NeWater

BUFFERING CAPACITY ASSESMENT AS A MEAN TO PROMOTE ADAPTIVE MANAGEMENT ALTERNATIVES IN WATER QUANTITY ISSUES

Towards the integration of the buffering capacity concept in decision making processes

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

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1 Introduction

According to the description of work (DoW), “NeWater focuses on the transition of current water management regimes to adaptive water management”. Such a transition requires a clear and precise scientifical background to support a complex strategy definition process.

In the description of work package 1.5, the DoW mentions that “provision and management of storage capacity within a basin is one possibility to reduce uncertainties in water supply, and buffer natural as well as anthropogenic variability, in particular in extreme events”.

Work package 1.5 focuses on the concept of “buffering capacity”. This notion has an interesting particularity: it sounds familiar to many but a detailed analysis reveals a quiet complex picture. As usual, a concept may have diverging interpretations depending on the background of the person.

To avoid meaningless and general formulations, the first step is to identify the scope of our buffering capacity concept for this work package:

- **Buffering capacity analysis will focus on water quantity issues and more specifically surface water and groundwater storage management.**
- **The analysis focuses on variables at large river basin scale.**

The buffering capacity concept is meant to support water managers in their planning activities. The ultimate objective is to define a set of indicators useful to water managers when selecting policy alternatives. These variables could be directly calculated from available data or processed through models.

This document aims to clarify the content of buffering capacity concept in order to initiate discussions with case studies teams.

Here are some of the ideas that emerged when discussing of buffering capacity:

- Buffering capacity is high with large reservoir storages,
- Buffering capacity is higher in aquifers than in rivers because the response to withdrawals is slower.
- Buffering capacity is high when, at the basin outlet, discharge variations are limited compared to rainfall patterns,
- Buffering capacity is high when hydrological behaviour is not sensitive to modifications of climate regimes.

These elements show the great variety of buffering capacity understandings. Hence the first part of this report tries to identify the different types of buffering capacity and their main components. The second part provides examples of buffering capacity assessment. The last part describes the modelling tools required in work package 1.5 to assess buffering capacity.

2 A first approach to buffering capacity

As we mentionned in the introduction, there are several ways to understand buffering capacity. In the scientific literature, buffering capacity is most of the time discussed in connection with water quality preservation, the main concern being the design and operation of “buffer zones” (Correll 2005). Buffer zones are narrow strips of vegetation protecting water bodies from polluted runoff.

As far as water quantity issues are concerned, few analyses have been carried out on the subject. The buffering concept is mainly associated with two notions:

- Within a reservoir, the “buffer zone” is understood as a volume not affected to a particular use. This volume can correspond to water levels between flood control levels and low flows regulation levels as presented in Figure 1. Bras (1983) mentions such a buffer zone for Aswan High Dam reservoir where water levels range between 147 m and 160 m.

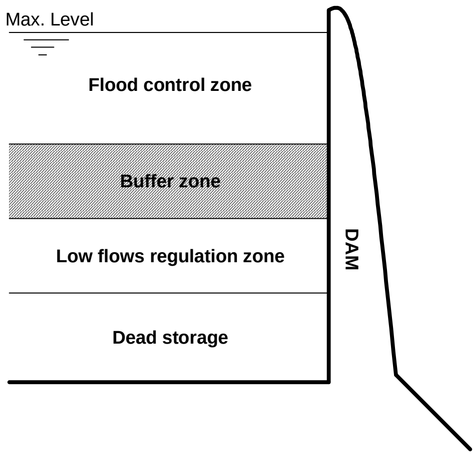

Figure 1: Buffer zone for a reservoir

- With flood protection structures, the buffering effect is the transformation of an upstream hydrograph into a delayed and reduced peak flow downstream hydrograph. Hawker (2000) describes such behaviours in the management of flood control oriented dams.

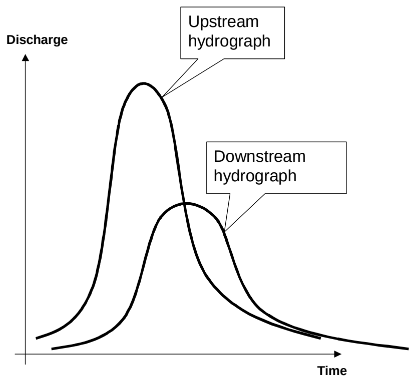

Figure 2: Buffered hydrograph

These two aspects of buffering capacity assessment have fundamental differences: one is a quasi-permanent characteristic (buffer zone is only dependant on management rules), the other is associated with the dynamic behaviour of the sytem (smoothing action over the upstream hydrograph).

The different elements available on buffering capacity can be summarized as follows:

- **In a hydrosystem, a buffer is an element that tempers the effects of driving forces on a part of this system. This part is called "the beneficiary".**
- **Buffering capacity reflects the level of protection provided to the beneficiary.**
- **The driving force is modified while interacting with the buffer and results in a buffered signal.**
- **In this work package, buffers and buffering capacity are related to water quantity and social issues at large basin scale.**

Figure 3 gives a schematic representation of the previous points.

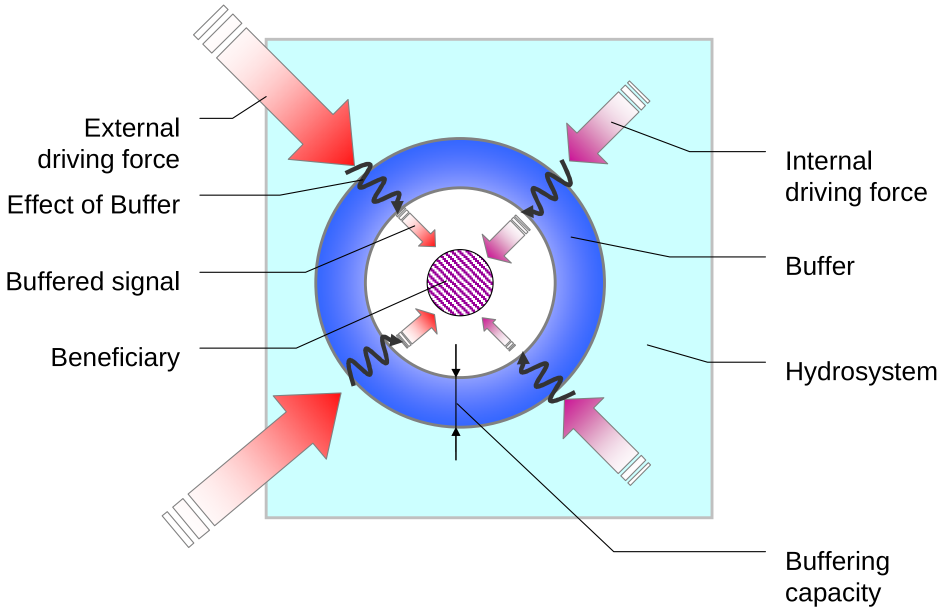

Figure 3: Buffer and buffering capacity

We must be careful with the buffering concept. A quick perception could lead us to a simple storage vision, which is a logical human behaviour: store when it is abundant to face droughts in the future. Such kind of definition could strongly orientate management strategy towards an increase of storage capacity: reservoirs capacity would then be seen as the only way to permanently increase buffering capacity.

This result would be catastrophic in the NeWater project as adaptive management should integrate all needs and uses with particular emphasis on respecting natural hydrologic regime. As a result, buffering capacity, even limited to quantitative aspects, should be in relation with a wider range of hydrosystems processes. Buffering capacity will have to be defined by several indicators to prevent a one-way analysis.

The following paragraphs detail the notions introduced previously and add the information required to draw a comprehensive picture of the buffering capacity concept. In particular, it is necessary to raise the following questions:

- What are the objectives of buffering capacity assessment?
- How it can be practically undertaken?
- What are the temporal and spatial scales?

- What are the associated management strategies with high buffering capacity?

2.1 Objective of buffering capacity assessment

Buffering capacity assessment can be undertaken with two main objectives:

- **Estimate natural characteristics of hydrosystems** : These characteristics cannot be modified at the basin scale (for example rainfall pattern, aquifer porosity,...). But the outcome of this assessment can be integrated in management strategies as invariant facts to cope with.
- **Describe the behaviours of elements under anthropogenic influence** : These elements are under the influence of basin scale management plans (for example a reservoir, a flood plain vegetation,...). Buffering capacity is used to establish a diagnostic or to set targets regarding their achievements (for example the minimal storage capacity of a reservoir at the beginning of the dry season).

2.2 Associated water management strategies

Buffering capacity concept aims to assist the decision making process in water management. It is therefore necessary to establish connections between buffering capacity assessment and practical water management solutions. For example, if dam operating rules reveal low buffering capacity during dry periods, the methodology should tell the operator:

- When does the critical period start?
- How to modify the operating rules to increase buffering capacity?

Another example: when analysing climate change, buffering capacity should quantify global impacts on hydrological regime but also on variables meaningful to water managers:

- What is the impact on flood peaks?
- What is the impact on flood/low flow duration?

