NeWater

METHODS TO USE THE DOMAIN MODELS IN AN ADAPTIVE MANAGEMENT PERSPECTIVE

Bridging the gap between simulation models and stakeholders

Report of the NeWater project -
New Approaches to Adaptive Water Management under Uncertainty

www.newater.info

Title	METHODS TO USE THE DOMAIN MODELS IN AN ADAPTIVE MANAGEMENT PERSPECTIVE Bridging the gap between simulation models and stakeholders
Purpose	Expose the final conclusions of work package 1.5 regarding the application of the buffering capacity concept to adaptive water management.
Filename	NW D156_v3.doc
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Document history	
Current version.	1
Changes to previous version.	
Date	2009-01-13
Status	Final
Target readership	
General readership	
Correct reference	

Julien Lerat, editor
CEMAGREF

December 2008

Prepared under contract from the European Commission

Contract no 511179 (GOCE)
Integrated Project in
PRIORITY 6.3 Global Change and Ecosystems
in the 6th EU framework programme

Deliverable title: METHODS TO USE THE DOMAIN MODELS IN AN ADAPTIVE MANAGEMENT PERSPECTIVE
Deliverable no. : D 1.5.6
Due date of deliverable: Month 48
Actual submission date: 13.01.2009
Start of the project: 01.01.2005
Duration: 4 years

Policy Summary

Buffering capacity is a powerful concept which integrates a wide range of physical processes and water management behaviour. In deliverable 1.5.1, we related this concept with adaptive management observing that increased buffering capacity enlarges the scope of management options and facilitates the transition towards adaptive water management.

As per the definition proposed in deliverable 1.5.1, buffering capacity is a property of a dynamic system that modifies an input signal called driving force and produces a signal perceived by an observer called the beneficiary.

The previous concept can be detailed as follows:

1. **Driving force**: set of external variables influencing the buffered system (for example atmospheric forcing variables acting on a catchment).
2. **Beneficiary**: any group of individuals or part of the hydrosystem benefiting from the existence of the buffering capacity (for example pikes utilising the flood plain retention capacity for spawning).
3. **Buffering effect**: modification of the time response between driving forces received by the buffered system and the buffered signal received by the beneficiary. Three kinds of transformation were proposed using an analogy with linear systems analysis: gain (modification of the average value), delay and diffusion.

Buffering capacity is a general concept only supported by a limited literature. As a result, there is a high risk of diluting it within general considerations on water management and hydrology. To avoid this undesired situation, it is essential to first define the elements constituting the buffered system and pay special attention to driving forces, beneficiaries and buffering effects. Examples of such procedure are given in deliverable 1.5.1.

The following paragraphs propose two recommendations to apply the concept of buffering capacity.

Recommendation #1: Buffering capacity needs indicators

The set of indicators measuring buffering capacity constitutes one of the key components of a study on buffering capacity. As the concept can be difficult to grasp, it is essential to use indicators that translate the buffering capacity assessment into concrete figures. Moreover, if simulation models or Bayesian belief networks need to be developed, indicators can be used as deterministic or probabilistic based performance assessment criteria.

Section 3.4 of this deliverable presents a good example of indicators building process in four steps:

1. **Discussion with the stakeholders to identify relevant features of the buffered system**: section 3.2 describes the involvement of the stakeholders during the building of the Bayesian network. This procedure permitted to identify a set of core variables describing the system.
2. **Participatory design of indicators describing the buffered system**: five questions should be considered when developing indicators:
    - *Conceptual relevance*: an indicator should be accepted by all the stakeholders from the scientific community to the general public. In the case of the La Mancha Occidental aquifer it was important that indicators include considerations on environmental protection (wetlands of the Las Tablas de Daimiel) as well as elements on the agricultural sector.
    - *Feasibility of implementation*: the data needs required by the calculation of indicators should be consistent with the available measurement networks. This elementary remark may prove to be challenging regarding variables such as unauthorised water withdrawals.
    - *Response variability*: the systems analysed in buffering capacity studies exhibit marked spatial and temporal variability. As a result, the indicators that reflect the state of the system will also show complex spatial and temporal patterns. In this

context, indicators may require a post-processing treatment to distinguish significant tendencies from the errors introduced during the data collection process (sampling, measurement errors, …).

- *Interpretation and utility*: indicator should be formulated in meaningful way for all stakeholders. Complex mathematical definitions should be avoided as they are suitable for a public with a technical background only. In the case of the La Mancha Occidental aquifer, indicators were formulated in terms of simple figures such as the number of years to recover a good ecological status (indicator n°1). To insist on the uncertainties attached with the indicator estimation, probabilities were associated with indicator values.
- *Degree of vulnerability*: Rather than generating an existing or single indicator, there is a need to develop new buffering capacity index representing the degree of vulnerability of different stakeholders or areas to the changing flow, supply and quality of water resources. Approaches where the interrelationships, links and dependencies are accurately expressed, uncertainty attached to date and understanding explicitly represented, where final results are clearly communicated and where new evidence can rapidly be entered are required.

Recommendation #2: Buffering capacity needs simple and transparent models

In many buffering capacity studies, a simulation model is required to extend the available information on the buffered system or a Bayesian belief networks with engagement of stakeholders is required for integration and reasoning under uncertainty. The main objective of such participatory modelling is to support the establishment and calculation of buffering capacity indicators mentioned previously.

A large number of simulation models can be used in the field of water resources management but few intercomparisons have been published. Moreover, models show a wide diversity of implementation cost with no clear relationship with performance improvement. As a result, model selection can prove to be a tricky issue.

In the context of buffering capacity assessment, the most important selection criteria is the transparency for the stakeholders: models introduce an additional level of complexity in the whole process of buffering capacity assessment. This complexity can induce rejection by the stakeholders if they feel disconnected from the model building process. Ideally, the model should be elaborated with the stakeholders like the building of the Bayesian network presented in section 3.2.

For comprehensive groundwater- and surface water models transparency and credibility of such models can be supported by quality assurance and by stakeholder interaction in the modelling construction process. Interaction i.e. to allow stakeholder to give advice to water manager and modeller in the modelling process is appropriate for obligatory public participatory processes. “Engagement” of stakeholders, which represent the level of participation above “interaction” is not evaluated as feasible in the process of construction of comprehensive models (Henriksen et al, forthsomming), but it may when simpler models are used for the construction be more feasible. However, as also demonstrated for Guadiana, stakeholders should be engaged in the simulations and scenario development, and here Bayesian belief networks as well as simple or comprehensive models are useful tools depending on the scope of the buffering capacity analysis.

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1 Introduction

There are different avenues for bridging the gap between simulation models and stakeholders. In this report simple models for reservoir and surface water simulations with the purpose of managing reservoir buffering capacity and Bayesian belief networks for integrating knowledge and reasoning under uncertainty for managing groundwater buffering capacity is described. The main purpose of bridging this gap between models and stakeholders is to improve decision making and learning by ensuring a better knowledge exchange and interaction between the water managers, modellers and stakeholders.

Work package 1.5 focused on the role of artificial and natural storages (reservoirs, groundwater and provisional storage due to a temporally allowed flooding) to investigate how new management approaches can increase the buffering capacity of a basin.

To develop and apply this new concept, research activities where organised around three points:

1. Precise the definition of buffering capacity which encompasses a wide range of physical processes and management situations (deliverable 1.5.1),
2. Develop methods and simulation models to test and compare different options related to buffering capacity management (deliverables D 1.5.2, D 1.5.3 and D 1.5.4),
3. Collect information regarding the present and future management scenario prevailing in two case study basins to confront the methods developed with field application (deliverable D 1.5.5).

This report has three objectives:

- Present a method to define the management rules of surface water reservoirs. This method brings to a whole the set of tools developed in the work package 1.5 to manage surface water buffering capacity.
- Present the results obtained in the management of groundwater in the Guadiana basin. This section proposes a feedback on the development of tools to manage buffering capacity related to groundwater.
- Conclude on a set of recommendations on the methods to manage buffering capacity based on the experience gained during the Newater project,

2 Case of the artificial buffer: managing reservoir releases

2.1 Tools developed in work package 1.5 for the management of surface water reservoirs

The aim of reservoir management is to adequately satisfy all the objectives (often conflicting) associated with a given reservoir or a system of reservoirs. This question encompasses three main problems (Miquel and Roche 1984):

- to determine the sufficient reservoir capacity in order to meet the water needs (quantitative, qualitative, for security), assuming a correct management;
- to allocate water between the different users;
- to set up the operating (management) rules in regards with the allocation choices agreed on.

The work package focused on dynamic management methods. As a result, we did not investigate the first point, namely reservoir design, and concentrated only on existing reservoir systems.

In this context, uncertainty arises mainly from the limited knowledge of future reservoir inflow. For medium size reservoirs, releases are bounded by expectation on future inflows to avoid emptying the reservoir on a year wise basis. As a result, a forecasting system on river flows constitutes the first element required to manage a reservoir. Two tools were proposed in work package 1.5 to address this issue:

1. **Parsimonious lumped rainfall-runoff models (Deliverable D 1.5.3)**: in most countries, rainfall records offer a good spatial coverage and a long history compared to river flow records. Rainfall-runoff models were then developed to take advantage of this situation and give access to extended flow simulations. Lumped models are well suited to real-time operational conditions due to their numerical robustness. As a result, such type of models where developed on the two case studies of the Rhine and the Guadiana.
2. **Rainfall simulation toolbox (Deliverable D 1.5.4)**: rainfall constitutes the main forcing variable of hydrological systems and obviously the main input to rainfall-runoff models. In a forecasting context, rainfall forecasts are then inseparable from rainfall-runoff models mentioned previously. Unfortunately, rainfall forecasting remains a challenging issue especially for medium-term lead-time (2-3 month). Consequently, future rainfall can only be estimated within a probabilistic framework. As a result, a simple rainfall simulation toolbox was proposed to produce future rainfall scenario based on a resampling of historical records.

In this section we present a third tool required to build a comprehensive reservoir management system. This tool permits to **transform the inflow forecasts produced by the two previous tools into reservoir releases**. The objective is to provide:

- baseline management rules for the benchmarking of more complex management tools (models);
- a simple, easy-to-implement tool in order to test different management scenarios for existing or future (planned) reservoirs.

The method aims at developing a parametric reservoir management rule relying on a small number of calibrated parameters.

Section 2.2 present a review of existing methods for managing reservoir releases. In section 2.3, details of the new method are provided and an application is presented in section 2.4.

2.2 Review of available methods for managing reservoir releases

Usually, when setting up reservoir management method, three time-scales are of-interest:

- long-term management (one year): storage and release objectives allowing inter-annual conservation of water can be established;
- mid-term management (some months): a compromise between conflicting or complementary objectives can be reached. For instance, this time-scale is adapted to fit an average curve of target volumes that should be stored in the reservoir compatible with the objective of high flow reduction;
- short-term management (some days): day-to-day operations (storage or release) in order to follow as closely as possible the objectives defined in the mid-term management.

The three time-scales for management are interdependent: in theory the performances of short-term management should be known in order to calculate the mid-term management performances which are then needed to calculate the long-term management performances. Once the best long-term management method is selected, the limit conditions of the problem required for the mid-term and then the short-term management are known.

