scenarios.

Moreover, Brazilian regulations (i.e. Federal Law 9433/97) provide participative decision processes for RBMPs drafting through basin committees. RP-DSS has also been developed with the purpose to obtain a "user-friendly" tool that allows the widest diffusion between stakeholders which compose the basin committees.

RP-DSS follows the principles of IFIM methodology (Instream Flow Incremental Methodology; *Stalnaker et al.*, 1995): it was elaborated in the 80's in USA for helping environmental resource managers in the evaluation of benefits and consequences due to possible management alternatives. It is based on interdisciplinary knowledge coming from biologists, engineers, ichthyologists and sociologists.

Materials and methods

Data collecting and analysis

The first step of RP-DSS realization has been an investigation on environmental, social and economic information ("Pressures", "State" and current "Responses") regarding river basin using data banks, digital cartography and field investigations. The main investigations pertained to meteorology (temperature, humidity and wind), hydrology (river discharge gauging stations position and time series), hydraulic (steady state rating curve), river morphology (slope, cross-section shape and substrate), demographic (urban and rural population), industrial, agricultural and urban water demand, industrial activities (production, position, technology employed), urban sewage systems (population coverage and discharge positions) and WWTPs (characteristics, removal efficiencies and discharge position) (DASS-UFBA, 2008). A 1.5-year water quality monitoring campaign at six discharge stations along Pojuca was conducted (DASS-UFBA, 2008).

Ichthyofauna survey and riverine ecosystem analysis was performed by local ichthyologists in order to define suitability graphs for Pojuca river reference species (USGS, 2001); they relate the considered river parameter values (mean velocity, *V*, mean depth, *D*, and bottom substrate, *S*) with suitability to life for the reference species using a value ranging between 0 and 1 defined as Suitability Index (*SI*). Ichthyologists found two reference species: *Parotocinclus bahiensis* for the upstream part of the river and *Characidium* for the downstream one (Figure 1; DASS-UFBA, 2008).

Spatial analysis by means of a GIS software (ESRI ArcGIS® Desktop 9.1) let to create the basis for the structure DSS: a diagram of the river basin with main river tributaries, discharge pollutants points, sewage water systems and WWTPs positions into the basin.

About Itapecirica Lake scenario, we created a volume-elevation curve and an area-elevation curve processing digital maps with ArcGIS® and Golden Software Surfer® (v7.0).

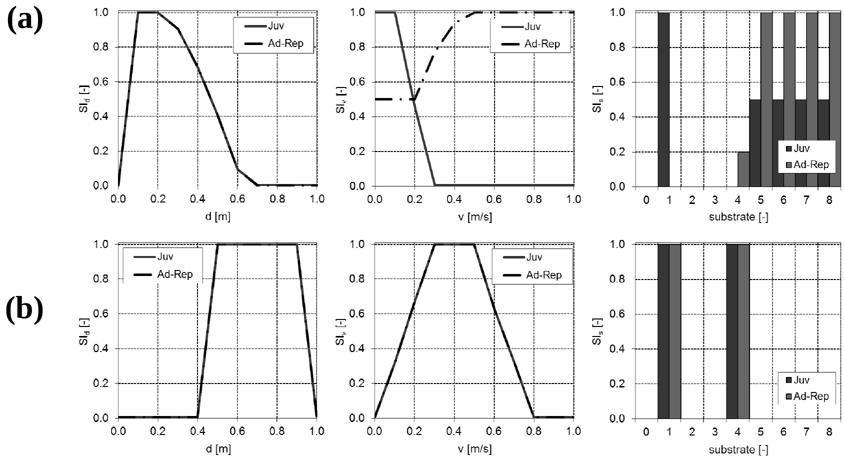


Figure 1. *Parotocinclus bahiensis* (a) and *Characidium* (b) habitat suitability graphs for three life-stages: juvenile (“Juv”), adult (“Ad”) and reproductive (“Rep”).

Software and “user-friendly” interface creation

Microsoft Excel® (v 11) has been used for the realization of both input and output interfaces, while HPS Stella Research® (v.7.0.3) visual language has been used for the models development. The softwares communicate and exchange data making easy the manual interventions by the end-users. Every interface has been translated in Brazilian-Portuguese to facilitate the comprehension by stakeholders. Moreover, a series of seminar on RP-DSS use and modification have been organized at the end of the 2-years project to involve stakeholders in tool utilization.

Models output data are exportable in a GIS software for spatial analysis.