This will be the most difficult task for this work package. It is also a fundamental prerequisite to any acceptance of the concept. The following paragraphs give examples of **groundwater management actions to increase buffering capacity**:

- An obvious first method is to utilize groundwater buffering capacity by changing surface water abstractions into groundwater abstractions where that is possible. In Denmark surface water was previously used for irrigation purposes. Today abstraction to irrigation takes place from groundwater, and that in a distance from the river which minimize the maximum reduction of baseflow in river. Establishment of boreholes or dug wells thus if quality is good enough may enhance water supply and reduce impacts on rivers and wetlands at the same time, compared to abstractions directly from the river.
- In some areas the groundwater is overexploited with a continuous lowering of the groundwater table (e.g. Mexico, Yemen, USA, China, Jordan, India, Spain etc.). A second method consists of construction of large-scale groundwater storage projects. Examples of this have been successfully implemented in California, Arizona and Nevada, some of these places water is diverted from streams for recharge into holding basins such as dry ponds, dry creek beds, or other appropriate sites. This method of groundwater recharge is relatively inexpensive. The Orange County Water District in Fountain Valley, California is a leader in groundwater recharge (annual recharge of 308 million m3).

- A third method of groundwater recharge today is the use of injection wells. Treated water is pumped into an aquifer, usually up to hundred meter deep or more, to recharge declining groundwater levels. The injected water must be of very high quality and o proper temperature, or ‘plugging’ of the aquifer can occur due to impurities collecting within pore openings of a groundwater formation. This method is expensive since the water must be treated before injection, and there are also the pumping costs, costs for wells etc. Hereby the groundwater aquifer may be used as a buffer e.g. for buffering seasonal variations in sources and consumption (an example is Las Vegas, where groundwater is infiltrated in groundwater through wells in periods of excessive surface water flow in the Colorado river, and abstracted in the ‘turist season’ with high water consumption).

2.3 Driving forces

As shown on Figure 3, driving forces are the initial factors entering in the buffering capacity concept. The list of driving forces is endless in hydrosystems, their precise identification is only possible in reference to a beneficiary (see §2.4). To concentrate on water quantity issues, we propose to start with the followings:

- **Hydrological processes** (rainfall patterns, streamflow patterns, temperature, evapotranspiration, flood propagation, ...),
- **Hydrogeological processes** (aquifer recharge, exchanges between aquifers and river, water table fluctuations...),
- **Water resource availability for human consumers** (reliability of supply at the head of an irrigation canal, boreholes productivity,...),
- **Social behaviours related to water management** (impact of institutional framework, willingness to pay…)

Many other subjects could be added to this list. The work with the case studies teams will certainly enrich the buffering capacity concept.

One could find this first definition restrictive. Buffering capacity could be also defined for water quality (pollutant dynamic) or environmental processes (variation of habitat quality). The limitation introduced here is in line with the definition of the WP 1.5 that “focuses on the role of artificial and natural storages for adaptive management. It investigates how new management approaches to stored water, new storage capacity, and better account of climate variability can increase the buffering capacity of a basin”.

2.4 Beneficiary

We propose a simple description of the beneficiaries:

- **Human beneficiary**: any body or group of individuals expecting services from the hydrosystem (water supply utility expecting water from a reservoir, village expecting flood protection from a dyke,...).
- **Non human beneficiary**: any part of the hydrosystem getting benefits from the existence of buffering capacity (for example pikes utilising the flood plain retention capacity for spawning, ...).

2.5 Buffers and buffering effects

Buffering capacity measures the ability of a part of the system named “buffer”, to temper driving forces effects on a beneficiary (see Figure 3). Buffers can be all parts of a hydrosystem able to perform such action. The main buffers that will be studied in this work package will be the followings:

- River catchments as a whole (with their capacity to integrate climatic forcing),
- Aquifers,
- Reservoirs,
- Flood plains,
- ...

Buffers can act on driving forces in numerous ways. **The most common buffering action is the modification of the time response.** If driving forces and buffered signal (see Figure 3) can be expressed with physical time-varying quantities, buffering capacity can be assimilated with the transformation of the time response between buffer inputs (driving forces) and outputs (buffered signal). Four kind of transformations are proposed:

- *Modification of the average properties of the signals*: Buffer does not modify the dynamic of the input signal but acts on its fundamental descriptors. Climate change impact is the most significant example of such action. Figure 4 provides a more precise illustration: if climate becomes dryer, annual flow is reduced. The level of annual flow reduction reflects the buffering capacity, the lesser the reduction, the higher the buffering capacity.

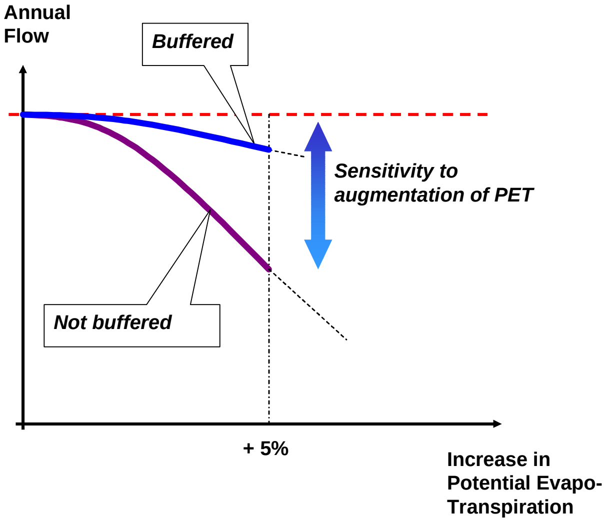

Figure 4: Climate change impact on streamflows

- *Delaying*: Buffer introduces a temporal shift in the driving force dynamic. The impact of a flood protection reservoir on flood peaks can be an example of such action (see Figure 2).
- *Smoothing*: Buffer reduces the variability of input signals (driving forces) to produce a smoother response (buffered signal) utilised by beneficiaries. Figure 5 illustrates this process.

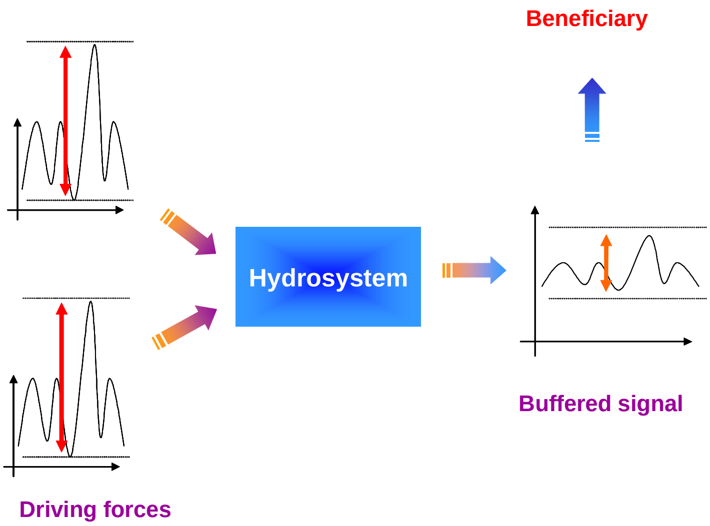

Figure 5 : Illustration of hydrosystem buffering action

Catchments can be assimilated as a buffer that combines all the previous effects in the rainfall-runoff transformation (see Figure 6).

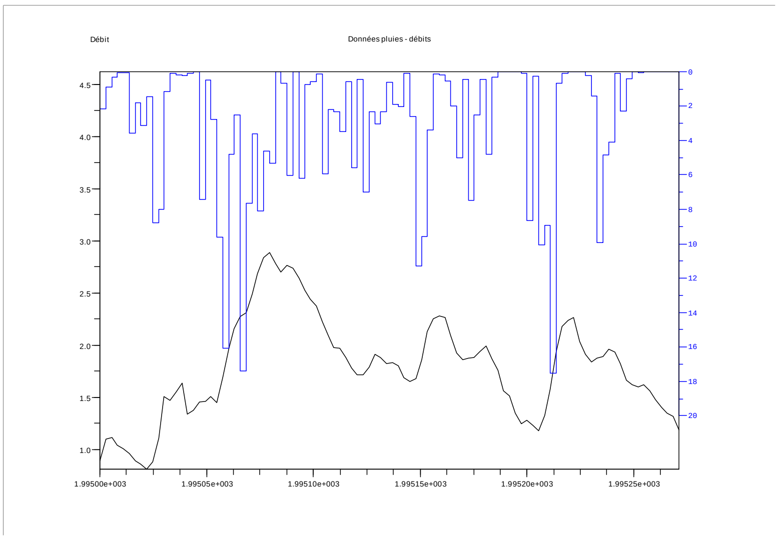

Figure 6: Rainfall-runoff smoothing transformation (Seine river in Paris with discharge and rainfall expressed in millimeters)

If the driving force or the buffered signal cannot be expressed by physical quantities, the definition of buffering effect becomes more complex. We propose to start with the idea that **<u>high buffering capacity increases the number of management alternatives</u>**.

The allocation of water from a reservoir between competing users can be expressed in these terms : the system will be qualified as buffered if the operator has identified a well established system of priorities among the users and can select between different water allocations. With a given storage level, he can choose to satisfy only the top priority users (in a very dry year for example) or equally share between all the users (if he estimates that top priority users can be satisfied later on). It is a direct measurement of the adaptive capacity of water management.

A second example can be found in flood alert systems. The first flood level is usually called "warning level". No damage to property is associated with this level but small increases could be problematic. The second level is the "alert level". At this level, the first damages appear. Hence, if the gap between these two levels is small (compared to local dynamics of water levels), the system will be qualified with a low buffering capacity. It offers limited possibilities to react when the warning level is exceeded. Controversially, if this gap is important, the managers will have time to launch evacuations.