In practice the combination of the three time-scales leads to constraining simplifications.

The determination of the best reservoir management methods is a key challenge in operational hydrology. Hence, there is an abundant literature dealing with this subject.

In the following sections, we give an overview of the different approaches used to tackle the problem of determining the best management method for a reservoir or a system of reservoirs.

Rigid or fixed methods – Annual plan of operations (rule curves)

For catchments with no or low data, a simple management rule is to release and store a constant amount of water during given periods, independently of the upstream flow. The amount of water released or stored and the corresponding periods are fixed in a plan of operations established at once (Figure 1). There is no real-time control of the releases and storages (Miquel and Roche 1986).

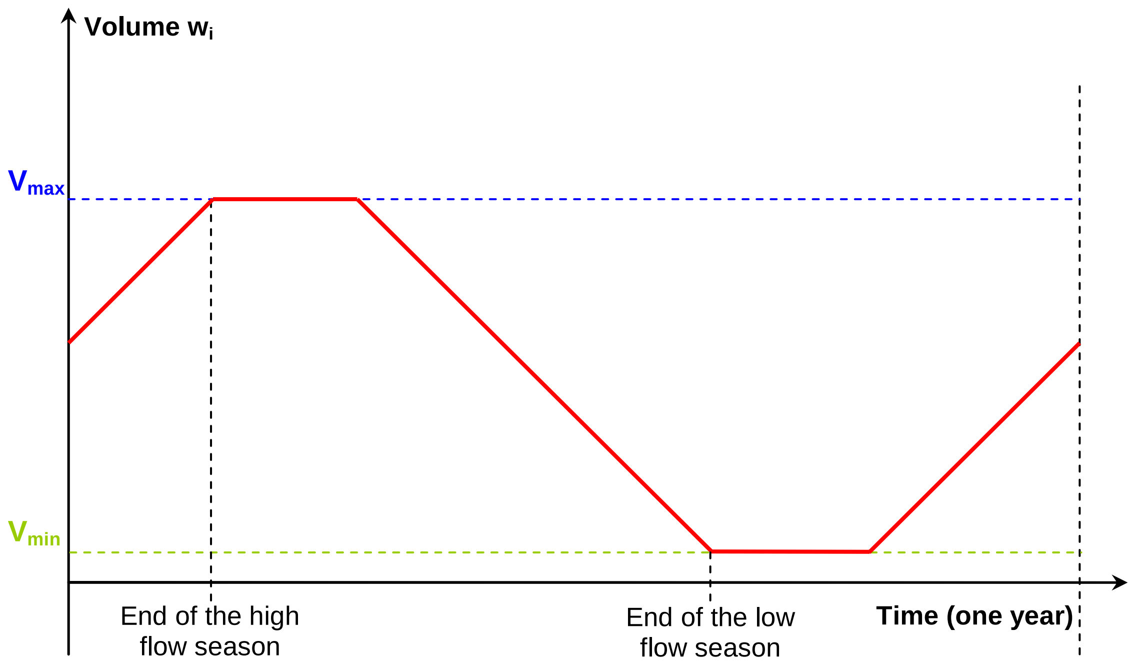

Figure 1: Example of a basic annual plan of operation for a reservoir

This one-year periodic curve gives the volume of water that should ideally be stored in the reservoir at each time step.

Annual plans of operation can be designed for the reservoir using the statistical information about the flow regime of the river. Direct (Cemagref, 1981) or parameterized methods (Michel and Thomas, 1984) can be used to establish the operational plans.

These management tools, far from being optimal, guarantee minimum performances for each of the objectives assigned to the reservoir. The curve describes an average management that can be inadequate for some situations. In this case, the manager should not strictly track the curve but take decisions (release or storage) in regards of the situation he is facing.

Rule curves are used for single-purpose reservoirs as well as for multi-purpose reservoirs. They can be defined not only by storage target levels, but also by various storage allocation zones (e.g. conservation zone, flood control zone, spill zone, inactive zone…). Hence, the reservoir releases and storages can depend on which zone the storage volume is.

Rule curves can also be defined conditionally not only as a function of the existing storage volume and time of the year but also as a function of the expected natural inflows into the reservoirs (Loucks and Sigvaldason 1982).

Optimizations methods

Several optimization techniques are used for the management of (complex) reservoir systems. The choice of methods depends on the characteristics of the reservoirs systems, on the availability of data, and on the objectives and constraints specified (Hall and Dracup 1970; Buras 1972; Loucks, Stedinger et al. 1981; Yeh 1985; Mays and Tung 1992; Wurbs 1996; Labadie 1997; ReVelle 1999; Labadie 2004).

These techniques have the capability to systematically select optimal solutions under agreed upon objectives and constraints. They can be classified in two categories (Labadie 2004):

- Implicit Stochastic Optimization;
- Explicit Stochastic Optimization.

Implicit stochastic optimization

These methods, also called Monte Carlo optimization, optimize an objective function over a long continuous historical or synthetically generated unregulated inflow time-series. Hence, most stochastic aspects of the problem, including spatial and temporal correlations of unregulated inflows, are implicitly included, allowing the direct use of deterministic optimization methods described below:

- The linear programming methods (Nash and Sofer 1996): in this technique all relations among the variables are linear (in constraints and in the objective function to be optimized). Although objective functions and some of the constraints are often non linear, various linearization techniques can be successfully used (e.g. piecewise linearization or first-order Taylor series expansion). The most used technique for reservoir system optimization is the simplex method of linear programming (Nelder and Mead 1965). Linear programming efficiently solves large-scale problems, converge to global optimal solutions and is easy to setup (readily available standard low-cost solvers);
- Nonlinear programming methods (Nash and Sofer 1996): this technique is needed when reservoir system optimization problems cannot be realistically linearized (e.g. when hydropower generation is included in the objective function and/or constraints). All relations among the variables should be differentiable. Among the existing algorithms, we can mention the successive linear programming algorithm which proved powerful and robust for the management of reservoir systems (Grygier and Stedinger 1985; Hiew 1987; Barros, Tsai et al. 2003). Nonlinear programming techniques can face problem of convergence and require a larger amount of computer storage and time than linear programming;
- Dynamic programming methods (Bellman 1957): Bellman's principle of optimality states that: "no matter what the initial stage and state of a Markovian decision process, there exists an optimal policy from that stage and state to the end". These techniques are used to describe the process of solving problems where one needs to find the best decisions one after another. Therefore, the original optimization problem is decomposed into subproblems that are solved sequentially over each time period (also called stage). Dynamic programming models are based on recursive algorithms. They are widely applied to water resources planning and management in general, and reservoir operations in particular (Yakowitz 1982). One advantage of dynamic programming is that computational effort increases linearly with the number of stages.

Explicit stochastic optimization

These methods are designed to operate directly on probabilistic descriptions of random variables (e.g. streamflows) rather than deterministic hydrologic sequences. The optimization is performed without the assumption of perfect knowledge of future events.

- Stochastic linear programming methods: "the deterministic linear programming of reservoir system optimization problem (as described in the previous section) assumes that all future inflows and other random phenomena are known with certainty. A more realistic assumption is that first period decisions can be made with certainty, but future decisions and their consequences are random. The so-called two-stage problem is formulated to minimize total costs (or maximize net benefits) from first stage decisions, plus the total expected costs (or net benefits) of future decisions, which depend on the first stage decisions and future random inflow realizations (Kall and Wallace 1995). If several scenarios of future streamflow time series have been generated, each with an assumed probability of occurrence, then a deterministic equivalent problem can be formulated for each possible inflow sequence or scenario. Future reservoir release decisions are specified that would be made as a consequence of the occurrence of each scenario. Only the first stage decisions are actually implemented, since future decisions are not known with certainty. Following implementation of the first stage decisions, the problem is reformulated starting with the next period decisions and solved over the remainder of the operational horizon (Labadie 2004)." The use of nonlinear programming in the stochastic case requires important computational capacities, therefore this kind of techniques is rarely implemented for reservoir management optimization.

- Stochastic dynamic programming methods: "two stochastic techniques are used in solving reservoir operation problems: the Markov chain method of successive approximation and the policy iteration algorithm" (Howard 1960). The successive approximation has some advantages over the policy iteration in terms of computation time and ease of implementation. In the case of multireservoir systems, stochastic dynamic programming is hard to implement (state dimensionality aggravated) especially when spatial correlation of unregulated inflows must be maintained.

Heuristic programming models

All the optimization methods presented in the previous section are based on algorithmic programming using mathematically well-structured and provable procedures and applied on quantitative information. Heuristic methods are part of artificial intelligence, characterized by self-learning programs getting better with experience. Unlike most of the optimization algorithms, heuristic programs do not always reach the very best result but usually produce a satisfying solution.

For reservoir management problems, three heuristic methods are mainly used (Labadie 2004): genetic algorithms, artificial neural network and fuzzy rule-based modelling.

A genetic algorithm is a search technique used in computing to find exact or approximate solutions to optimization and search problems. They use techniques inspired by evolutionary biology such as inheritance, mutation, selection and recombination (Goldberg 1989). These techniques (inheritance, mutation and recombination) are applied probabilistically to discrete decision variables that are coded into binary strings. "Rather than generating progressions of single solutions, as all the previous optimization methods, a genetic algorithm produces groups (or populations) of solutions whose offspring display increasing levels of objective function values".

"Genetic algorithms can be directly linked with hydrologic and water quality simulation models without requiring simplifying assumptions. The algorithm adjusts populations of release rule structures based on predictions of the impacts of the rules as provided by the simulation model". Genetics algorithms are robust tools to solve highly nonlinear, non-convex problems but they require expensive computations, which limit their use to single reservoir systems. Another disadvantage of genetic algorithms is that don't easily account for constraints, particularly inequality constraints.

Artificial neural networks are inspired by the parallelism with the brain. They consist of an interconnected group of artificial neurons and processes. In most cases an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase. Neural networks are non-linear statistical data modelling tools. They are particularly valuable to model complex relationships between inputs and outputs, to find patterns in data or to perform classification and pattern recognition functions.

Fuzzy rule-based modelling "provides a non-frequentist approach to dealing with uncertainty and vagueness that are not bound by the laws of probability measure theory". The originality of this technique is to provide a means of translating linguistic descriptors into a usable numerical form.

Simulation models

In simulation modelling, the behaviour of a system is approximated by a mathematical or algebraic description. It differs from the optimization techniques aiming at finding an optimum decision for system operation meeting all constraints while maximizing (or minimizing) an objective function (see previous section). Simulation models provide the response of the system for given inputs including decision rules. Simulation models are useful tools to examine the consequences of various scenarios of an existing system or a new system without actually building it. Typically, a simulation model simulates for each time-step, operation of the system with specified inflows, system characteristics and operating rules. These models, also called descriptive, help answer what if questions regarding the performance of tested reservoir management rules.

A mathematical programming method usually requires assumptions on system structure and constraints for practical implementation, whereas a simulation model is more flexible and versatile in simulating the response of the system. This adaptability is counterbalanced by the fact that simulations are limited to a finite number of tested management scenarios whereas optimization methods implicitly look at all possible decision alternatives (Yeh 1985).

The distinction between simulation models and optimization methods is not always clearly clear-cut as some simulation models can perform certain degrees of optimization (Yeh 1985).