DSS structure

General description

The RP-DSS is composed of five interconnected models (Figure 2).

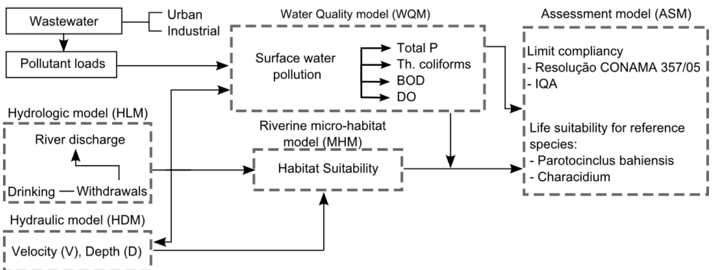


Figure 2. Structure of the RP-DSS and relationship between the models.

Hydrologic model (*HLM*) simulates flow (Q) along the river considering junctions with tributaries, water withdrawals and in-series reservoirs. The outputs are flow time series for each considered cross section.

Hydraulic model (*HDM*) simulates the river mean velocity (*V*) and depth (*D*) thanks to flow (Q) coming from *HLM*. The output is a mean velocity and depth time series for each considered cross section.

Surface-water quality models (*WQMs*) simulate the behaviour of the physical (temperature), chemical (total phosphorus, BOD_5 and dissolved oxygen concentration) and bacteriological (Coliforms) parameters along the river, considering flow conditions time series (Q, V and D), the pollution loads (localized and non-point) coming from economic activities and urban wastewater discharges. The outputs are five parameters time series for each considered cross section.

River micro-habitat model (*MHM*) assesses the level of suitability to life of the reference species in an instream riverine habitat considering the variation of three micro-habitat parameter (*V*, *D* and *S*) with flow (Q). *MHM* uses habitat suitability graphs of Figure 1 and flow (Q) to create a new set of three graphs for each cross section: $AWL_S(Q)$, $AWL_V(Q)$ and $AWL_D(Q)$, where *AWL* represents the Available Weighted Length, a weighted mean of river bottom suitable for the reference species function of flow (Q).
Assessment model *(ASM)* processes data coming from WQM and MHM in order to evaluate the compliance with Brazilian regulations drinking water withdrawal and bathing in lotic and lentic environments (CONAMA, 2005). It also evaluates a partial value of a Brazilian water quality index, IQA (Indice da Qualidade do Agua; ANA, 2005). *ASM* outputs are two daily time series which answer to water regulations compliance ("yes" or "no") and show IQA value for each considered cross section.
ASM also assesses a Composite Habitat Suitability Index (CHSI) for the references species during year, accounting for micro-habitat variation with flow (*AWL)*, water quality (OD concentration) and reproduction period for each considered cross section.
ASM is a useful tool for a fast evaluation of interventions ("Responses") to mitigate the effects ("State") of social and economic scenarios ("Pressures").
RP-DSS models are composed of a series of cascade connected standard modules.
Because of lack of spatially detailed information, RP-DSS has only eight modules.

Hydrologic model
In order to evaluate average monthly discharge we adopted a regression model (Moisello, 1999) based on discharge data recorded at eight gauging stations into the river basin. The longest time series gauging station is set as the "reference". Monthly mean discharges are calculated station by station and correlated with the concurrent reference station monthly mean discharge. Hence, hydrologic model simulates flow rate at the gauging station by means of the reference station average monthly hydrograph. Flow rate changes can be varied taking actions both on average annual discharge and on average monthly hydrograph shape of the reference station.
The hydrologic balance equation for the in-series reservoir module is the classical water balance equation (Chow *et al.,* 1988) where the outflow is composed of downstream river discharge and losses (infiltrations and evaporation). The evaporation is computed using Visentini's formula (Da Deppo *et al.*, 2000). The evaporation rate is calculated multiplying the evaporation with the reservoir surface area, obtained from the reservoir area-elevation curve.

Hydraulic model
In HM, mean velocity (*V*) and mean water depth (*D*) are computed in each station using the steady state rating curves and flows coming from the HLM. The *i-th* stretch average transit time (Δt_i) has been estimated using the formula $\Delta t_i = L_i / V_i$, where L_i is the distance between two consecutive cross-section stations (Chow *et al.*, 1988).