2.6 Assessment methods

The previous paragraphs describe buffering capacity concept in terms of driving forces, buffer and beneficiary. All this remains at a conceptual stage and does not provide the final elements or figures used by water managers.

This will constitute a key element in the sub-sequent work package activities as it covers both scientific issues (how to measure a reliable buffering capacity?) and communication issues (what kind of buffering capacity is meaningful for water managers?).

At present 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",...).

2.7 Temporal and spatial scales

Selecting proper temporal and spatial scales is decisive in analysing the different elements constituting buffering capacity concept. 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, see Figure 2).
- **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.

In this work package, spatial reference will cover mainly large basin scale. Temporal reference will concentrate on monthly or larger time steps.

2.8 Conclusion on the buffering capacity concept

The previous paragraphs offer a first description of what buffering capacity can cover. To develop indicators used in the decision making process, one should clarify the following points:

- Objective of buffering capacity assessment,
- Associated water management strategies,

- Driving forces,
- Beneficiary,
- Buffer and buffer effects,
- Assessment methods,
- Temporal and spatial references.

All these elements are necessary to build robust and useful indicators. The following paragraphs show illustrations of such indicators.

3 Buffering capacity in real life

This section presents a list of examples illustrating the concept of buffering capacity. These examples aim at:

- Presenting cases in which a preliminary buffering capacity assessment is performed,
- Identifying the usefulness of this assessment,
- Applying an assessment methodology to practical cases.

3.1 Control over annual streamflows

Context description

The buffering capacity of surface water systems is naturally associated with reservoirs. A simple question can then be asked: how much do we store? The dam capacity cannot be the only answer considering the great variety of hydrological regimes targeted by dam construction. Storing 10 Mm^3 has not the same meaning on an upstream tributary of the Seine River and on the Nile at Aswan. This example provides a simple way to assess the relative importance of a storage capacity considering the local hydrology.

According to paragraph 2, this example can be described in the following terms:

- Objectives: First assessment of flow regulation level,
- Driving forces: Streamflow regime,
- Beneficiary: users of the stored water (Seine reservoir main purpose is downstream low flow regulation for Paris area water supply),
- Buffer: storage capacity of artificial reservoir,
- Buffering effect: Smoothing the regime by lowering peak flows and augmenting low flows,
- Buffering capacity assessment: dimensionless criteria (see below),
- Temporal and spatial reference: Time is fixed, two locations covered: upstream and downstream of reservoir.

Benefits to gain from such buffering capacity assessment

This assessment of buffering capacity provides a first assessment of the level of artificialisation in a river basin. It can be used to present the impact of a reservoir on a downstream point (such impact is often less important that what is perceived by most of the stakeholders).

Criteria formulation

Buffering capacity is assessed according to the following formula:

$$BC = \frac{V}{\overline{Q_a}}$$

where **V** is the normal storage capacity (Mm^3)

$\overline{Q_a}$ is the mean annual discharge at the outlet of the studied basin (Mm^3).

Example of calculation and analysis of results

Figure 7 presents the location of the four reservoirs on the Seine river basin upstream of Paris. The normal storage capacities are the following:

- Reservoir "Marne" : 350 Mm³
- Reservoir "Aube": 170 Mm³
- Reservoir "Seine" : 205 Mm³
- Reservoir "Pannecière": 80 Mm³

The total storage capacity is then 805 Mm³.

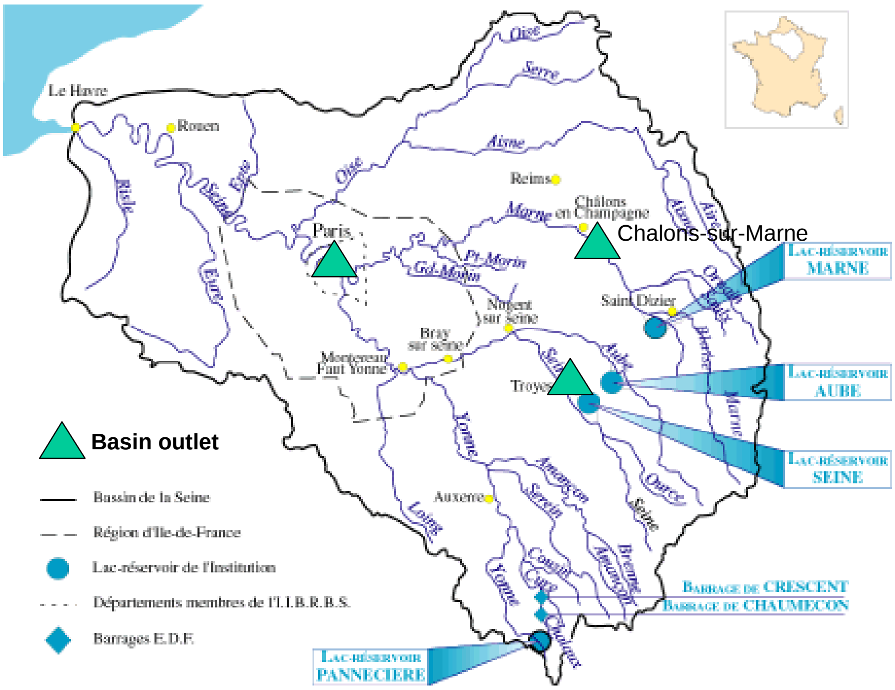

Figure 7: Reservoirs system on the Seine river basin upstream of Paris[1]

Different basin outlets will be considered as presented in the Table 1.

Outlet point	Upstream normal storage capacity (Mm³)	Catchment area (km²)	Mean annual discharge 1975 – 2001 (Mm³/year)
Paris	805	43 800	10 300
Châlons-sur-Marne	350	6 280	2 400
Troyes	205	3 410	1 000

Table 1: Summary of characteristics for the Seine river basin

Daily discharge data for these outlets are presented on Figure 8.

[1] Cf. Web site of "Institution Interdépartementale des Barrages-Réservoirs du Bassin de la Seine" (http://www.iibrbs.fr/crue/crue.htm).

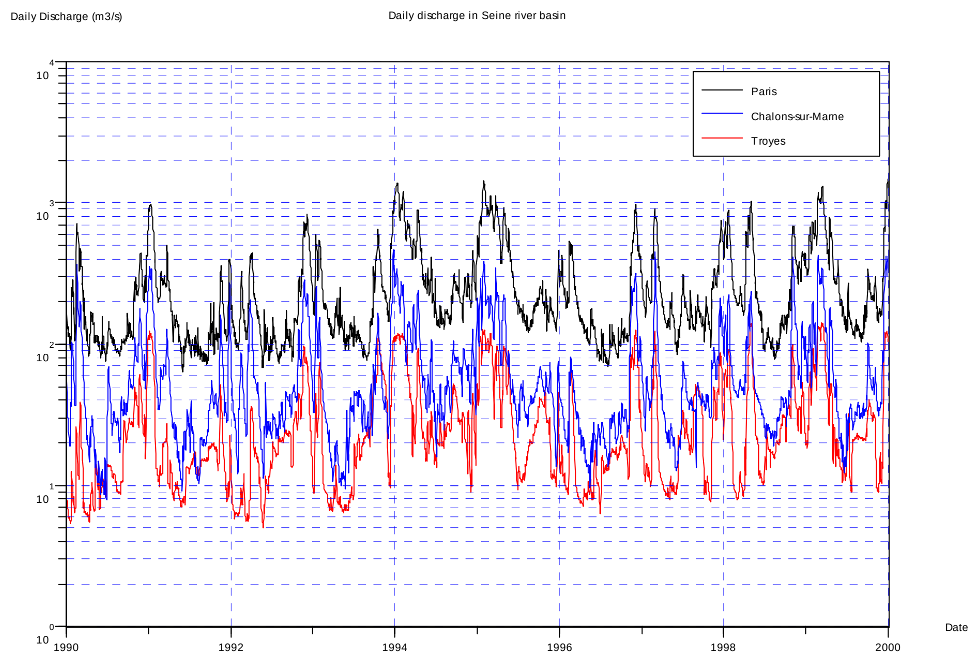

Figure 8: Daily discharges in the Seine river basin

Buffering capacity calculated according to the previous criteria gives the following results:

- **For the Seine river basin in Paris: BC = 8% (805 / 10 280),**
- **For the Seine river basin in Troyes: BC = 19 % (205 / 1 070),**
- **For the Marne river basin in Chalons-sur-Marne: BC = 14 % (350 / 2 440).**

These figures reveal that control over Seine river flows in Paris is important although limited to moderate range of events. They also confirm that reservoir impact is decreasing with downstream distance.

Based on the data communicated by Bras (1983), the same criteria can be calculated for the Aswan High Dam:

- The live storage volume of Lake Nasser is 147 000 Mm^3,
- The Nile provides approximately 84 000 Mm^3 per year.
- Buffering capacity would then reach an impressive 165 % value.

In this case, control over Nile flow is tremendous. The difficulty with such storage capacities is the inertia of the reservoir management due to low renewal rate. Emptying lake Nasser is a decision that will influence a much longer period than in the case of Seine river reservoirs.

3.2 Storage capacity and respect of downstream flow targets

Context description

The main problem in reservoir management is the uncertainty in future climatic and therefore hydrological conditions. With a given storage level, the operator is not sure whether this volume will be sufficient to meet the demand in the coming days or months. To face this uncertainty, managers rely mostly on pre-defined operational rules. Hawker (2000) describes these rules for selected large dams.