Decision support systems

Despite the great number of available optimization methods and several decades of intensive research on the application of these methods to reservoir, a gap still exist between theoretical developments and real-world implementations of such methods (Yeh 1985; Wurbs 1993). Labadie (Labadie 2004) gives seven possible reasons:

- " many reservoir system operators are sceptical about models purporting to replace their judgment and prescribe solution strategies and feel more comfortable with use of existing simulation models;
- computer hardware and software limitations in the past have required simplifications and approximations that operators are unwilling to accept;
- optimization models are generally more mathematically complex than simulation models, and therefore more difficult to comprehend;
- many optimization models are not conducive to incorporating risk and uncertainty;
- the enormous range and varieties of optimization methods create confusion as to which to select for a particular application;
- some optimization methods, such as dynamic programming, often require customized program development;
- many optimization methods can only produce optimal period-of-record solutions rather than more useful conditional operating rules".

Decision support systems help to overcome the previous difficulties. These systems are usually generalized (meaning not site-specific) river basin modelling environment providing the decision makers with a set of tools (simulation models, optimization methods, screening facilities, data analysis,…) he can usefully employ to find his own solution. Hence, the decision maker is the one who takes the final decision for management and so his is less reticent about using optimization methods.

RiverWare (Zagona, Fulp et al. 2001) is an example of decision support system developed to provide river basin manager or electric utility with a tool for scheduling, forecasting and planning operations.

It is an object-oriented modelling approach (model construction kit) allowing to define a specific river or reservoir system and its operating policies. The user constructs a model by graphically selecting significant features of the modelled system (reservoir, reach, confluence,…) from a palette and by liking them together. Corresponding data are then associated with each feature. The user can also select calculation methods such as river reach routing, power calculation, reservoir management optimization… Reservoir operating policies can be added through a constraint editor or a rule base editor. Depending on the inputs given to the model, several outputs can be calculated (river discharge on specific points, reservoir levels, releases…).

Several RiverWare model applications have been developed and are in operational use. The Tennessee Valley Authority and the United-States Bureau of Reclamation use this tool to manage some of the basins they are in charge of. This agencies use the tool at different time-scales going from short-term scheduling to long-term planning (Zagona, Fulp et al. 2001).

2.3 A method to control reservoir release with a double objective of flood alleviation and low flow augmentation

The problem is to regulate the flow of a river, at point A located downstream of reservoir represented by an off-stream storage (see Figure 2).

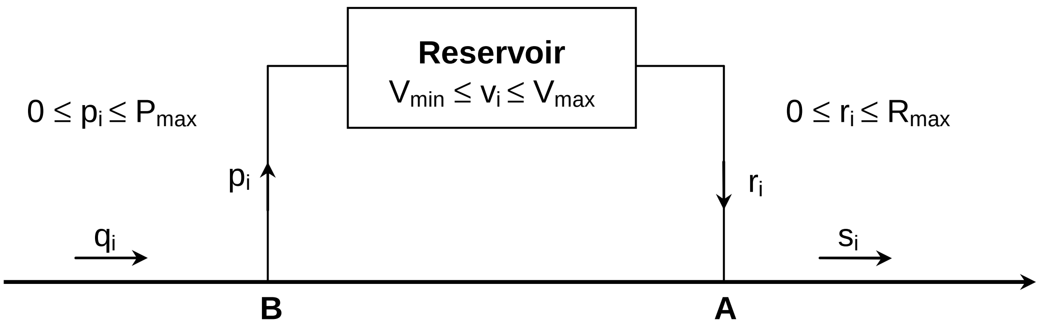

Figure 2: Functioning of a reservoir used for flow regulation

With:

q_i: daily upstream flow (or "natural" flow)
s_i: daily downstream influenced flow
p_i: daily amount of water diverted to the reservoir
r_i: daily amount of water released in the river
P_{max} : maximum capacity of the intake canal
R_{max}: maximum capacity of the outlet canal
v_i: daily volume stored in the reservoir
V_{max}: maximum capacity of the reservoir
V_{min}: minimum capacity of the reservoir

In this approach, the influence of the intermediary area between B and A is not accounted for (i.e. when $p_i = 0$ and $r_i = 0$, $q_i = s_i$). It is also supposed that the diversion or the release of water can not be simultaneous (i.e. $p_i \times r_i = 0$).

The management objective is to regulate the flow, i.e. to store an amount of water when available (flood alleviation) and to release water when needed (low flow augmentation):

- flood alleviation requires to empty the reservoir before high flows;
- and low flow augmentation requires to store a sufficient amount of water before low flows.

Objective of the reservoir release management

We suppose that the flow (q_i) becomes problematic when it goes outside the interval $[q_n;q_x]$. q_n and q_x are respectively the minimum and maximum allowed (acceptable) flows:

- **Low flow conditions**: when $q_i < q_n$, flows require to be augmented (water release, $r_i > 0$)
- **Flood conditions**: when $q_i > q_x$, flows require to be reduced (water diversion, $p_i > 0$)

For clarity purpose, we can distinguish two kinds of actions in the management process (Figure 3):

- when **qi $\notin [q_n;q_x]$, reservoir inflow goes outside of the accepted range**. In this case, the "natural" flow is problematic and needs to be regulated (see above). This case is called "**tactical regulation**" because it deals with immediate actions to be taken to regulate the flow (short term actions).
- and when **qi $\in [q_n;q_x]$, reservoir inflow stay within the accepted range**. This case is called "**strategical regulation**" because the regulation actions to be taken don't aim at reducing or augmenting the "natural" flow but rely on the foresight of the future situation (long term actions): store a sufficient amount of water for low flow alleviation during low flow periods and adequately empty the reservoir to reduce problematic high flows.

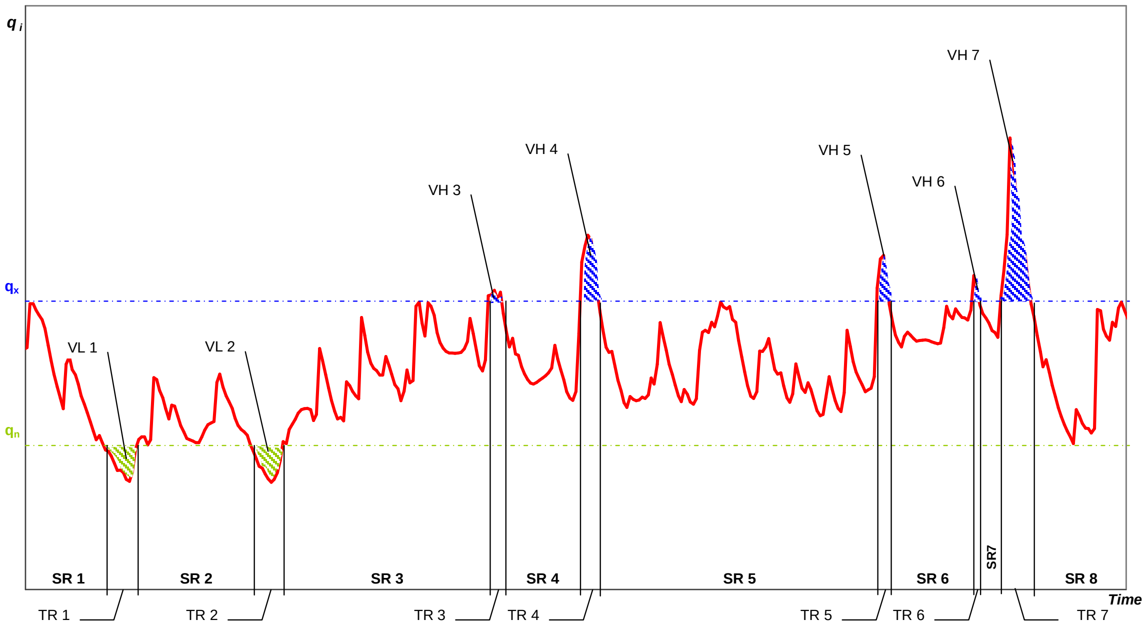

Figure 3: Illustration of the Tactical Regulation (TR) and Strategical Regulation (SR) periods on a hydrograph

VL1 and VLE2 are the volumes of water required to augment low flows during TR1 and TR2 periods. VH3,…,VH7 are the empty volumes needed to reduce high flows during TR3,…,TR7 periods.

The management method exposed in the following section relies on the two kinds of actions presented above.

Management rules during tactical regulation periods

During these periods, the management rules depend only of the upstream flow (natural flow) (q_i). The method proposed a parametric relationship between the reservoir inflow $q_{i,}$ the diversion q_i and release r_i:

- for $q_i > q_x$ $$p_i = \frac{(q_i - q_x)^2}{q_i - q_x + X1}$$
- for $q_i < q_n$ $$r_i = \frac{(q_n - q_i)^2}{q_n - q_i + X2}$$

X1(m3/s) and X2 (m3/s) are two calibrated parameters.

Management rules during strategical regulation periods

During these periods, the management rules depend on the upstream flow as well as the expected future inflow. For example, if a severe drought is awaited, it is important to keep an important quantity of water in the reservoir in order to face future needs.

With the help of an inflow forecasting system, a plan of operation can therefore be designed which gives the volume of water that should ideally be stored in the reservoir at each time step during strategical regulation periods.

During the strategical regulation periods, the stored volume v_i should remain as close as possible of the planned volume w_i:

- when $v_{i-1} > w_{i-1}$, the amount of water $r_i = v_{i-1}-w_{i-1}$ is realised from the reservoir to the river (with $s_i = r_i + q_i \leq q_x$ and $r_i \leq R_{max}$);
- when $v_{i-1} < w_{i-1}$, the amount of water $p_i = w_{i-1}-v_{i-1}$ is diverted from the river to the reservoir (with $s_i = q_i - p_i \geq q_n$ and $p_i \leq P_{max}$).

Without any rainfall-runoff forecasting model, the method can be applied in a degraded mode by selecting an invariant annual curve that define the planned volume for each day of the year. The proposed annual curve will linearly vary between the parameters X3 and X4 corresponding to the dates X5 and X6 respectively as shown in Figure 4.