Water quality models
WQMs are simplified water quality models based on complete mixing (Thomann and Mueller, 1987).
The *conservative pollution* submodel considers the chemical dispersion due only to dilution and advection. The sub-model has been used to estimate total phosphorus concentration (to a first approximation assumed conservative). It is considered useful to evaluate eutrophication effects into lentic water, such as Itapecirica Lake. Possible input loads can be (civil and industrial) wastewater discharges and (cultivated lands and urban) runoff.
According to CONAMA (2005), *bacteriological pollution* model considers thermo-tolerant coliforms. A classical decay law is implemented (Thomann and Mueller, 1987), with a bacteria

decay rate (K_T) depending on water temperature: $K_T = K_{B\,20}\,(1.07)^{T-20}$, where $K_{B\,20}$ is the bacteria decay rate at 20 °C. Possible input loads can be civil and industrial wastewater discharges.
The *BOD-DO* model considers the classical interaction between BOD and DO (Thomann and Mueller, 1987): the organic biodegradable substance can be degraded only if dissolved oxygen is available. The oxidation rate of the carbonaceous material (K_{1T}) depends on water temperature: $K_{1T} = K_{1\ 20}\,(1.04)^{T-20}$, where $K_{1\ 20}$ is the oxidation rate at 20 °C. Atmospheric reareation is taken into account using O'Connor formula (Thomann and Mueller, 1987). Possible input loads can be civil and industrial wastewater discharges.
Water temperature change is simulated using a cosine function of time that best fits field measurements with the least squares method.
About the in-series *reservoir module*, the basin is considered completely mixed. DO concentration downstream the reservoir is influenced by dam spillway and it is described through Hydroscience formulation (Thomann and Mueller, 1987). CEPIS method for evaluation of eutrophication state of tropical reservoir is implemented (Salas and Martino, 1991).
Loads has been calculated for each point discharge by multiplying the daily per-capita production by the number of inhabitants at the simulated year, the percentage of sanitary installations and efficiency of WWTPs. Pollutant loads has been considered uniformly in time.
WQMs time step is 0.25 d while the an Euler explicit integration method has been adopted (Thomann and Mueller, 1987).

Riverine micro-habitat model
MHM computes the Habitat Suitability Curves following a simplified PHABSIM method (USGS, 2001) applied to each cross-sections (the so-called "transect method"). A multiplicative weighting method has been adopted (Gordon *et al.*, 1992; McMahon, 1982).

Assessment model
ASM concerning water quality is only based on comparison between regulation targets and *WQMs* outputs. About the habitat, *ASM* combines micro-habitat curves *AWL(Q)* with discharge (*Q*) time series.

Model calibration

Water quality monitoring and concurrent discharge data has been used to calibrate the WQMs. Chosen parameters are listed in Table 1; Figure 3 shows results in one of the monitoring stations.
Parameters fall within the literature values ranges (Thomann and Mueller, 1987; Von Sperling, 2005) and numerical results moderately well fit measured data.

Table 1. RP-DSS parameters chosen in RP-DSS after calibration procedure.

Parameter	Unit	Adopted value
Total phosphorus daily per-capita production	kg/(inh d)	0.001
Thermo-tolerant coliforms daily per-capita production	MPN/(inh d)	10^9
Bacteria decay rate at 20 ° C ($K_{B\,20}$)	d^{-1}	1.5
BOD_5 daily per-capita production	kg/(inh d)	0.050
Oxidation rate of the carbonaceous material at 20 °C ($K_{1\,20}$)	d^{-1}	0.26
Tributary non-polluted water DO concentration	% DO saturation	80

Possible applications to Pojuca river basin

Here we present a set of possible applications of the DSS to Pojuca basin. We evaluated future scenarios with possible interventions as consequence of population growth and possible water withdrawal for Salvador water supplying. Moreover we present a possible use of the MHM for the assessment of riverine microhabitat. The year of simulation was set to 2022 in order to give a possible prevision useful for the design of a new infrastructure, such as sewage systems or WWTPs.