Here we suggest an indicator comparing storage levels and the volume required to meet reservoir objective. For a given objective, the same amount of water does not have the same value in the middle of the dry season and during winter. So buffering capacity needs to take into account the stored volume but also the needs for this water in the coming period.

According to paragraph 2, this example can be described in the following terms:

- Objectives: Assessment of operational rules reliability,
- Driving force: reservoir inflow,
- Beneficiary: downstream users of reservoir outflows,
- Buffer: storage capacity of artificial reservoir,
- Buffering effect: Smoothing the regime by lowering peak flows and augmenting low flows,
- Buffering capacity assessment: dimensionless criteria (see below),
- Temporal and spatial references: Varying time (criteria calculated on a daily basis) and fixed location (criteria calculated at the reservoir site only).

Benefits to gain from such buffering capacity assessment

This indicator is to be used in a diagnostic phase, to check the efficiency of operational rules and identify critical periods and level of deficiency.

Criteria formulation

The criterion establishes a ratio between a storage level at a given time and the volume required to meet the objectives in coming period of defined length.

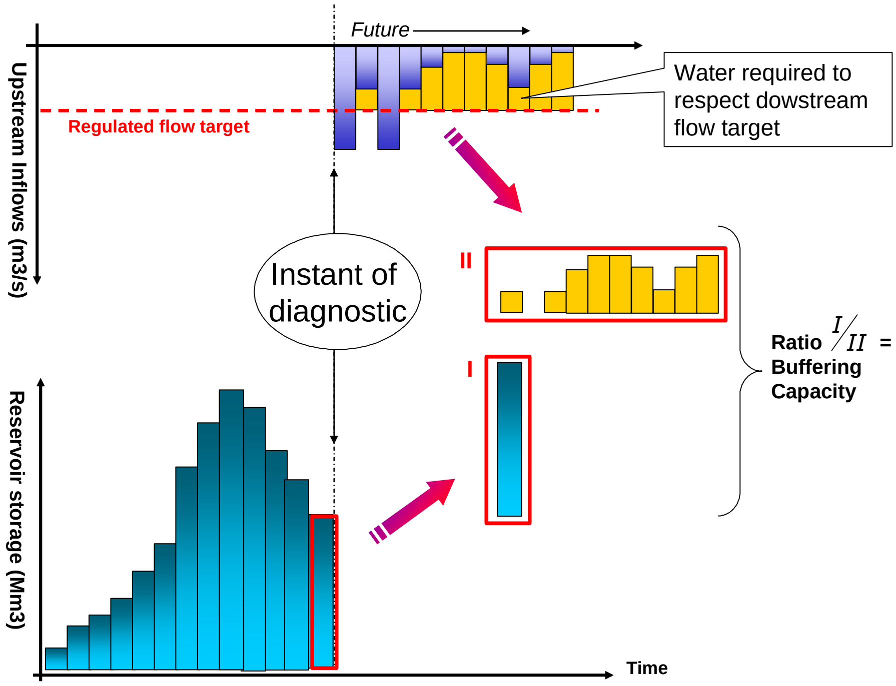

Figure 9: Storage capacity and respect of downstream flow targets

For low flow regulation objectives, the aim is to maintain downstream flows over a given level. When upstream flow is larger than the objective, no regulation is required; when upstream flow is lower, the reservoir has to release the difference between upstream flow and the objective. The criteria can then be formulated as follows (see also Figure 9) :

$$BC_i = \frac{S_i}{\sum_{k=i}^{i+D} \max(Q^{LOWFLOW} - Q_k, 0)}$$

where i is the day when the criteria is calculated,

D is the length of the period during which the objective has to be met,

$Q^{LOWFLOW}$ is the downstream low flow regulation objective,

S_i is the storage level on day i,

Q_i is inflow on day i.

A value greater than 1 means that the storage level on day "i" is sufficient to maintain downstream discharge over the low flow regulation objective for the next "D" days period.

For a flood protection objective, the aim is to lower peak flows under a given level. The problem is reversed and the criteria can be formulated as follows:

$$BC_i = \frac{S_i}{\sum_{k=i}^{i+D} \max(Q_k - Q^{FLOOD}, 0)}$$

where Q^{FLOOD} is the downstream flood protection objective.

A value greater than 1 means that the storage level on day "i" is sufficient to maintain downstream discharge under the flood protection objective for the next "D" days period.

<u>Example of calculation and analysis of results</u>

The two criteria have been applied to reservoirs in the Seine river basin, the reservoir "Seine" and reservoir "Marne" (see Figure 7).

Figure 10 shows the inflows series of the two reservoirs with the low flow and flood targets. Figure 11 shows the same data with discharge of the Seine River in Paris. Figure 12 shows the daily storage value in the two reservoirs.

Figure 13 shows the results of the buffering capacity calculations in summer periods for low flow buffering capacity (April to October) and winter periods for flood buffering capacity (November to April). Outside those periods, the criteria reach very high and meaningless values.

Table 2 indicates the parameters used to calculate buffering capacities.

	Flood protection objective	Low flow regulation objective	Objective respect period
Reservoir "Marne"	80 m³/s	30 m³/s	200 days
Reservoir "Seine"	80 m³/s	30 m³/s	200 days

Table 2: Parameters used for the buffering capacity calculations

These objectives are arbitrary and do not reflect any real operational rule.

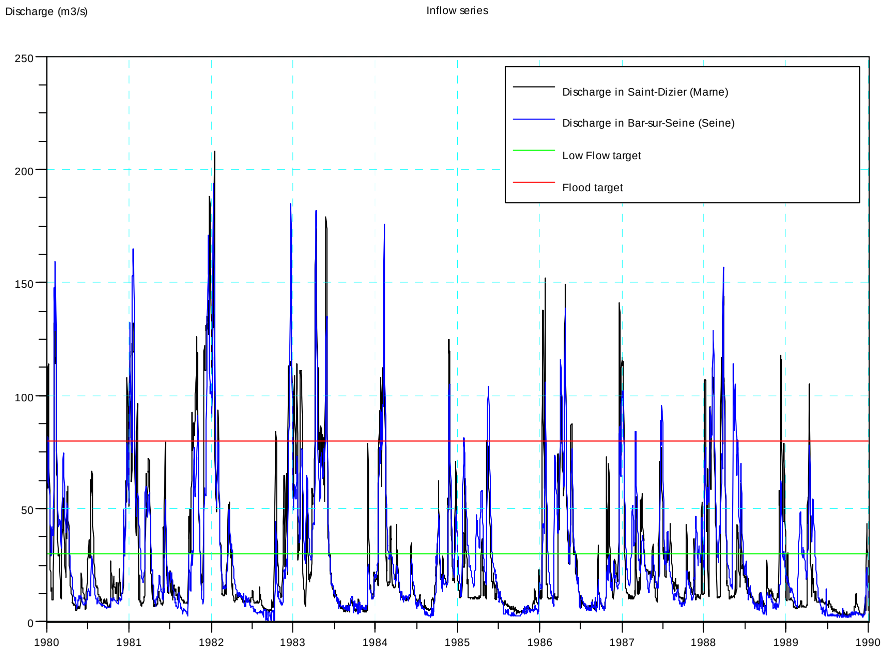

Figure 10: Reservoirs inflows (m³/s) with low flow and flood regulation objectives

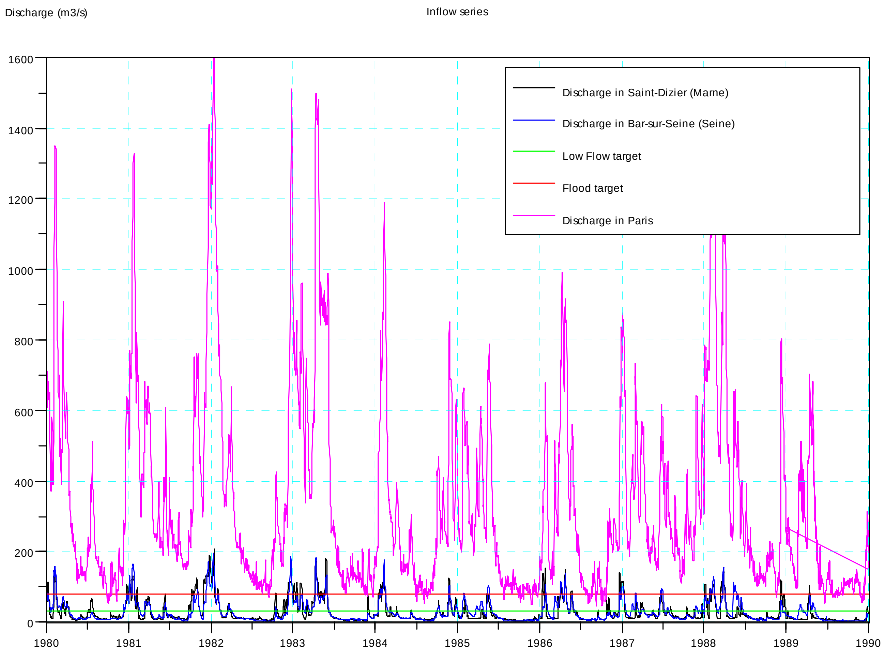

Figure 11: Reservoirs inflows with discharge in Paris (m³/s)