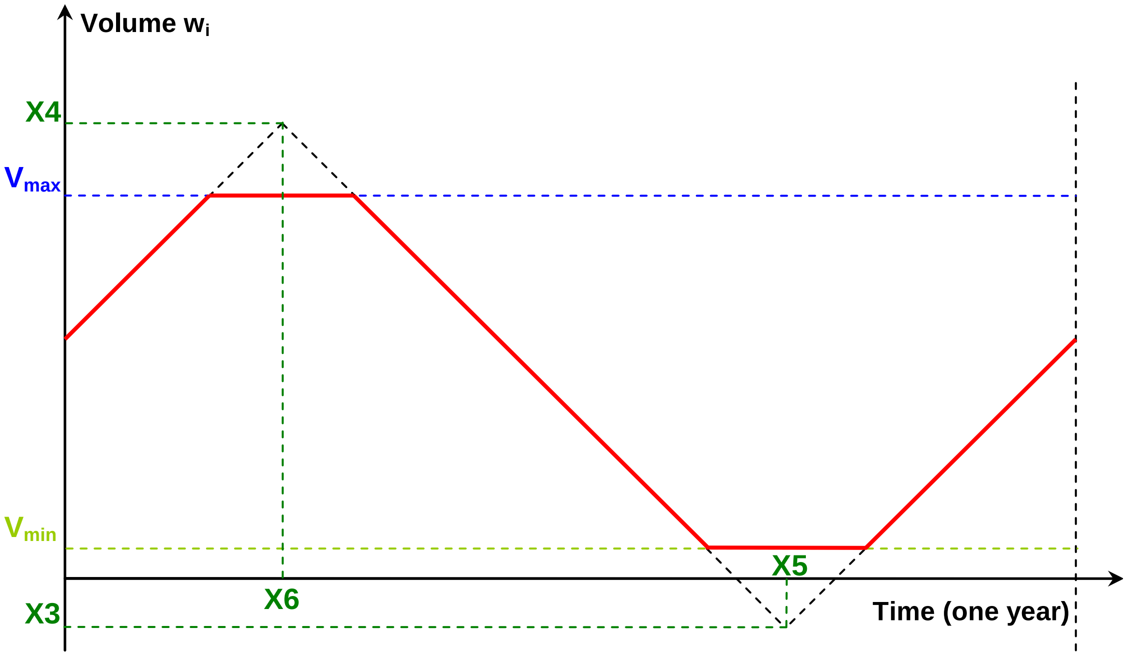

Figure 4: Parameterised annual plan of operation for a reservoir

Parameters X3 to X6 will be calibrated such as X1 and X2.

Quantifying the usefulness of a management method

In order to assess the efficiency of a management method, the following indicator (called gain, G) is defined:

$$G = 100.\left(1 - \frac{Y}{X}\right)$$

With:

$$X = \frac{1}{N}\sqrt{\sum_{i=1}^{N}(q_i - q_X)^2 + C\sum_{i=1}^{N}(q_n - q_i)^2}$$

$$Y = \frac{1}{N}\sqrt{\sum_{i=1}^{N}(s_i - q_X)^2 + C\sum_{i=1}^{N}(q_n - s_i)^2}$$

N: total number of time steps
C: coefficient to put more or less emphasis on low flows. It varies between 10 and 100.

X can be interpreted as an indicator of the number of times the upstream flow ("natural" flow) goes outside the interval $[q_n;q_x]$. Y can be interpreted as an indicator of the number of times the downstream flow ("influenced" flow) goes outside the interval $[q_n;q_x]$.

When G < 0, the management method worsen the downstream situation and when G > 0, the downstream situation is improved when applying the management method (i.e. the method is suitable to regulate flows). When G = 0, the management method has no influence on the flow.

In the approach presented here, G is also selected as the objective function used to calibrate the parameters X1 to X6.

Summary

Aim of the method: provide a parametric reservoir management method

Application: flow regulation with a double objective of flood alleviation and low-flow augmentation

Input data: time-series of upstream flows, reservoir maximum and minimum capacities, maximum capacities of the intake and outlet canals, maximum and minimum allowed (acceptable) flows

Parameters: X1 – parameter for the quadratic diversion formula
X2 – parameter for the quadratic release formula
X3 – minimum volume of the reservoir annual plan of operation
X4 – maximum volume of the reservoir annual plan of operation
X5 – date of the minimum volume of the reservoir annual plan of operation
X6 – date of the maximum volume of the reservoir annual plan of operation

Outputs: time-series of downstream flows, of stored volumes, of amounts of water diverted to the reservoir, and of amounts of water released in the river, efficacy of the method.

2.4 Application : The Caia reservoir (Guadiana basin, Portugal)

This method has been applied on the Caia reservoir located on the lower Guadiana in Portugal (see Figure 5).

Figure 5: Localisation of the Caia reservoir

This reservoir has a capacity of 192 hm3 and an upstream catchment of 222 km². Data collected on this reservoir are described in deliverable D 1.5.2.

A theoretical study has been conducted by applying the previous method of reservoir release management to the Caia reservoir inflow time-series (sum of the flows observed at the stations of Monte-Pisão and Ponte-Algalé) with the following objectives:

- Low flow target of 0.5 m3/s (q_n = 0.5 m3/s),
- Flood control level of 10 m3/s (q_x = 10 m3/s),

The results are given in Table 1.

X1	0 mm/day	**0 m^3/s**
X2	0 mm/day	**0 m^3/s**
X3	100 mm	**33 hm^3**
X4	800 mm	**177 hm^3**
X5	180	**30th june**
X6	10	**10th jan.**
G		**52.2**

Table 1: Calibrated parameters on 01/01/1970-31/12/1980 – Caia reservoir

The gain is equal to 52.2, meaning that the management method is efficient in regulating the flow. Indeed, as it can been seen on Figure 6, all periods of high flows are reduced and low flows augmented, except for few periods.

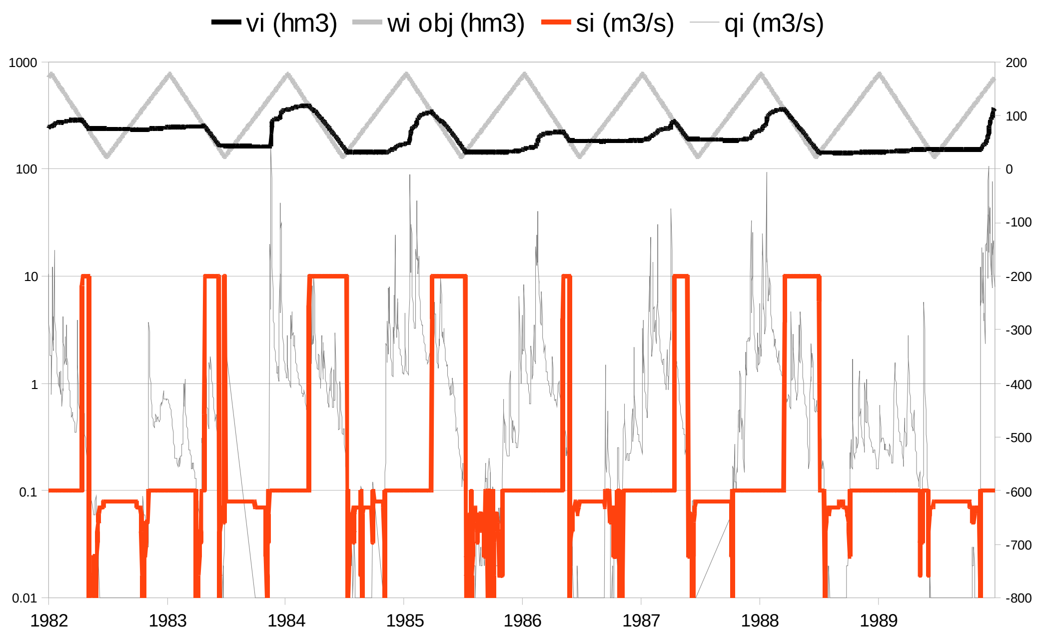

Figure 6: Observed upstream flow (q_i), calculated downstream flow (s_i), target volume (w_i) and calculated stored volume (v_i)

The regulation is efficient but the stored volume does not closely follow the target volume with important deviations especially at the beginning of the year. This can be explained by the large capacity of the reservoir that cannot be refilled by upstream inflows during the winter period.

The calibration gave X1 and X2 = 0, so the amount of water released in the river when $q_i < q_n$ (r_i) and $q_i > q_x$ is equal to q_n-q_i and q_i-q_x respectively. Therefore the regulated flows are constantly equal to q_n and q_x respectively.

The application of the method in this case is only theoretical as water withdrawals for irrigation and water supply have not been considered.

2.5 Conclusion on tools to manage surface water buffering capacity

Partners associated with the work package 1.5 have developed an integrated chain of models to simulate the management of surface water reservoirs:

1. a rainfall simulation toolbox has been developed to generate probabilistic rainfall-scenario (deliverable 1.5.4),
2. a rainfall-runoff model was set-up to transform these rainfall-scenario into medium-term stream flow forecasts (deliverable 1.5.3),
3. a reservoir releases management method was proposed to translate the streamflow forecasts into operational decision rules (this deliverable).

These 3 tools present a minimal algorithmic complexity which makes them suitable for an application in real-time conditions. Comparison with alternative methods (see deliverable 1.5.3 and 1.5.4) has revealed that their parsimony does not prevent them from reaching a high performance level.

3 Case of the natural buffer: managing water levels of a groundwater system

3.1 Bayesian network for groundwater management

A Bayesian network (BN) is a type of decision support system based on probability theory which implements Bayes' rule of probability for interference and reasoning under uncertainty (Jensen 2002; Bromley 2005). This rule shows mathematically how existing beliefs can be modified with the input of new evidence. BNs organise the body of knowledge in a given area by mapping out cause-and-effect relationships among key variables and encoding them with numbers that represent the extent to which one variable is likely to affect another. BNs allows targeted modelling, participatory integrated assessments and strong support for decision making in cases with multiple frames, e.g. when stakeholders perceive the environmental challenges differently, and frame and construct their world in different ways, which might create ambiguous situations and conflicting interests hindering sustainable solutions for management of the environment (Henriksen et al. 2007a).

A BN is a powerful technique to model complex problems involving uncertain knowledge and uncertain impacts of causes. Ideally, BNs is a technique to assist decision-making that is especially helpful when there are scarcity and uncertainty in the data used in making the decision, and when the influencing factors are highly interlinked, all of which makes the problem highly complex. The graphical nature of BNs facilitates formal discussion of the structure of the proposed model, and the ability of a BN to describe the uncertain relationships between variables is ideal to describe the relationship between events, which may not be well understood (Henriksen et al. 2007b).

BNs can help water managers, stakeholders and scientists to visualize and recognise, in the face of complexity and uncertainty, the relationships between different actions and consequences, to make learning about water resource systems more efficient, and encourage the involvement of social and political values in water resource management (Henriksen 2007b). Furthermore BNs is an excellent tool for integrating different domains, e.g. groundwater resources, land uses and socio-economy, and for integrating different knowledge types, e.g. monitoring data, models and expert opinions (Henriksen 2007c).

One of the strength of BNs is the possibilities of integrating results of different domain models, like hydrological models (e.g. MikeShe) and economic models (SIWAP) and stakeholder involvement. A resent study has compared BN and numerical models with respect to stakeholder involvement and domain integrity (Martínez-Santos in press).

Management strategies for dealing with a potential risk for pollution of vital groundwater resources with pesticides from farm applications have been analysed using BN. In the Danish case study Havelse the regional water manager wants to introduce farming contracts compensation farmers for not using pesticides in vulnerable areas. The stakeholder involvement facilitated by the use of BN showed diverse perceptions of groundwater vulnerability and willingness to accept the idea of farming contracts. The BNs allowed stakeholders divergent values, interests and beliefs to be viewed and discussed in a participatory way (Henriksen 2006).

BNs are ideal for water managers to analyse the effects and implications of different management actions and measures on e.g. groundwater resources and socio-economy. In order to assist water managers in evaluating cost and benefits of different management strategies and encircle the optimal solutions to the actual water resources problems, an integrated methodology combining Evolutionary Multi-objective Optimization (EMO) and BNs has been successfully tested (Farmani 2009).