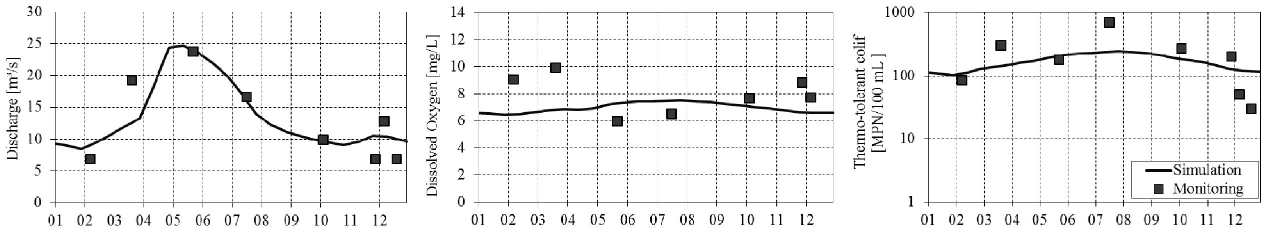
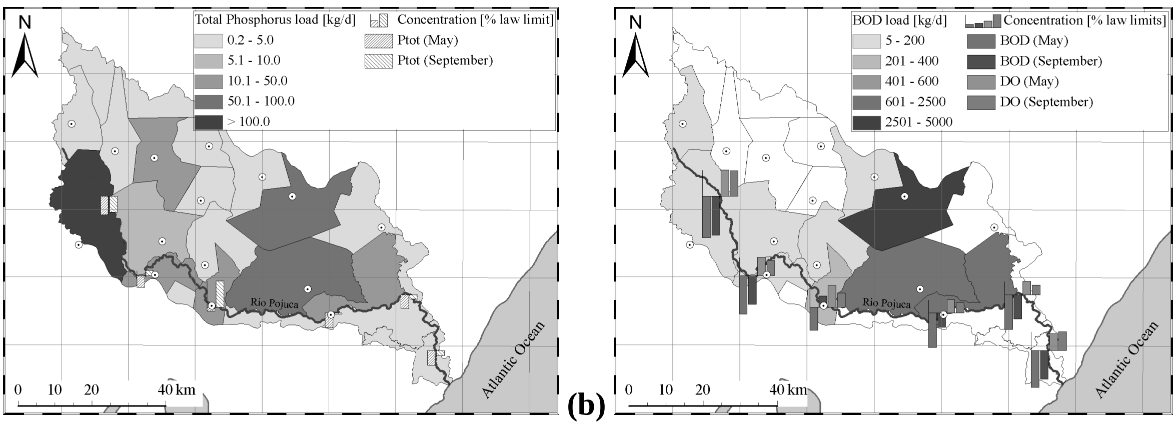


Figure 3. Example of comparison between some numerical and monitoring results at the reference monitoring station.

Future scenarios: impact on water quality and quantity and possible technological responses
A first simulation run without any kind of intervention (the so-called S0 scenario) has been carried on. Results of WQM for total phosphorus, BOD and DO were described, respectively, by Figure 4a and b. Results are shown as percentage difference from Brazilian regulation limits for drinking water use (Class II; CONAMA, 2005*)*. The maps also depict daily pollutant loads distribution for each municipality; it allows the spatial analysis of pollution along the river, facilitating the singling out of the critical situations.



(a) (b)

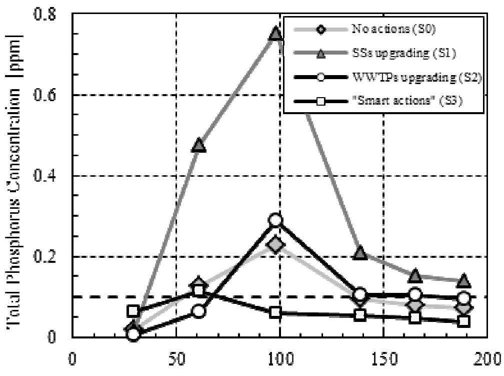
Figure 4. Maps with results of S0 scenario (no interventions) for total phosphorus (a), BOD, DO (b) along Pojuca River stretch during the best (May) and worst (September) month.

The most critical situations occur in the upper stretch of the river and during September, because of scarce dilution due to river discharge and the temperature effects on biological kinetics.
As a result, actions have to be taken. Two solutions were suggested and, as consequence, two scenarios were simulated (Figure 5):

- S1 scenario, based on sewer systems upgrading in the major villages and towns only. According with a realistic hypothesis, the upgrading was set to 30% of the 2001 situation;
- S2 scenario, based on both sewage systems (see S1) and WWTPs upgrading. According to Bahia State available and most diffused technologies, the enhancing of removal efficiencies was set to 30% for total phosphorus (up to 50% of the input), 30% for BOD (up to 90% of the input) and 60% for coliforms (up to 99% of the input) removal efficiencies. Remote septic tank was employed for remote habitations and, in general, for rural population.