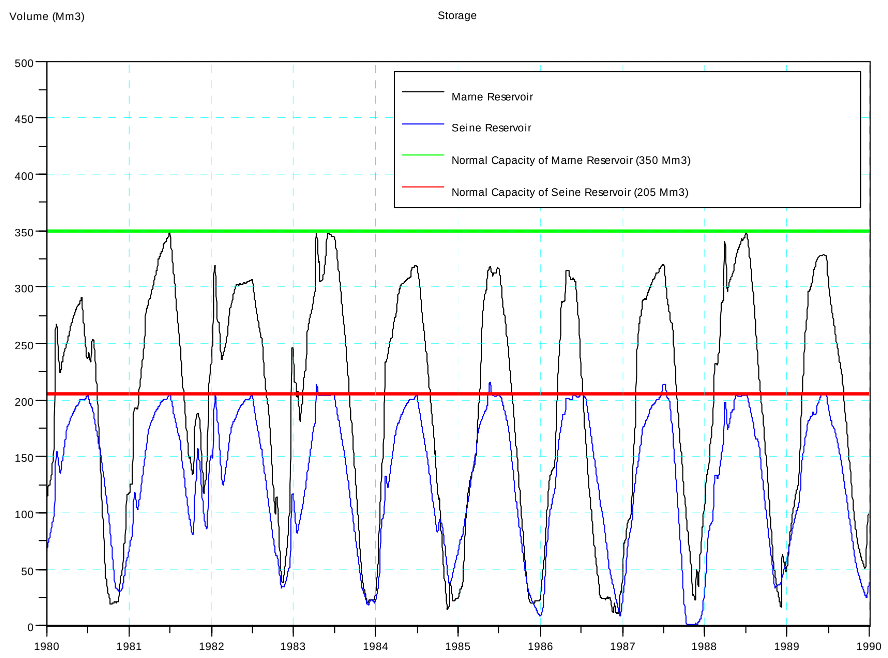

Figure 12: Reservoirs storage with normal capacity (Mm3)

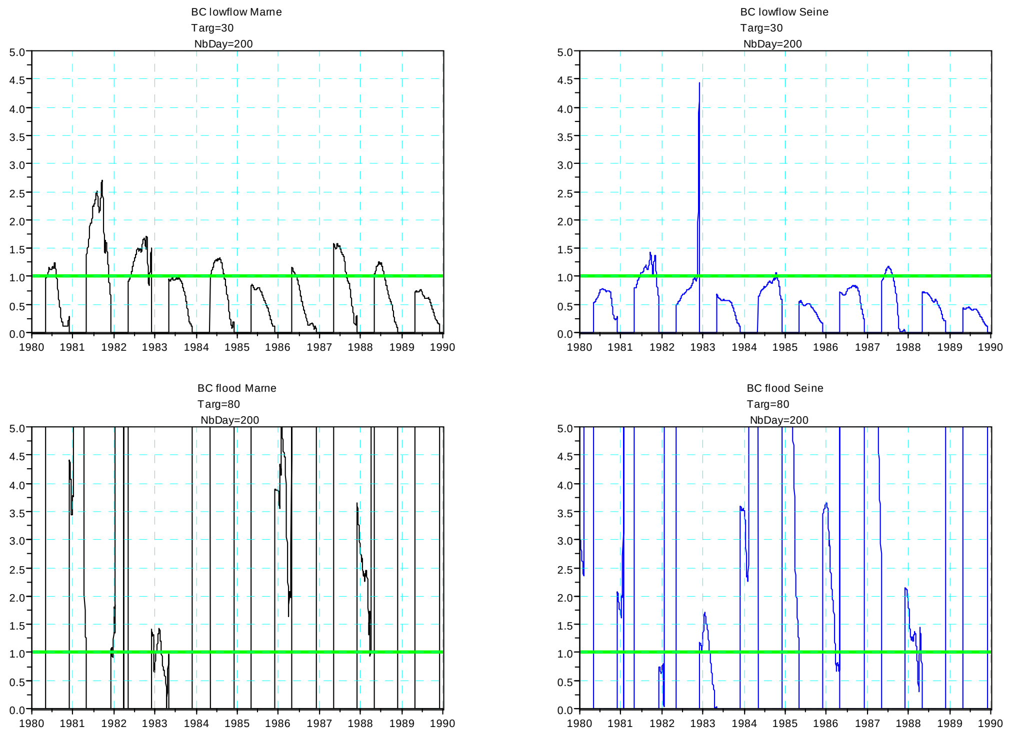

Figure 13: Buffering capacity calculation results with the “BC = 1” level

The different results indicated in the previous figures lead the following analysis :

- The objective would have major impacts at the reservoir level (see Figure 10) but remain modest comparing to streamflows in Paris (see Figure 11).
- The reservoir "Marne" shows greater buffering capacity due to its bigger size (350 versus 205 for reservoir "Seine") with similar inflows.
- Buffering capacity associated with flood control is much more important than with low flow regulation with the objectives defined in Table 2. In fact, the objectives are more ambitious for low flow regulation than for flood protection, therefore volumes required for flood protection are small compared with low flow regulations.
- The results of this buffering capacity analysis integrate:
    - Local hydrological regime (through inflow series),
    - Operational rules (through storage level series),
    - Objective to be defined by local stakeholders (downstream flow objectives and duration of regulation impact).

3.3 River basin response to rainfall pattern

Context description

River basin acts as an integrator of the rainfall signal. This behaviour influences (among many others) our relationship with the hydrosystem. It impacts on flood generation, drought conditions and variability of water resources.

The sensitivity of streamflow to modifications in rainfall pattern is a crucial issue and the subject of many research programs (Sankarasubramanian and Vogel 2001).

According to paragraph 2, this example can be described in the following terms :

- Objectives: Assessment of the impact of rainfall pattern modification on streamflows,
- Driving force: Rainfall pattern,
- Beneficiary: no clearly identified beneficiary,
- Buffer: Catchment (impact on rainfall-runoff transformation),
- Buffering effect: reduction of rainfall signal variability when transformed into runoff,
- Buffering capacity assessment: dimensionless criteria (see below),
- Temporal and spatial references: fixed time (criteria based on inter-annual data) and fixed location (criteria calculated for a single catchment at a gauging site).

Benefits to gain from such buffering capacity assessment

This criterion could be used to identify regions highly exposed to climate change.

Criteria formulation

Buffering capacity is assessed according to the following formula:

$$BC = \frac{\sigma_{P_a}}{\sigma_{Q_a}}$$

Where σ_{Q_a} is the standard deviation of annual discharge serie Q_a (mm),

σ_{P_a} is the standard deviation of annual rainfall serie P_a (mm),

Example of calculation and analysis of results

To apply the previous criteria, a database has been set up out of data collected from the internet :

- Discharge data from www.rivdis.sr.unh.edu: these data originate from UNESCO river archives and cover monthly flow values upto 1990 if available,
- Rainfall data from http://cdiac.ornl.gov/epubs/ndp/ndp041/ndp041.html : data have been collected during the Global Historical Climatology Network (GHCN) project. Data were produced jointly by the U.S. Department of Energy's Carbon Dioxide Information Analysis Center (CDIAC), the National Oceanographic and Atmospheric Administration's National Climatic Data Center (NCDC). Datasets cover monthly precipitation up to 1990 if available.

Figure 14 presents the results of the buffering capacity calculations.

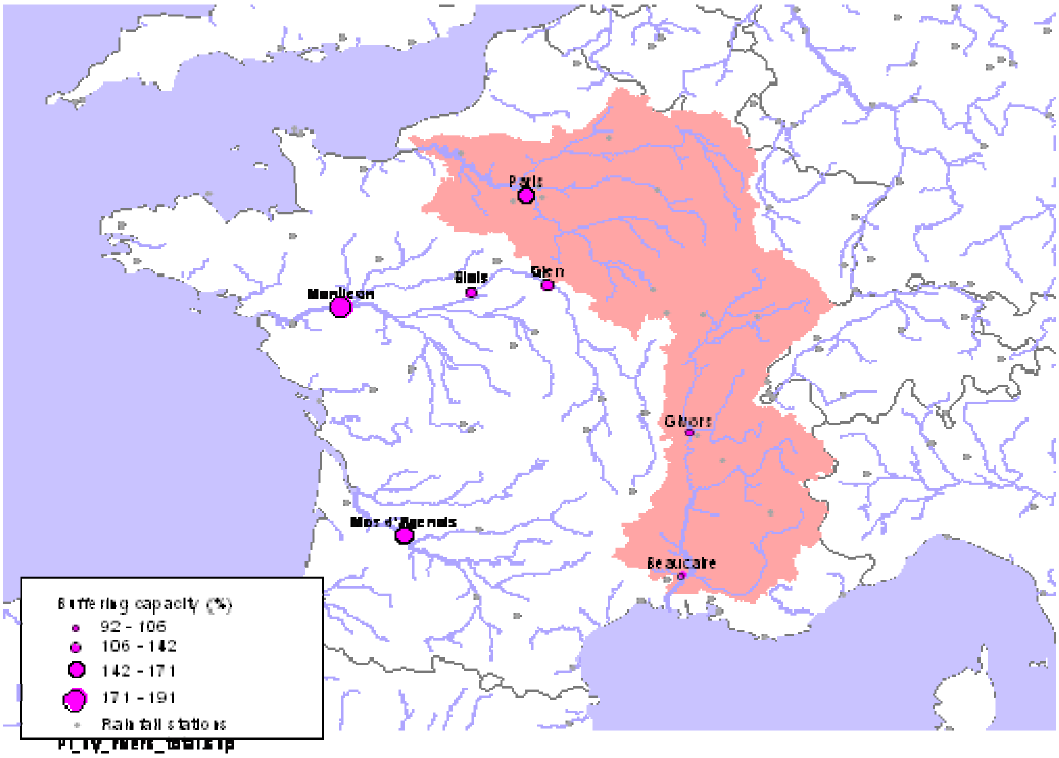

Figure 14: Gauging stations, rainfall stations and buffering capacity

The results are presented only for French gauging stations due to uncertainty with other results. Here we can see that the Rhône river basin is much less buffered than its French neighbours. The corresponding values are indicated in the Table 3.