3.2 Key aspects in developing Bayesian networks

Bayesian Networks

A Bayesian network (BN) is used to model a domain containing uncertainty in some manner. This uncertainty can be due to imperfect understanding of the domain, incomplete knowledge of the state of the domain, randomness in the mechanisms governing the behaviour of the domain, or a combination of these. A BN is a network of nodes connected by directed links with a probability function attached to each node. The network or graph of a BN is a directed acyclic graph, there is no directed path starting and ending at the same node. A node represents either a discrete random variable with a finite number of states (used in the present case) or a continuous (Gaussian distributed) random variable. The links between the nodes represent causal relationships between the nodes (Hugin 2007).

If a node does not have any parents, no links pointing towards it, the node will contain a marginal probability table. A discrete node contains a probability distribution over the states of the variable that it represents. If a node does have parents, the node contains a conditional probability table (CPT). For a discrete node each cell in the CPT contains a conditional probability for the node being in a specific state given a specific configuration of the states of its parents. Thus, the number of cells in a CPT for a discrete node equals the product of the number of possible states for the node and the product of the number of possible states for the parent nodes. BNs that are concerned with the causal relations between variables at a given instance are sometimes called Static Bayesian Networks (SBN) (Hugin 2007). The design of a BN for a specific (water resources) problem follows a number of general steps illustrated in Figure 5 (Bromley 2005).

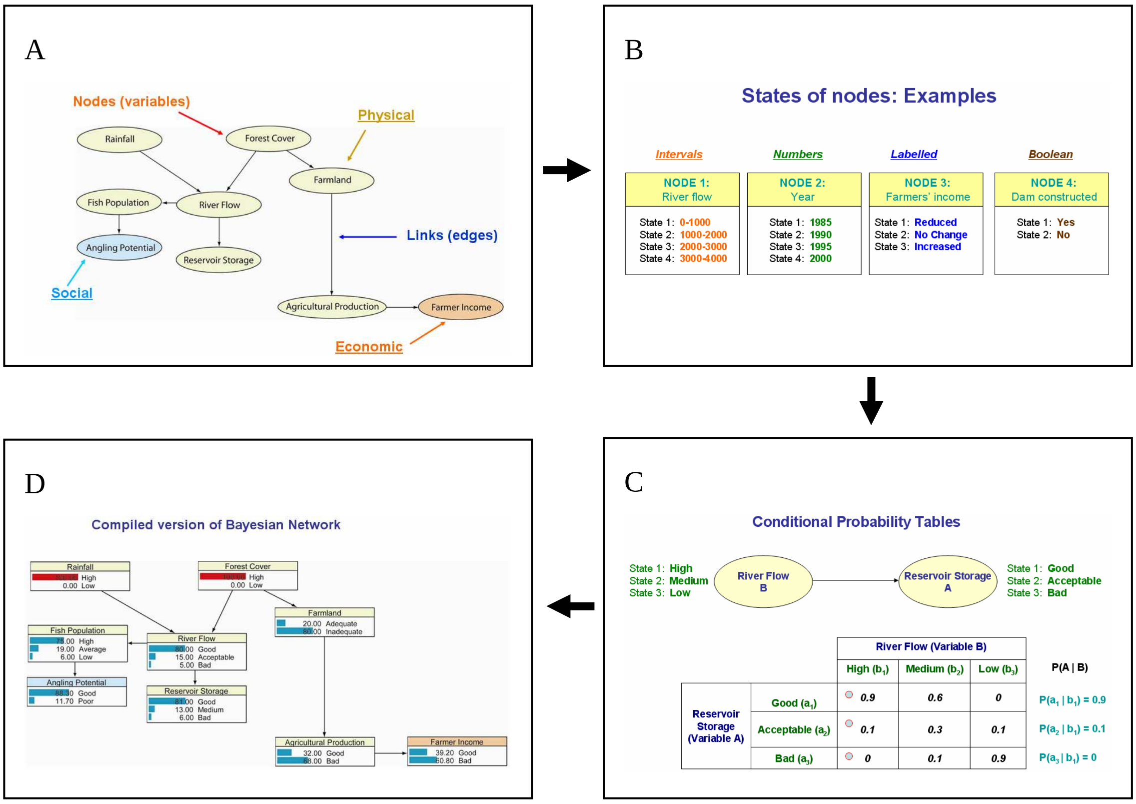

Figure 5: Design of Bayesian network: A) Define nodes and links; B) Assign states and values to nodes; C) Enter values in the Conditional Probability Table; D) Compile BN (Bromley 2005).

In many problem domains it is almost inconceivable to represent data and reason about them without using a temporal dimension, since things evolve through time. SBNs can not be used for such systems and thus the network has to be expanded to include temporal information. Such networks are known as Dynamic Bayesian Networks (DBN). The simplest way to extend an SBN into a DBN is by including multiple instances (time slices) of the SBN and linking these together. An Object-Oriented Network is a network that, in addition to the usual nodes, contains instance nodes. An instance node is a node representing an instance of another network; an instance node represents a subnet (Hugin 2007).

3.3 Application of natural buffer: La Mancha Occidental aquifer, Upper Guadiana Basin

Description of La Mancha Occidental aquifer, Upper Guadiana Basin

The Upper Guadiana Basin (UGB), located in the central plateau of Spain, represents a clear example of social conflict caused by divisive water management strategies. Since the 1970s the region has experienced an agricultural boom based on irrigation resulting in a significant socio-economic development in the area, over-exploitation of the aquifers and a high degree of degradation of natural water-related sites, e.g. Tablas de Daimiel National Park. As a result, conflicts have arisen between the different stakeholder groups: between farmers, environmentalists and the regional water authority, and between legal and illegal water users (Zorrilla 2007).

The wetland Las Tablas de Daimiel was catalogued as a Biosphere Reserve Area in 1981, as part of the UNESCO Man and the Biosphere programme. Between the mid 1970s and the late 1980s over 150.000 hectares of new irrigation areas were established in UGB. Irrigation now accounts for 90% of the total water use in the area and 95% of the irrigation is based on groundwater abstraction. The abstraction reached 600 million m^3 per year by the end of the 1980s and is now around 400 million m^3 per year. The average recharge rate of the groundwater in the western La Mancha aquifer in UGB is estimated to be on average 230 million m^3 per year (Martínez-Cortina 2003).

The intensive use of groundwater has been a main factor for the improvement of the economic situation in region, where agriculture has become a very important sector. Water table drawdown due to the intensive abstraction of groundwater for irrigation has caused severe negative impacts on wetlands, streams and rivers, and has resulted in the lowering of groundwater levels by more than 30 metres (Llamas 2006).

The main conflicts in the area are between farmers and conservationists, between central, regional and local government water agencies, and between small farmers and large farmers. The conflict began about three decades ago (Llamas 1988). In 2001 the Spanish Parliament asked the Government to present a hydrological plan for the Upper Guadiana Basin within one year. More than twenty draft proposals have been presented, and finally in 2008 an Upper Guadiana Water Plan (Plan Especial Alto Guadiana, PEAG) with a budget of almost four billion Euros was passed by the local government.

Water management challenges and opportunities in UGB

The management objectives for UGB is to face and solve the problem of the current unsustainable abstraction of groundwater for irrigation purposes causing severe negative impacts on wetlands and river system due to the significant lowering of the groundwater levels in the area (Henriksen 2007a).

In the UGB, buffering capacity is oriented towards the long-term management of groundwater resources. The buffering capacity is here defined as the number of years required to obtain a recovery of wetlands under various management actions, and economic and climate scenarios (Lerat 2005). The effect of the management actions on the groundwater level in the aquifer is a key parameter. The water management also faces the requirements of the WFD as well as climate changes foreseen by IPCC. The objectives of the WFD have been guiding principles for drafting the water action plan PEAG.

The available groundwater modelling results are associated with La Mancha Occidental aquifer. The present case study is therefore focussing on this aquifer which constitutes 40% of the total area of UGB. La Mancha Occidental aquifer area covers an area of 5500 km^2 and has around 300.000 inhabitants.

Stakeholder involvement for the construction of the Bayesian networks

Stakeholder involvement is essential as a source of data and information in all the steps of the BN construction. But stakeholder involvement can also be very useful for the resolution of conflicts, as it creates a "culture of transparency" stemming from the open use of data within the network. Stakeholder engagement generates a sense of ownership towards the network, and therefore towards any decision based on the outputs of the network (Bromley 2005, Henriksen 2007b, Zorrilla 2007, Martínez-Santos 2008).

The BNs in the Upper Guadiana Basin (UGB) were developed during several meetings between stakeholders and researchers. The construction of the Bayesian network followed the steps described in the MERIT guidelines (Bromley 2005):

1. Define the problem.
2. Identify variables, actions and indicators.
3. Design pilot network.
4. Collect data from all available sources.
5. Define states for all variables.
6. Construct CPTs.
7. Check, collect feedback and evaluate network.

The collaboration with stakeholders in UGB had started long before the idea of BN development was initiated. Several thematic meetings have been organized since beginning of 2005 as a platform for discussion. The specific objectives of these meetings were to: A) Facilitate an informal, unbiased framework for discussion on different aspects of water management; and B) Draft a series of scenarios relating to the development of specific integrated water resources management tools such as hydrological and agronomic models suited to the basin conditions (Martínez-Santos 2008).

The approach took the form of five meetings focused on different aspects of water management in UGB and designed to cover the concerns of all participating stakeholders (Figure 6). These first five meetings were based on a methodology which involves a series of steps, including stakeholder analysis and participation, questionnaire and meeting design, meeting implementation, and reporting (Varela-Ortega 2007).

To initiate the design of the pilot Bayesian networks, two more meetings were held with stakeholders to obtain their contributions to the network design and to identify new sources of data. Stakeholders were separated into two different groups according to their main interests: One group consisted of farmers and regional agriculture institutions; the other group of environmentalists and water authorities. The reason for separation was that the conflicts between the different stakeholder groups made it potentially difficult for them to talk freely, openly and constructively about every issue. These meetings sought to identify as many variables and relationships as possible, and it was decided to have forums that did not restrict discussions to the most contentious issues, something that could have happened in a joint meeting (Zorrilla 2007).

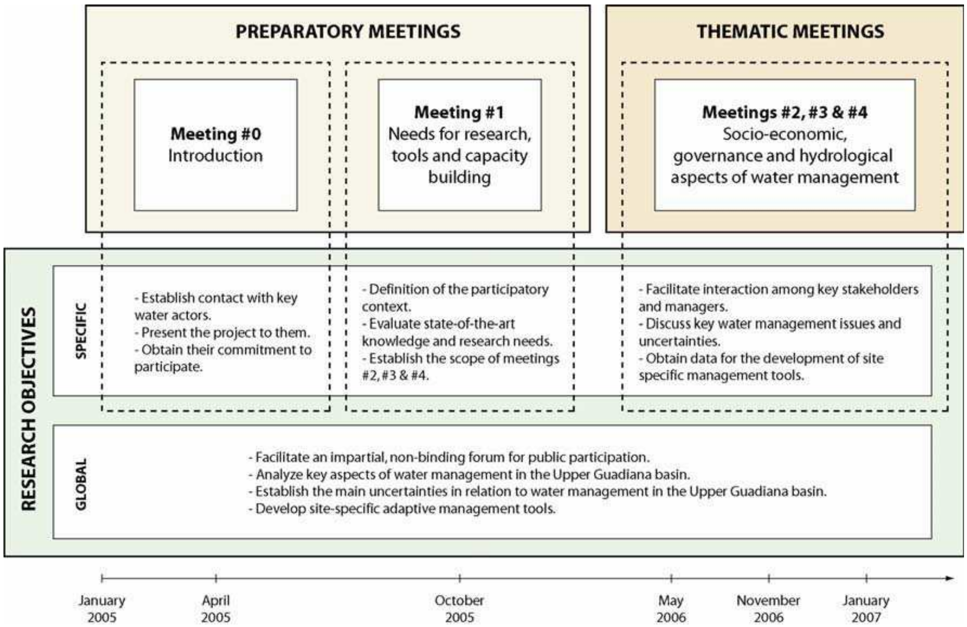

Figure 6: Methodology applied in first series of stakeholder meetings (Martínez-Santos 2007).