Sewage systems upgrading (S1) worsens the situation. The combination of sewage systems and WWTPs (S2) allows to respect regulations for BOD, but not for total phosphorus.
S3 scenario, based on "smart actions", has been proposed. It is the outcome of a simulated confront carried out among the stakeholders (municipalities, inhabitants, industries, farmers). The aim is the achievement of Res. CONAMA 357/2005. The best solution has been focused only on the sewage system management of the upper reach of Pojuca River basin. Results recommend focusing the

treatment on total phosphorus loads removal rather than on organic ones.



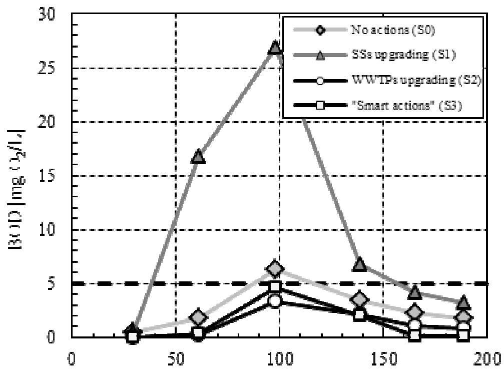


Figure 5. River profile of total phosphorus concentrations (a) and BOD (b) during September with different scenarios. Broken lines refer to regulation limits (Class II; CONAMA, 2005).

RMS water supplying: construction of an in-series reservoir

The construction of an in-series reservoir was added to previous simulated scenarios. CEPIS method results for Itapecirica Lake gave a prevision of mesotrophic state for S3 scenario.

Riverine microhabitat change assessment

Statistical analysis of discharge data has been shown a negative trend (-10% during the last ten years) in Pojuca River annual average flows due to climate change. The RP-DSS is also useful for evaluating the effects of water discharge changes on riverine micro-habitat. Here we propose the results of the analysis of the cross section where dam of Itapecirica Lake should be built. Two scenarios were examined:

a. climate change, comparing 2012 (Q2012) and 2032 (Q2032) annual average discharge.
b. building of Itapecirica Lake (hydraulics experts of the working team estimated a downstream water discharge of about 10 m^3/s in order to ensure Salvador water supplying).

The cross section downstream Itapecirica dam was considered. Model outcomes (Figure 6) highlighted the increase of habitat suitability up to the 30% due to climate change during low discharge season, while dam water regulation could generate sensible reduction of microhabitat suitability (up to 40%), with negative consequences for aquatic life species and decrease of biodiversity.

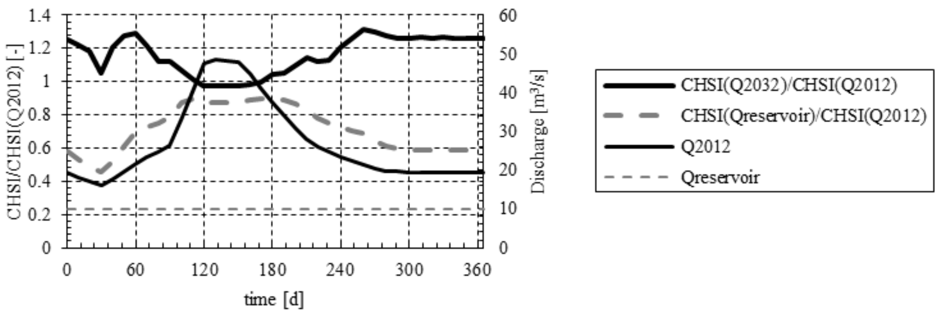


Figure 6. Behaviour of composite habitat suitability index (CHSI; thick lines) due to discharge changes at the cross section next to Itapecirica dam (reference station). Comparison between 2032 discharge scenario without the dam (Q2032) and discharge scenario with the dam (Qreservoir), normalized by 2012 discharge situation (Q2012).