River	Station	Catchment size (km²)	Standard deviation of annual discharge (mm)	Standard deviation of annual rainfall (mm)	Buffering capacity (%)
Loire	Montjean	110 000	82	157	191
Seine	Paris	44 320	76	130	171
Garonne	Mas d'Agenais	52 000	116	169	146
Loire	Blois	38 240	92	131	142
Loire	Gien	35 890	111	131	118
Rhone	Beaucaire	95 590	144	152	106
Rhone	Givors	51 080	165	152	92

Table 3: Annual rainfall and discharge values for the French gauging stations

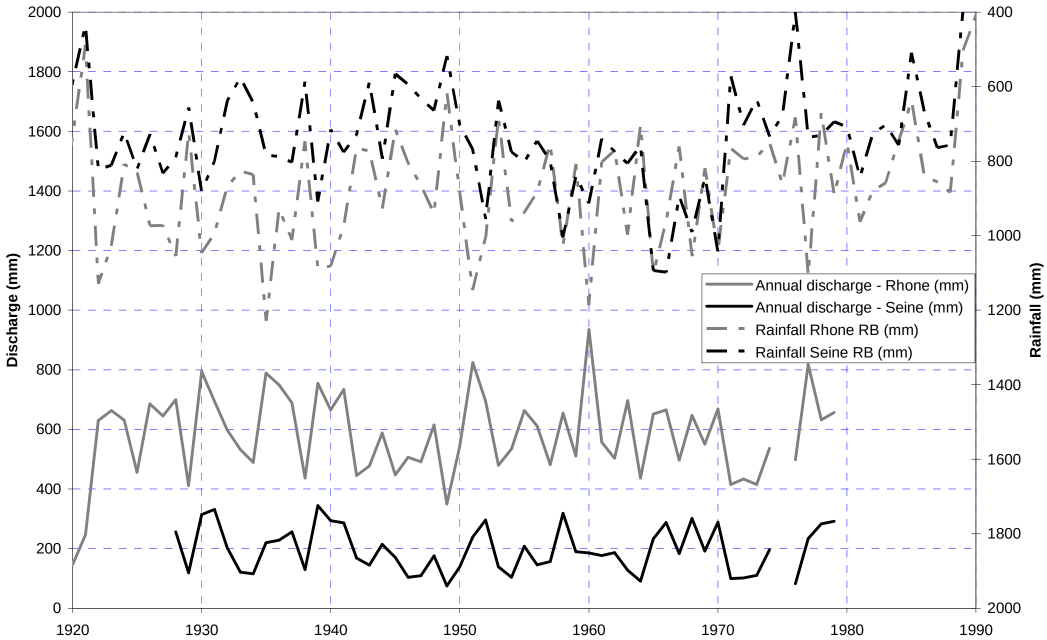

Figure 15: Annual rainfall and discharge values on the Rhône and the Seine basins

Annual rainfall patterns are quite comparable but discharges in the Rhône basin show a greater variability leading to a smaller buffering capacity.

More elaborated research has been carried on by Risbey and Enthekhabi (1995), Sankarasubramanian and Vogel (2001) and Sauquet, Leblois et al. (2005) with the use of streamflow elasticity.

3.4 Streamflow reliability

<u>Context description</u>

Here, we compare the long-term variations of two rivers, whose catchments are of similar size, but which are located in very different climates. We are looking at the water streamflow from a resource point of view. Which river is the most *reliable* for a manager as a source of withdrawal?

According to paragraph 2, this example can be described in the following terms:

- Objectives: Assessment of surface water reliability from a user point of view,
- Associated management strategies: see "benefits to gain" section,
- Driving force: all the variables influencing hydrological regime,
- Beneficiary: users abstracting water,
- Buffer: Catchment (generation of a streamflow pattern),
- Buffering effect: integration of driving force variabilities and generation of a smoother runoff signal,
- Buffering capacity assessment: dimensionless criteria (see below)
- Temporal and spatial references: fixed time (criteria based on inter-annual data) and fixed location (criteria calculated for a single catchment at a gauging site).

Benefits to gain from such buffering capacity assessment

If we look at the river flow as a resource, we need to take into account that it is variable from year to year, and users design water withdrawal structures to use only the "regular" or "warranted" part of the resource. Indeed, if they would aim to use the streamflow module, they would lack water roughly[2] 50 % of the time. Often, the "available" resource is defined as the water quantity which is flowing at least 3 years in 4, or 9 years in 10. If we retain the definition of 3 years in 4, we can see that it corresponds to only 50% of the module (i.e. 17 m^3/s) on the Oued Cheliff (Algeria), but to 80 % of the module (i.e. 490 m^3/s) on the Rhône River (France).

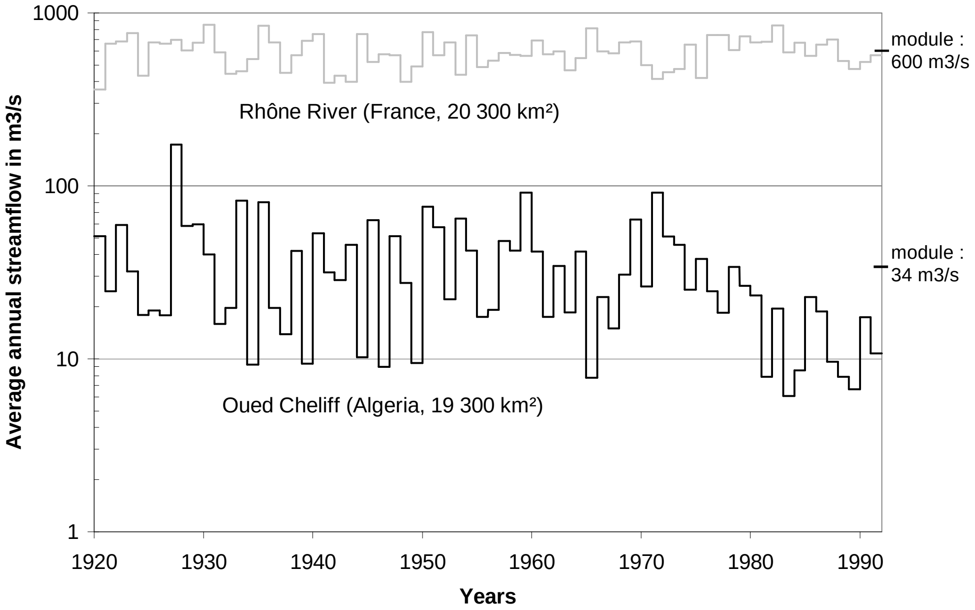

Figure 16: Annual streamflows of the Rhône river and the Oued Cheliff

[2] The flow module corresponds to the average of annual flows, it differs thus somewhat with the median.

Criteria formulation

Thus, we could use the ratio of the 0.25 flow percentile to the mean flow as a measure of its buffering capacity. This would yield:

$$BufferingCapacity = Q_{25} / Q_{mean}$$

(where Q_{25} is the annual flow which is exceeded 75% of the time, Q_{mean} is the mean annual flow)

Example of calculation and analysis of results

The Buffering Capacity value would reach 50% for Oued Cheliff and 80% for the Rhône.

It is only on a few over-damed rivers that BC could reach a value close to 100%, i.e. when the stored volume is such that the dams completely regulate river flow. Examples can be found in the United States: the Colorado River for example, with the huge Hoover and Glen Canyon reservoirs can store up to four and a half years of mean annual flow (68 km^3). In Egypt, the Aswan dam reservoir can store up to two years of mean annual flow (164 km^3 of storage for a mean annual flow estimated to be 84 km^3). Note however that buffering has a definite cost in terms of water resources: losses to evaporation by the Aswan dam amount to 10 km^3 per year (i.e. 12% of the incoming flow).

3.5 Buffering capacity in groundwater

Context description

As with all common pool resources users need to have incentives and effective management instruments and mechanisms to preserve the resource. For this, different and better institutional arrangements for groundwater management are needed (Figueres et al., 2003). Furthermore, groundwater acts as the primary buffer against the impact of climate variability and spatial variability in drought (FAO, 2003). These facts have significant implications for sustainable development of groundwater.

In principle, two physical parameters are crucial for a sustainable management of groundwater aquifers: 1) "balance" between groundwater abstraction and groundwater recharge and 2) "balance" between "surface water abstraction- effluent return – reservoir compensation" and "a selected Q-minimum natural flow eg. Q95".

According to paragraph 2, this example can be described in the following terms :

- Objectives: Assessment of hydrological severity,
- Driving force: abstractions from groundwater and surface water, aquifer recharge, effluent return to surface water, reservoir compensation,
- Beneficiary: no clearly identified beneficiary,
- Buffer: Catchment (balance of the inputs and outputs),
- Buffering effect: Catchment retention capacity,
- Buffering capacity assessment: dimensionless criteria (see below)
- Temporal and spatial references: fixed time (criteria based on inter-annual data) and fixed location (criteria calculated for a single catchment).