One meeting was organized for each group, maintaining a common structure and development. The meetings, both of which were controlled by a facilitator, opened with a brief introduction to BNs followed by an explanation of the steps to build a network based on the methodology proposed by Bromley (2005). Questionnaires were then handed out and the responses were used to help leading discussions, prevent sidetracking, and avoid the predominance of one or another view, and to guarantee the discussion of as wide a range of issues as possible (Table 2) (De la Hera 2007).

Methodology of the questionnaire design
• Networks previously drafted by research team were used as reference for the questionnaire • The questions aimed to clarify the importance and relations of variables • The questions aimed to find out new possible variables • Most of the questions expected to get possible data and states • The questions touched familiar issues for the stakeholders • "Easy to understand" question wording were used

Table 2. Methodology used for the design of the questionnaires that guided the stakeholder meetings (De la Hera 2007).

The questionnaire was developed including questions on social factors, incomes from the agricultural sector, regional distribution of crops, prices and irrigation rights, and environmental and hydrological issues of the Upper Guadiana Basin as a whole (Zorrilla 2007).

The facilitator read out each of the questions one by one, which the stakeholders had answered, and during the course of discussions variables and links were identified, which made it possible to construct a BN based on the input received from the group. This transparent and open approach made it possible for stakeholders to see how the networks were being constructed and enabled them to make changes if they felt this was necessary. Following the meetings each group produced a network which reflected the views and opinions of that group. But by closely examining both networks, and the answers to the questionnaires that were set, it was possible to identify variables and relationships in the system that was common to both groups (Zorrilla 2007).

Data collection began during the first stage of the network construction to help establish the states of the variables and to complete the conditional probabilities tables (CPTs). But data was also obtained from individual interviews with stakeholders including water managers, farmers and environmentalists, and from other sources as statistical data, legislation material, and from scientific reports and papers (Zorrilla 2007).

Some of the variables whose states were defined by stakeholders were: water abstraction costs, farm income, production costs, and agricultural subsidies. One example of the inputs (variables and states) provided by stakeholders is farm income identified by type of farm (type 1, 2 and 3 defined according to farm size) and type of year (good, average and bad). During this step, significant uncertainties about the state of some variables were revealed. It was difficult to establish the degree to which farmers complied with their water allocation under the Water Abstraction Plan. Non-compliance is a major problem, but the question is to what extent. Another difficult variable to define is "Marketing improvement". To quantify this it is important to know how the prices of crops are likely to change in the future, something which is subject to a whole range of influences (Zorrilla 2007).

3.4 Buffering capacity indicators

The buffering capacity concept is meant to support water managers in their planning activities. The objective is to define a set of indicators useful to water managers when selecting policy alternatives. These indicators should be estimated directly from available data or processed through models (Lerat 2005).

Indicators are simple instruments that tell us what is happening in e.g. the fresh water environment. Since the fresh water environment is very complex, indicators provide a more practical and economical way to track the state of the environment than if we attempted to record every possible variable in the fresh water environment. Indicators are tools that can serve different purposes like to see if environmental objectives are being met, to communicate the state of the environment to the general public and decision makers, and as a diagnostic tool detecting trends in the environment. Selecting the type of indicators to work with should be partially based on who will be using the information from the indicators. There are generally three possible audiences to consider, each with different information needs: 1) policy-makers, decision makers and resource managers, 2) technical experts and science advisors and 3) general public and media (Wikipedia 2008, Ditor 2001, Rice 2005).

In UGB the buffering capacity is related to long-term objectives and can be defined by the number of years required to obtain a recovery of wetlands under various management actions and economic scenarios. The development of Bayesian networks for the area covers the two concepts: 1) the "filling level" is integrated through the recovery of wetlands. Wetlands status is the most critical consequence of groundwater over-exploitation. Hence, wetlands recovery is the key variable to qualify the impact of aquifer management and 2) the "time" is naturally present with the estimation of the number of years to reach the objective of wetland recovery.

Note that the concepts present an optimistic vision of buffering capacity in the area. A more pessimistic presentation could be based on the "number of years required emptying the aquifer and destroying the current buffering capacity of the groundwater system", e.g. by creating a set of irreversible conditions in the aquifer due to deterioration of groundwater quality by over-exploitation the aquifer.

Four questions should be considered when developing indicators: 1) Conceptual relevance, 2) Feasibility of implementation, 3) Response variability, and 4) Interpretation and utility (US EPA 2000).

For the present case study five indicators have been defined along with the development of the BNs:

1. Years to wetland recovery (year).
2. Renewable resource / recharge (mm).
3. Number of agricultural jobs.
4. Regional agricultural production (M€).
5. Aquifer status: groundwater level (m.b.g.l).

The indicators are is described in further details below. Each indicator is defined by a scale ranging from "good status/improved conditions" to "poor status/unacceptable conditions" and a colour scale covering "green, yellow, orange and red" (Table 3).

Buffer	Indicator	Probability	Description of consequences
Years to wetland .recovery (year)	0 – 7	20%	Probability of 0,2 for wetland recovery within 0 – 7 years
	8 – 20	40%	Probability of 0,4 that the wetland will recover within 8 – 20 years
	More 20	30%	Probability of 0,3 that the wetland will recover after 20 years
	Never	10%	Probability of 0,1 that the wetland will never recover

Table 3: "Years to wetland recovery", an example of a buffering capacity indicator based out output from a BN.

Description of indicators

1. *Years to wetland recovery:* The expected number of years it will take for recovery of the wetlands, Las Tablas de Daimiel. It is assumed that the water table is 30 m below the bottom of the Las Tablas de Daimiel National Park, and that the full recovery of this wetland requires the water table at level 0 m, i.e. to recover 30 m
2. *Renewable resource, the recharge:* The renewable resource is 425 mill m^3 per year if water level depth is above -3 meters. The renewable resource is 500 mill m^3 when the water level depth is lower than -3 meters. This variable is depending on climate and on the depth of the water table, because the water table influences the evapotranspiration which was significant in the undisturbed situation in UGB. When the water table is low (e.g. below than -3 m) it is assumed that the evapotransporation from the water table is negligible (Martínez-Cortina 2003)
3. *Number of agricultural jobs:* Number of people employed in the irrigated agricultural sector (estimated as full time jobs). It has been calculated multiplying the area of each crop (ha) by the work needed in one hectare of each crop (INE 1999).
4. *Regional agricultural production (M€):* Gross revenue from irrigated agricultural production (in M€). Sum of the value of the regional irrigated products. It has been calculated multiplying the production (ton) by its price sold by the farmers, including subsidies (Valero 2003).

5. *Aquifer status: water level and water quality:* The new aquifer status refers to the expected status of the aquifer after implementation of management measures given the initial state of the aquifer. Five different buffer zones for an aquifer status are defined (see below and Figure 9). The annual change in groundwater level refers to water table level in Mancha Occidental Aquifer. Based on model calculations it is estimated that each 125 mill m^3 difference between renewable resources and abstraction means 1-1.25 m change in groundwater level. When the water table becomes close to the land surface, e.g. 3 m below the surface level, the renewable resources will be smaller due to the evapotranspiration from the water table. (Martínez-Cortina 2003).

Based on the concept of buffer zone in surface water reservoirs (Bras 1983) a concept of five buffer zones for a groundwater aquifer is suggested with reference to the lowering of the groundwater table (Figure 7):

– *Surface water protection zone*, for sustaining the groundwater dependent associated aquatic ecosystems or terrestrial ecosystems.
– *Dry year's buffer zone*, for managing the short term variations in groundwater recharge and water demand.
– *Long drought periods buffer zone*, for managing a several years drought situation.
– *Groundwater quality problems*, natural water quality or man induced deterioration of groundwater quality makes the groundwater less or not usable.
– *Groundwater scarcity problems*, for managing a long period of water scarcity, over-abstraction, or the transition to a dryer climate due to climate change.

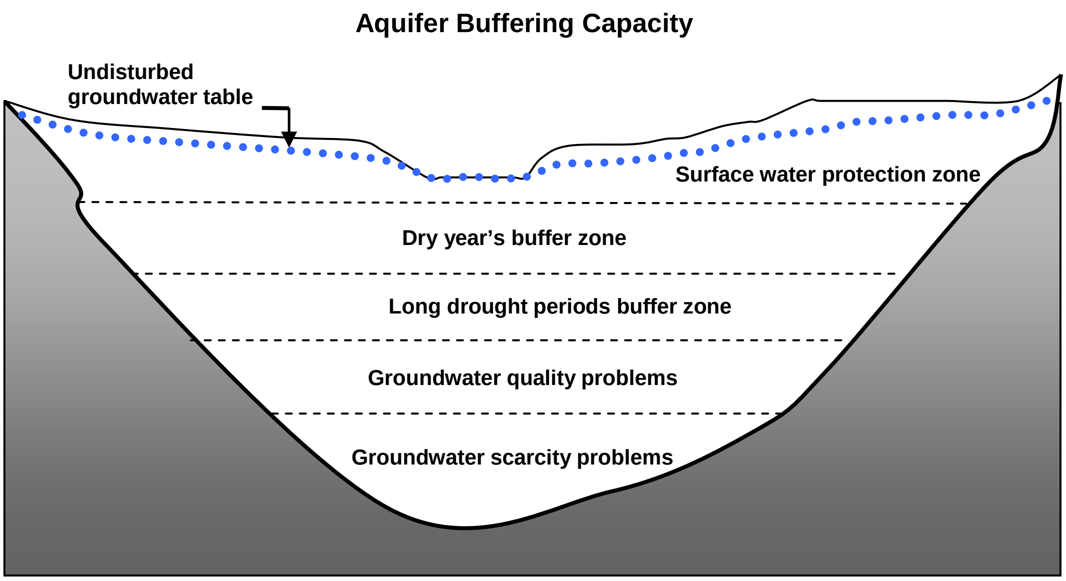

Figure 7: Buffer zones for a groundwater aquifer.

The limitations of this simple buffer zone concept for groundwater aquifers are among other things the aquifer interaction with other aquifers vertically and horizontally, complicated hydgeological settings, various hydrogeological factors governing the groundwater – surface water interaction, and the fact that groundwater quality problems may arise at any depth of an aquifer / aquitard system and may or may not be induced by groundwater abstraction.