Conclusions

This paper describes the RP-DSS, a DSS developed with a multidisciplinary approach for the making out of a sustainable RBMP on Pojuca River (Bahia, Brazil); it comprises dynamic models

considering water resource quantity and quality. The water quality models, calibrated with field measurement and based on a hydrologic model, allow to simulate the effects of water withdrawals, an in-series reservoir, the management and the upgrading of sewer systems and WWTPs. Furthermore, RP-DDS gives an answer regarding the compliance of the water quality to regulations in force. Riverine microhabitat suitability is evaluated using a simplified model, useful in such situation where economic difficulties and inaccessible geographical situations are present, considering only reference cross sections evaluated by biologists and ichthyologists.
The DSS was developed with stakeholders for helping them in the assessment of the best and cheap strategy to preserve surface-water quality and ecological suitability to riverine life, without stopping the use of the river and the development of local communities.
RP-DSS shows its importance in evaluating the risk of eutrophication and habitat injuries due to the construction of an in-series reservoir for Salvador water supplying. Moreover, the DSS allows to evaluate the “smart actions” (able to be efficient and cost-effective) to reduce water body pollution of and artificial reservoir eutrophication risk. The “smart actions” consists in a combination of the upgrading of city sewage systems and WWTPs arisen from a stakeholder simulated face-off.
RP-DSS has been built in a visual language and it is composed of modules which can be simply transferred to other river basin for helping and directly involving stakeholders, with their own ideas, in the solution of a broad range of environmental issues.
Moreover, the cooperation project and the RP-DSS development have been characterized by a large involvement of local technicians and specialists with the aim to emphasize the existing qualifications and considering local tradition and culture.

Acknowledgments

We wish to thank Prof. Valerio Vendegna (Pavia University, Italy), researchers of Brescia University (Italy) and Universidade Federal da Bahia (Brazil) who contributed their expertise to get the results presented in this paper. Moreover, the authors thank Regione Lombardia (Italy) and Secretaria do Meio Ambiente e dos Recursos Hidricos do Estado da Bahia-Brazil (SeMARH) for giving the financial support to the study.

References

ANA – Agencia National da Agua, Governo do Brasil (2005). *Panorama da qualidade das aguas superficiais no Brasil*. Brazil.
Chow V.T, Maidment D.R., Mays L.W. (1988). *Applied Hydrology*. McGraw-Hill, USA.
Collivignarelli C., De Felice V., Di Bella V., Sorlini S., Vaccari M. (2012). Assessment of sanitary infrastructures and polluting loads in Pojuca River (Brazil). *Water Practice and Technology* (accepted).
CRA - Centro de Recursos Ambientais (2002). *Rumo a um desenvolvimento sustentável: indicadores ambientais*. Salvador, Bahia, Brazil.
DASS-UFBA Università dell’Insubria – Dip. Ambiente, Salute e Sicurezza, Universidade Federal da Bahia - Fundação Escola Politecnica (2008). *Progetto Integrato di Sviluppo Sostenibile dell’area del bacino del Rio Pojuca, Stato Di Bahia, Brasile*. Final Report, Varese.
Da Deppo L., Datei C., Salandin P. (2000). *Sistemazione dei corsi d’acqua*. Cortina, Padova.
Di Mauro C., Nordvik J.P. (2010). Decision support system for crisis management planning. *Dangerous Materials: Control, Risk Prevention and Crisis Management*, Springer, Netherlands.
Gordon N.D., McMahon T.A., Finlayson B.L. (1992). *Stream Hydrology, an introduction for ecologists*. John Wiley & Sons, England.
Lautenbach S., Berlekamp J.,Graf N., Seppelt R., Matthies M. (2009). Scenario analysis and management options for sustainable river basin management: application of the Elbe DSS. *Environmental Modelling & Software*, **24**, 26-43.
McMahon T.E. (1982). *Habitat Suitability Index models: Creek Chub. Fish and Wildlife Service*,

Report FWS/OBS-82/10.4, Department of the Interior, USA.
CONAMA - Ministério do Meio Ambiente e Conselho Nacional do Meio Ambiente (2005). *Resolução n. 357 de 17 de Março de 2005*.
Moisello U. (1999). *Idrologia tecnica*. La Goliardica Pavese, Pavia.
Salas H.J., Martino P. (1991). A simplified phosphorus trophic state model for warm-water tropical lakes, *Water Resources*, **25**(3), 341-350.
Stalnaker C., Lamb B.L., Henriksen J., Bovee K., Bartholow J.M. (1995). *The Instream Flow Incremental Methodology: A primer for IFIM*. Report 29, U.S. Department of the Interior.
Thomann R.V., Mueller J.A. (1987). *Principles of Surface-water Quality Modelling and Control*. Harper & Row, New York.
USGS - U.S.Geological Survey (2001). *PHABSIM for Windows – User's manual and Exercises*. Open File Report 01-340, USA.
Von Sperling M. (2005). *Introdução à qualidade das água e ao tratamento de esgotos. Vol. 1*, 3° edição, DESA UFMG, Belo Horizonte.