Criteria formulation

Acreman (2000) suggests a simple ‘hydrological severity indicator HSI = H1 + H2 where

- H1 = annual groundwater licensed abstraction / annual recharge in the 1-in10 drought and
- H2 = (daily max surface water abstraction – effluent return – reservoir compensation) / Q 95 natural

Then the HSI = (H1 + H2) may have the classification “low severity” (HSI = 0.0 – 0.4), “medium severity” (HSI = 0.4-0.8) and “high severity” (HSI > 0.8).

Benefits to gain from such buffering capacity assessment

It can be seen that for an area without groundwater abstraction the ‘reduction in flow due to surface water abstraction minus effluent return and reservoir compensation’ can amount up to 40 % of the Q95 natural and still belong to the class “low severity”.

The parameter H2 is rather easy to calculate, compared to H1. Groundwater recharge can not be directly estimated and has to be assessed using ‘indirect’ methods like groundwater models based on estimates of baseflow discharges to rivers. A special problem with H1 is that it may be important to select a depth for the recharge which corresponds to the depth below which ‘groundwater quality is good’ and from where current groundwater abstraction takes place. In an estimate of the Danish groundwater available resources, this depth was estimated to 30-50 meter below the surface, and the groundwater recharge to this depth was considerably less than the recharge to the shallow groundwater. The sustainable abstraction was assumed to approximate 30-35 % of groundwater recharge to deeper aquifers (H1 = 0.3-0.35) (Henriksen and Sonnenborg, 2003).

There is no such thing as no impact when water is abstracted from surface water or groundwater. There will be a critical abstraction rate (related to both groundwater recharge and influence of river discharge regime) above which groundwater levels will fall, groundwater quality will detoriate, or groundwater flows to rivers and wetlands will be reduced to a level that threatens ecosystem health (Acreman, 2003). Quantifying these critical abstraction rates is dealt with through a modelling strategy. However, it is important to point out that where data are scarce and scientific understanding is poor, critical abstraction rates cannot be defined accurately and will thus become a matter of dispute between stakeholders, making the achievement of management objectives very difficult. This will particularly be the case where the hydrological processes are changing due to climate change or land use change. Consequently, there must be a political decision to make the necessary investment in monitoring and research. Even where good data and models do exist, uncertainties in predictions will remain, thus defining critical abstraction rates will never be absolutely certain. Due to this fact, adaptive management, where novel attempts to improve ‘the total buffering’ of the system, by abstracting more water from groundwater in stead of surface water, by increasing reservoir compensation etc. followed up by proper monitoring could be the only way to reach intergrated water resource management goals.

Since groundwater levels, river flows or wetland water levels can be naturally low, any hydrological objectives must be set within probabilistic framework. Petts et al. (1996) advocated the definition of a target flow duration curve for a river. Such a graph shows river flow on the vertical axes, but the concept could be equally well applied to groundwater or a wetland by re-labeling the axis groundwater level or wetland water level. The horizontal axis defines the time that given flows (or levels) are found or exceeded. In such a system there will be a curve for both the ‘natural’ regime (without dams and abstraction), historical regime and ‘target regime’, with novel plans to utilizing buffering capacity of both groundwater and surface water systems. The difference between the curves defines the volume that can be abstracted.

The flow duration curve has the disadvantage that it does not account for the relative timing of different flows, such as long periods below specified thresholds. An operational problem is that there is often a significant time delay between groundwater abstraction and its impact on river flows or wetland water levels. Thus a water allocation model that takes these delays into consideration is needed.

Based on the above three indicators for characterizing buffering capacity for groundwater management can be proposed:

- Principles of hydrological severity indicator HIS = H1 + H2 (based on the EU research project GRAPES) balancing groundwater abstraction against annual recharge (H1) and balancing surface water abstraction corrected for effluent return and reservoir compensation against Q 95 natural)
- Evaluation of groundwater buffering capacity based on model assessment of A) natural flow duration curve (without dams and abstraction), B) Historical flow duration curve (current situation, climate and land use) and C) Adaptive target flow duration curve (for different management options eg. 1) dams, 2) groundwater abstraction etc.) Similar probabilistic duration curve principles may be applied for “groundwater table” and “wetland water levels”, including an open eye to spatial variability. How much the natural flow duration curves can be ‘altered’ (reduced) depends on environmental flow requirements. How much ground water levels can be altered depends on ‘groundwater quality requirements’ (e.g. upcoming of saltwater, intrusion of saltwater and other groundwater quality problems related to variation in groundwater table). How much wetland water levels can be altered depends on ‘aquatic habitat requirements’, and
- Beside the above physical buffering capacity indicators, other indicators are necessary in order to characterize the institutional framework (user partnerships and many other issues). Such indicators have to be established with involvement of case studies, stakeholders etc.

4 Tools to assess buffering capacity

In the paragraph 2.6 (“Assessment methods”), we described different types of methods to assess buffering capacity. The following paragraphs describe the tools that could be used to apply these methodologies in practical cases.

4.1 Simple data processing

We will not detail all the data processing techniques that can enter into buffering capacity calculations. Simple data processing can be understood as usual statistical data processing: sums, averages, standard deviation, statistical tests, ... Section 4.3 provides examples of such treatments.

It should not be omitted that **simple data processing remains the best vision we can have on environmental dynamics**. To estimate the climate elasticity of streamflows, (Sankarasubramanian and Vogel 2001) prefer to rely on data processing (through a non parametric test) than on hydrological models considering “how sensitive climate elasticity is to the assumed model structure”.

4.2 Modelling tools

In some cases simple data processing is not sufficient and a modelling approach is required. Models are particularly useful when extrapolation based on observed data is not sufficient. In this work package “modelling tool” is understood as a software program complying with the following requirements:

- Centred on water quantity issues at the large basin scale and more specifically the artificial and natural storages (hence modelling tool should represent processes associated with buffered phenomenon, see § 2.2),
- Offering the possibility to simulate the effect of adaptive management strategies,
- Permitting exchanges with stakeholders (integration of stakeholders point of view and results sharing),
- Relying on well validated code and robust user interface (tool development is not an objective of work package 1.5).

As stated by Soncini-Sessa (2003): “the choice of (...) models as well as the degree of detail depends on both the selected indicators and the alternatives to be evaluated”. We subscribe to this approach. **Therefore the process of tool selection will have to be validated with case study teams**.

The following table presents the different processes to be modelled as well as the models frequently associated.

Context	Process	Type of model frequently associated
Hydrologic and hydrogeologic water cycle processes		
	Rainfall – runoff transformation, general water balance	Distributed physically based models, Lumped conceptual rainfall-runoff models
	Routing along fluvial channels including overflow to flood plains	Saint Venant Hydraulic Models, Simplified hydraulic models
	Ground water recharge processes	Groundwater dynamic equation solving model, Lumped models
	Ground water levels and flow dynamic	Groundwater dynamic equation solving model, Lumped models
	Interactions between surface water and groundwater systems	Lumped rainfall-runoff models, Groundwater dynamic equation solving model
Artificial structures		
	Water supply facilities management (pipes, pumps, reservoirs…)	Pressured pipes hydraulic models
	Sewage system management (treatment plants, pipes, pumps, detention basins…)	Saint Venant Hydraulic Models
	Storage infrastructures (dams, reservoirs)	Saint Venant Hydraulic Models, Lumped models, Simple balance models
	Transportation infrastructures (canals, large pipes)	Saint Venant Hydraulic Models, Simplified hydraulic models
	Flow and level regulation infrastructures (weirs, dykes, …)	Saint Venant Hydraulic Models

Table 4 : Processes associated with buffering capacity

The above model types are very different in terms of practical implementation, and Figure 17 indicates the differences on the basis of a simple dual classification. Model types can be considered[3] as either conceptual (limited number of parameters, based on empirical or mathematical equations) or physically based (large number of parameters, based on laws derived from physical equations).

[3] In a very simple approach

	Conceptual representation of the hydrosystem		Physically based representation of the hydrosystem
Model type	*Lumped models, Simple balance models, simplified hydraulic models*		*SW Saint Venant models, GW dynamic models*
Data requirements	*Moderate*	→	*High*
Modelling framework	*Partial*	→	*Comprehensive*
Model set up and calibration	*Rapid*	→	*Time consuming*
Management strategy testing capacity	*Partial*	→	*Extended*
Interaction with stakeholders	*Reactive*	→	*Heavy*
Appropriation by end users	*Rapid*	→	*Complex*

Figure 17 : Conceptual of physically based, what to choose ?

We can see here the difficulty in selecting a particular tool for analysis of buffering capacity:

- *Practical implementation* would require a conceptual model having limited data requirements and a rapid setting-up (considering the size and complexity of the case-study basins). This approach will permit to explore easily a wide variety of scenarios. As stated by Schluter (2005): "The model should be simple and easy to use for interactive scenario analysis and impact assessment without demanding much modelling experience from the user".

- *Overall objectives of NeWater project* could require additional physically based component able to test adaptive management strategies like land cover management, flood plain storage structures. However, it is clear that no model will be able to simulate accurately all the processes involved in adaptive management strategies.