Similar to the concept of "aquifer buffering capacity" and concept of "wetland buffering capacity" a concept of three buffer zones for a wetland system is suggested (Figure 8):

– *Surface water protection zone*, for sustaining the groundwater dependent associated aquatic ecosystems or terrestrial ecosystems.
– *Dry year's buffer zone*, for managing the short term variations in groundwater recharge and water demand.
– *Zone of devastating impact on wetlands*, for managing over-abstraction of groundwater, or the transition to a dryer climate due to climate change.

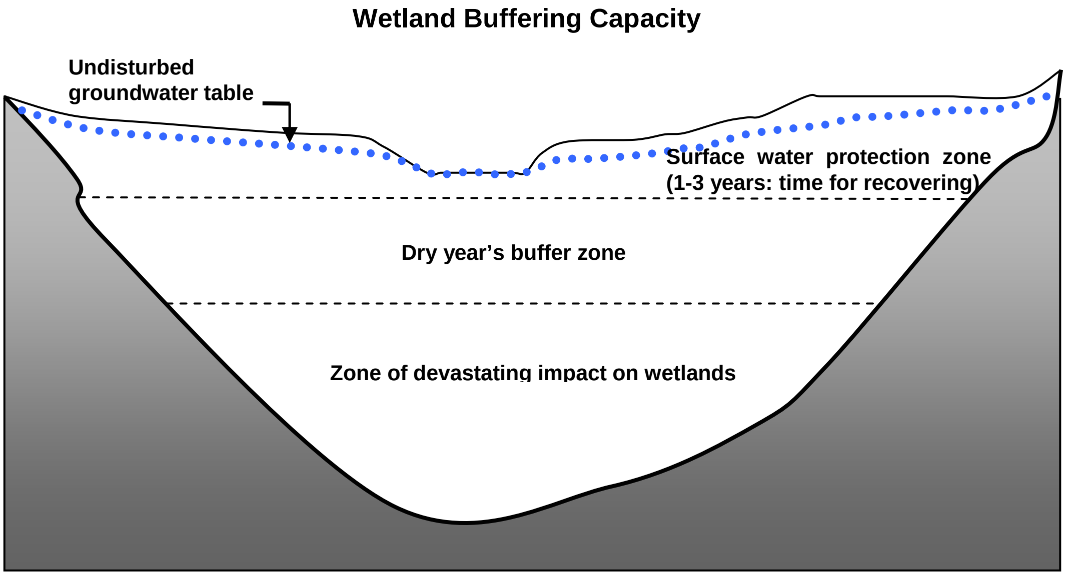

Figure 8: Buffer zones for groundwater aquifer dependent wetlands.

The aquifer scale network, the static network.

The Bayesian network of La Mancha Occidental aquifer works at the aquifer scale. It is used to evaluate the planned actions of the new Upper Guadiana Water Plan (PEAG). The seven management actions evaluated are:

1. A reforestation plan.
2. The purchasing of irrigation rights by the local government.
3. The improvement of the hydrological authority capacity of closing illegal wells.
4. The improvement of the hydrological authority capacity of enforcing irrigation restrictions.
5. A vineyard technology plan.
6. Improvements of the irrigation technology.
7. Tejo-Guadiana water transfer.

The management actions are indicated by yellow nodes in Figure 9. Five variables have been selected as indicators (orange coloured nodes): Years until aquifer recovery, renewable resource, number of agricultural jobs, regional agricultural production (Figure 9), and groundwater level (Figure 10).

The green variables to the right in the BN (Figure 9) affect the increase or decrease of the potentially irrigated land. The decrease of the irrigated land is the main objective of the

Hydrological Authority because it is seen as a key factor for reduction of the groundwater extractions. The light blue variables to the left of the network affect mainly the groundwater recharge and other “not irrigation” water withdrawals. The dark blue variables involve the irrigation crop requirements and technology, and the light green nodes represent climate change issues. The olive coloured variables involve the agricultural issues of the network.

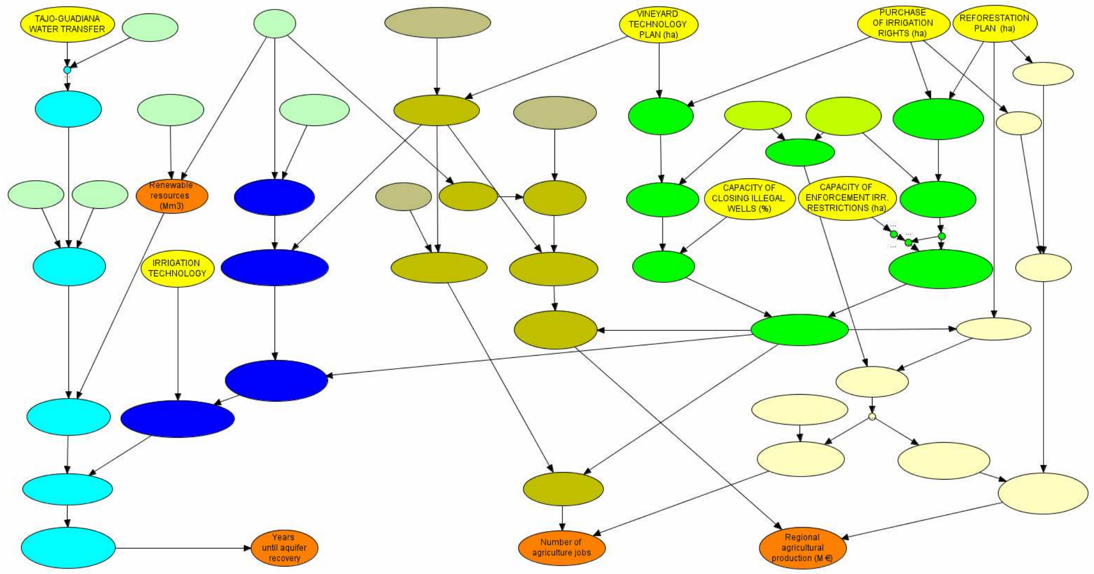

Figure 9: Bayesian network of La Mancha Occidental aquifer, the static network (Zorrilla in prep.).

The states have been constructed for a time scale of one year. Each year the agriculture production and the recovery of the aquifer will be different, depending on the states and probabilities of the parent variables, the management actions. Most of the management actions included in the PEAG are planned to be fully implemented in 2015. The conditional probabilities tables have been completed to evaluate how the situation is expected to be in the year 2015. The probability tables of the management actions have been completed with the probabilities that the stakeholders found that would be the most likely situation in 2015, e.g. a 50% probability that the irrigated land already purchased by the government in 2015 will be between 50.000 ha and 60.000 ha. The outputs of the network, the indicators, reflect the agricultural production and the groundwater extracted in the year 2015. Assuming that the groundwater extractions will be the same each year in the future, the years until the recovery of the aquifer are calculated (Table 4).

The time sliced network, the dynamic network

The time sliced or dynamic network is used to evaluate how different management actions and external factors will affect the actual groundwater level in the aquifer over time, from 2008 - 2027 (Figure 10).

The dynamic Bayesian network represents the aquifer system of La Mancha Occidental from 2008 to 2027, the year in which compliance with the latest extension to fulfil the goals of the Water Framework Directive. The dynamic Bayesian network has been built using the method Object Oriented Network. This method has the advantage that you can use the same Bayesian network, and repeat it as many years as you like (Zorrilla in prep.)

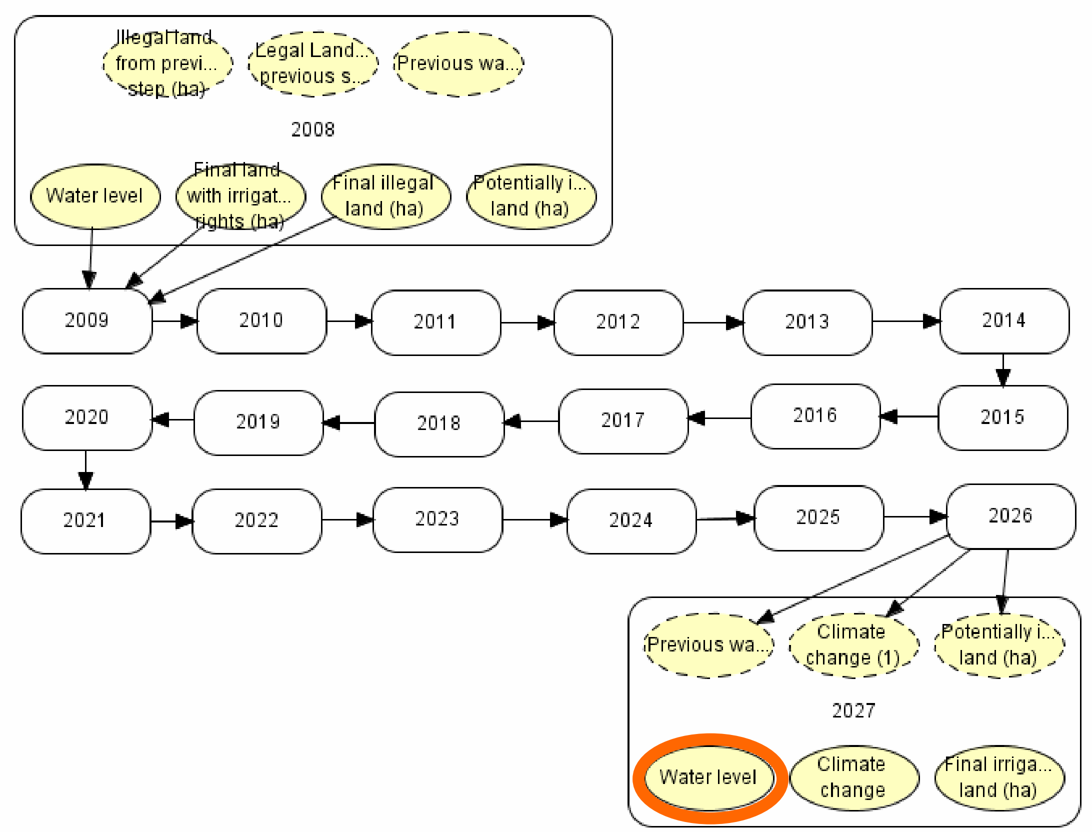

Figure 10: Bayesian network of La Mancha Occidental aquifer, the time sliced dynamic network (Zorrilla in prep.).

Scenarios

Scenario analysis is a process of analyzing possible future events by considering alternative possible outcomes. The analysis is designed to allow improved decision-making by allowing more complete consideration of outcomes and their implications.

Based on the stakeholder meetings three management scenarios have been defined: 1) Business as usual, 2) Most probable implementation of PEAG, and 3) Full implementation of PEAG. The two BNs, the static network and the dynamic network, have been used to analyse the consequences of the three scenarios. The results of the scenario runs by the BNs are shown in Table 4 and 5.

The scenario "Most probable implementation of PEAG" has been constructed with the input of stakeholder. Although the PEAG has set clear and numeric objectives, which are included in scenario 3, the stakeholder meetings have indicated that it is not clear that the objectives are going to be reached. The stakeholders were asked about the rate of success they though each management action was probable to reach. The results showed that stakeholders thought that most of the measures are not going to be as successful as the river basin authority expects.

The scenarios have been built on the assumption that today there are approximately 130.000 ha of irrigated crops. Recent studies show that it seems to be the most probable area. This is an important issue, since some authors calculate that there could be up to 260.000 ha, i.e. a doubling of the number of irrigated crops. It is a sensitive number as using one or the other size of irrigated area completely changes the results of the Bayesian networks (Zorrilla in prep.).

Results

The three management scenarios: 1) Business as usual, 2) Most probable implementation of PEAG (the Upper Guadiana Water Plan), and 3) Full implementation of PEAG, have been analysed with the developed BNs. The results are shown in Table 4 and 5.

Buffer		Indicator	Probability Scenario 1	Probability Scenario 2	Probability Scenario 3
1	Years to wetland recovery(year)	Before 2027	5%	25%	40%
		2027-2055	10%	20%	25%
		Never	85%	55%	35%
2	Renewable resource / recharge (mm)	680-425	20%	20%	20%
		425-300	20%	20%	20%
		300-200	15%	15%	15%
		<200	45%	45%	45%
3	Number of agricultural jobs	>20.000	10%	5%	0%
		15.- 20.000	25%	30%	0%
		10.- 15.000	50%	40%	30%
		< 10.000	10%	25%	70%
4	Regional agricultural production (M€)	550-400	20%	5%	0%
		400-250	65%	45%	15%
		90-250	15%	45%	80%
		0-90	0%	5%	5%

Table 4: Buffering capacity indicators, static network.

The static BN analyses show that both the most probable implementation of PEAG (scenario 2) and the full implementation of PEAG (scenario 3) will increase the probability that the wetland will recover within a period of about 40 years. Only a full implementation of PEAG gives a probability of more than 50% that the wetland will ever recovery (Table 4).

As a consequence of a full implementation of PEAG the static BN analyses show that it is most likely that the number of jobs in the agricultural sector will decrease from 10-20.000 jobs to less than 10.000 jobs, and that the regional agricultural production will decrease from 250-400 mill Euro to 90-250 mill Euro.

Buffer	Indicator	Scenario 1	Scenario 2	Scenario 3	Description of consequences
Aquifer status: ground-water level (m b.g.l)	0 / -5	0%	0%	45%	Surface water protection zone, for sustaining the groundwater dependent associated wetland Tablas de Damiel
	-5 / -20	0%	35%	35%	Buffer zone for managing the short term variations in groundwater recharge and water demand, e.g few dry years. Severe impact on wetland.
	-20 / -50	85%	60%	20%	Long drought periods buffer zone, for managing a several years drought situation or over abstraction. Devastating impact on wetland.
	Below 50	10%	0%	0%	Mining of groundwater resources or the transition to a dryer climate. Risk of groundwater quality problems. Devastating impact on wetland.

Table 5: Buffering capacity indicators, dynamic network

The dynamic BN analyses show that the full implementation of PEAG (scenario 3) will result in a 45% probability that the groundwater level will rise to a level of 0 – 5 meter below surface in 2027, i.e. to level required for sustaining the groundwater dependent associated wetland Tablas de Damiel (Table 5).

4 Conclusion: managing buffering capacity through engagement of stakeholders in the use of simulation models and the use of Bayesian belief networks for reasoning under uncertainty

4.1 Buffering capacity, a powerful concept to handle with care

Buffering capacity is a powerful concept which integrates a wide range of physical processes and water management behaviour. In deliverable 1.5.1, we related this concept with adaptive management observing that increased buffering capacity enlarges the scope of management options and facilitates the transition towards adaptive water management.

As per the definition proposed in deliverable 1.5.1, buffering capacity is a property of a dynamic system that modifies an input signal called driving force and produces a signal perceived by an observer called the beneficiary.

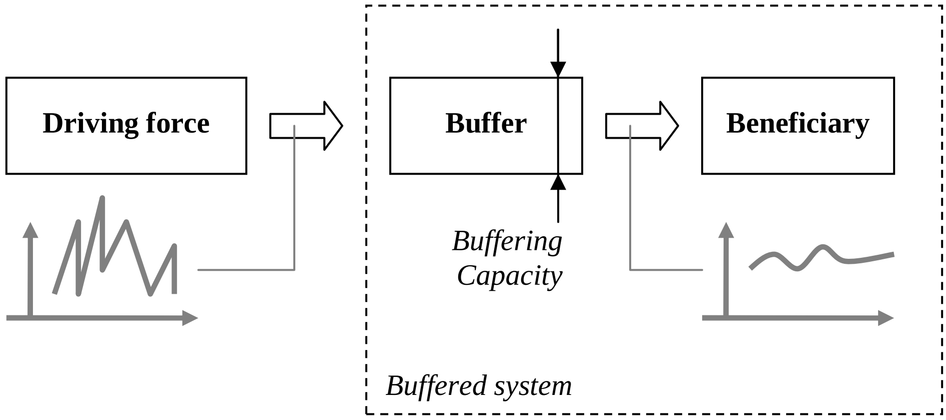

Figure 10: Buffering capacity concept

The previous concept can be detailed as follows:

4. **Driving force**: set of external variables influencing the buffered system (for example atmospheric forcing variables acting on a catchment).
5. **Beneficiary**: any group of individuals or part of the hydrosystem benefiting from the existence of the buffering capacity (for example pikes utilising the flood plain retention capacity for spawning).
6. **Buffering effect**: modification of the time response between driving forces received by the buffered system and the buffered signal received by the beneficiary. Three kinds of transformation were proposed using an analogy with linear systems analysis: gain (modification of the average value), delay and diffusion.

Buffering capacity is a general concept only supported by a limited literature. As a result, there is a high risk of diluting it within general considerations on water management and hydrology. To avoid this undesired situation, it is essential to first define the elements constituting the buffered system and pay special attention to driving forces, beneficiaries and buffering effects. Examples of such procedure are given in deliverable 1.5.1.

Second, one should raise the two following questions:

1. **What are the temporal and spatial scales**? Four set-ups can be found:

- Fixed location, variation in time: Buffering capacity reveals an evolution of the hydrosystem at a given point (for example a comparison of buffering capacity of the Seine basin in Paris on the first and second halves of 20th century).
- Fixed time, variation in location: Buffering capacity reveals the transformation of a signal during its travel through the hydrosystem (for example the transformation of an upstream hydrograph in a reservoir release).
- Fixed time and location: Buffering capacity describes a process in the hydrosystem without any reference to other time periods or locations (for example an aquifer porosity value).
- Variations in time and location: Buffering capacity combines the previous definitions.

2. **How to measure buffering capacity**? We can distinguish two main ways of assessing buffering capacity:
    - Quantitative assessment: buffering capacity is measured by numerical values (physical quantities like a storage capacity expressed in cubic meters, dimensionless criteria, probabilistic assessment...).
    - Qualitative assessment: buffering capacity is associated with subjective qualifications (arbitrary values like "low", "average", "high", ...).

4.2 Buffering capacity needs indicators

The set of indicators measuring buffering capacity constitutes one of the key components of a study on buffering capacity. As the concept can be difficult to grasp, it is essential to use indicators that translate the buffering capacity assessment into concrete figures. Moreover, if simulation models or Bayesian belief networks need to be developed, indicators can be used as deterministic or probabilistic based performance assessment criteria.

Section 3.4 of this deliverable presents a good example of indicators building process in four steps:

1. **Discussion with the stakeholders to identify relevant features of the buffered system**: section 3.2 describes the involvement of the stakeholders during the building of the Bayesian network. This procedure permitted to identify a set of core variables describing the system.
2. **Participatory design of indicators describing the buffered system**: five questions should be considered when developing indicators:
    - *Conceptual relevance*: an indicator should be accepted by all the stakeholders from the scientific community to the general public. In the case of the La Mancha Occidental aquifer it was important that indicators include considerations on environmental protection (wetlands of the Las Tablas de Daimiel) as well as elements on the agricultural sector.
    - *Feasibility of implementation*: the data needs required by the calculation of indicators should be consistent with the available measurement networks. This elementary remark may prove to be challenging regarding variables such as unauthorised water withdrawals.
    - *Response variability*: the systems analysed in buffering capacity studies exhibit marked spatial and temporal variability. As a result, the indicators

that reflect the state of the system will also show complex spatial and temporal patterns. In this context, indicators may require a post-processing treatment to distinguish significant tendencies from the errors introduced during the data collection process (sampling, measurement errors, …).

- *Interpretation and utility*: indicator should be formulated in meaningful way for all stakeholders. Complex mathematical definitions should be avoided as they are suitable for a public with a technical background only. In the case of the La Mancha Occidental aquifer, indicators were formulated in terms of simple figures such as the number of years to recover a good ecological status (indicator n°1). To insist on the uncertainties attached with the indicator estimation, probabilities were associated with indicator values.
- *Degree of vulnerability*: Rather than generating an existing or single indicator, there is a need to develop new buffering capacity index representing the degree of vulnerability of different stakeholders or areas to the changing flow, supply and quality of water resources. Approaches where the interrelationships, links and dependencies are accurately expressed, uncertainty attached to date and understanding explicitly represented, where final results are clearly communicated and where new evidence can rapidly be entered are required.

3. **Calculation and interpretation of indicators:** three situations may arises:
    - *Indicators can be directly calculated from field data:* in this case, the soundness of indicators relies exclusively on the quality of the data collection process. Examples of such indicators where provided in deliverable 1.5.1 based on mean values of hydrological variables (streamflow and rainfall).
    - *Indicators calculation requires a simulation model:* this case corresponds to studies where field data are not sufficient to characterise the system or when a projection on future conditions is required. This point is detailed in the following paragraph.
    - *Indicators evaluation based on a combination of data, results from comprehensive models, expert and stakeholder elicitation:* This case corresponds to studies where Bayesian belief networks and stakeholder engagement is used in a focused dialogue to identify, and for interference on indicators. This point is detailed in the following paragraph.

4.3 Buffering capacity needs simple and transparent models

In many buffering capacity studies, a simulation model is required to extend the available information on the buffered system or a Bayesian belief networks with engagement of stakeholders is required for integration and reasoning under uncertainty. The main objective of such participatory modelling is to support the establishment and calculation of buffering capacity indicators mentioned previously.

A large number of simulation models can be used in the field of water resources management but few intercomparisons have been published. Moreover, models show a wide diversity of implementation cost with no clear relationship with performance improvement. As a result, model selection can prove to be a tricky issue.

In the context of buffering capacity assessment, the most important selection criteria is the transparency for the stakeholders: models introduce an additional level of complexity in the whole process of buffering capacity assessment. This complexity can induce rejection by the stakeholders if they feel disconnected from the model building process. Ideally, the model should be elaborated with the stakeholders like the building of the Bayesian network presented in section 3.2.

For comprehensive groundwater- and surface water models transparency and credibility of such models can be supported by quality assurance and by stakeholder interaction in the modelling construction process. Interaction i.e. to allow stakeholder to give advice to water manager and modeller in the modelling process is appropriate for obligatory public participatory processes. “Engagement” of stakeholders, which represent the level of participation above “interaction” is not evaluated as feasible in the process of construction of comprehensive models (Henriksen et al, forthsomming), but it may when simpler models are used for the construction be more feasible. However, as also demonstrated for Guadiana, stakeholders should be engaged in the simulations and scenario development, and here Bayesian belief networks as well as simple or comprehensive models are useful tools depending on the scope of the buffering capacity analysis.

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