Note that as part of on going research program, CEMAGREF is investigating the possibility to address complex management problems (such as reservoir operation) in the framework of a simple lumped water balance model. If the success of these approaches is confirmed, we believe that it could be well adapted to the objectives of NeWater.

In conclusion, we identify the following characteristics for modelling tools:

- **Conceptual modelling of the entire continental water cycle**: the tools selected should be based on an association of simple and global models (lumped rainfall/runoff, lumped groundwater model or simplified hydraulic models) able to simulate the entire continental water cycle at large basin scale.

- **Open modelling architecture:** as mentioned previously, adaptive management asks questions that cannot always be solved within a single modelling framework. Therefore, the selected tools should easily interact with other simulation tools developed within the project. As stated by de Kok and Wind (2003): "selecting models implies understanding of the integration with other models". Practically, the tools used in WP 1.5 should offer the possibility to couple water cycle simulations with other processes not explicitly treated inside the main software. This implies two functionalities:

- *Result extraction*: tools should easily provide required results to external models. This is usually easily performed when advanced reporting functionality exist.
- *Feedback integration*: in the course of a simulation, tools should be able to integrate information from other sources. For example, within a particular climate change scenario, water allocation priorities may dynamically evaluate (which would be a important AM implementation).

- **Scenario oriented modelling tool**: Tools should make possible the simulation of numerous scenarios integrating climatic variability (climate change scenario), design options (creation of small scale storage units, ...) and management options (modifications of allocation rules and/or reservoir operation rules). A specific module called "scenario manager" could be particularly useful.

A review of existing tools complying with the previous requirements has been undertaken. A large majority represent hydrosystem processes with a networks constituted by nodes[4] and arcs[5] (Schluter, Savitsky et al. 2005). This representation ranges from schematic diagrams (Pallottino, Sechi et al. 2005), up to GIS based interactive maps (Jha and Das Gupta, 2003; DHI, 2003; Mysiak, Giupponi et al., 2005).

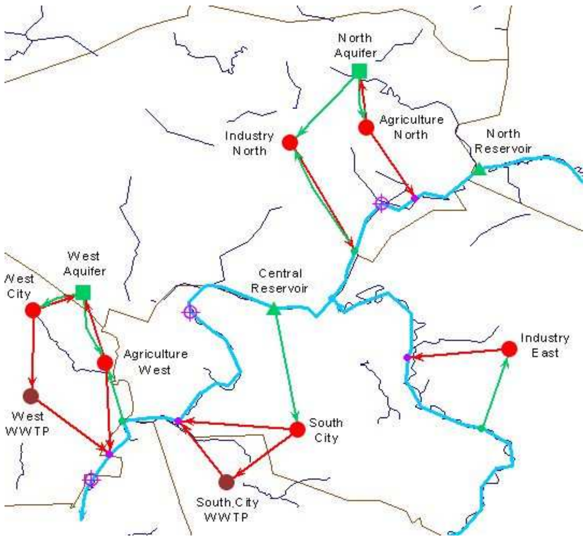

Figure 18 : Network representation of hydrosystem (WEAP software)

Time steps ranges from day to year with a majority of monthly simulations models (Schluter, Savitsky et al., 2005; Wurbs, 2005). Decision support system analysed show differences on the following points:

- **Nature of the software product**: the available software range from open source product developed for research purposes to commercial softwares.
- **Links between surface water and groundwater**: some decision support systems do not integrate a groundwater component; others model it through lumped models. Decision support systems can even be constructed on the basis of a 3D finite elements ground water model (Recio, Ibanez et al., 2005).

[4] Nodes agregate source and sink elements in the hydrosystem: catchment outlet, aquifer (, water intake or return flow

[5] fluvial channel, important pipe or canal

- **Hydrological modelling** : some decision support system do not integrate any explicit hydrological component and rely on discharge time series upstream of the system (Mysiak, Giupponi et al., 2005; Pallottino, Sechi et al., 2005; Wurbs, 2005). Others rely on statistical aggregated values (Holmes, Young et al. 2005). Another class of decision support system simulate explicitly the rainfall-runoff process (Simons, Podger et al., 1996; DHI, 2003; Shen, Parker et al., 2005).

Table 5 presents the characteristics of 8 basin scale decision support systems. Additional inforamtions can be found on the following web sites:

- MIKE BASIN : http://www.mikebasin.com/mikebasin/
- WEAP : http://www.weap21.org/
- IQQM : http://www.sciencedirect.com/science/article/B6VSW-3Y2FTKG-W/2/40e75238ed013ff71bd2184fe10b2293
- WRAP : http://ceprofs.tamu.edu/rwurbs/wrap.htm
- EPIC : http://www.ce.utexas.edu/prof/mckinney/papers/aral/EPIC/EPICmodel.html
- BASIN : http://www.epa.gov/OST/BASINS/
- E2 : http://www.toolkit.net.au/cgi-bin/WebObjects/toolkit

Simulations from these tools will provide results in the form of frequency, probability, or reliability of meeting water supply, instream flow, hydropower, and/or reservoir and groundwater storage targets.

However, other tools are required to combine results from hydrological decision support tool and a broader stock of knowledge (experts, stakeholders, macro economic models etc.). A recent EU research project MERIT has shown promising results for the use of Bayesian networks in water resource management. This tool has been applied to stakeholders' involvement in management of groundwater contamination in a Danish case, irrigation in a Spanish case, reservoir management in an Italian case and development of groundwater demands in an UK case (www.merit-eu.net).

FUNCTIONALITIES Theme	Object	MIKE BASIN	WEAP	IQQM	WRAP	EPIC	BASIN	E2
Software caracteristics								
	Editor	DHI	SEI-Boston/Tellus Institute	Centre for Natural Resources			US EPA	CRC for catchment hydrology
	Date of latest release	June 2003	June 2005			2001	2001	
	Detailed documentation	Yes - Windows style help files	Yes - Windows style help files	Yes	Yes	Yes	Yes	Yes - PDF file
	Development language	?	?		Fortran		?	?
	Open Source	No	No	Yes	No	Yes	No	No
	GIS format	Arcview (Shp / Dbf)	Proprietary	?	No GIS base	Proprietary	Arcview (Shp / Dbf)	Arcview (Shp / Dbf)
	DBMS	Arcview 3.3	Proprietary	Proprietary	Text format			MS Access
	Macro writing possibility / Language	Yes / VB 6.0	No	No	Yes	No	No	No
	Open MI compatible	Yes	No	No	No	No	No	No
	Time Step	Day / Month	Anywhere from 1 day to 1 year	Hour / Day / Month / Year	Month			
	User friendliness of the interface	Average (No if the user is not trained with ArcView)	Yes	No	No (command line)	No	No	Average
	Sample data (quick handling oriented software)	Yes	Yes	No	No		Yes - Difficult to handle	Yes - Difficult to handle
Communication - Reporting								
	Additionnal GIS Layers insertion	Yes (GIS add in)	Yes (SHP or raster file only)	No	No	No	Yes (GIS add in)	?
	Numerical results format	Proprietary (dfs0)	Proprietary	Proprietary (dfs0)				Proprietary (dfs0)
	Graph generation based on results	Yes - Interactive map facility	Yes - Interactive map facility	Yes	Yes	Yes	Yes	Yes
	Convertion utilities for results	Export to Ascii / Clipboard / Excel	Export to Clipboard / Excel	Export to ASCII		No		
	Reports format	HTML	ASCII Text			ASCII Text		
	Customized reports generation		Limited					
	Report printing tools		Yes					
	Map printing tools	Yes (GIS add in)	No	No	No	No	Yes (GIS add in)	
	Statistical treatment of results	Yes - Various usual statistical variables	Yes - Percent of time value is excedeed	Yes -Means, Standard deviations, Skew coefficients, Coefficient of determination				
Warter cycle modelling								
	Ground Water model	2 layers aquifer - Linear reservoir	Alluvial systems - Simplified Darcy Equation based model	Alluvial systems - Simplified Darcy Equation based model / Direct connection with a MODFLOW model	No	No	No	Yes
	Hydraulic Routing	No routing / Muskingum	No	No routing / Muskingum / Lag		No	No	Yes
	Evaporation and losses along rivers	Yes	Entred as external time serie	Yes	Yes	Yes	No	
	Rainfall - Runoff model (if no external time serie is used for upstream inflow)	NAM model	Soil Moisture Method	Sacramento model	No	No	No	Yes
	Surface / ground water interactions	Yes	Yes	Yes		No	No	
	Calibation procedure	Yes	No			Yes		
Artifical structures modellilling								
	Reservoir operating rules on reservoir levels	Yes	Yes	Yes				
	Reservoir operating rules on downstream flows	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Reservoir operating rules - complex rules		Yes	Yes				
	Hydropower model	Yes	Yes	Yes				
	Economic model - Water pricing		Yes					
Constraints - allocation - Water sharing								
	Seniority priority system	Yes	No	Yes	Yes	Yes	Yes	
	Global priority system (alternative with previous system)	Yes	Yes					
	Fixed demands constrained by river flow conditions.	Yes	Yes	Yes				
	Demands subject to balancing reservoir constraints.	No	No	Yes				
	Dynamic evolution of constraints	No	Yes (defined by time series)					No
Optimlisation and scenario management								
	Optimisation algorithm	No (external routine can be used via VB program or Excel)	No	No				No
	Scenario management	No (external routine can be used via VB program or Excel)	Tree shape organisation	No				Tree shape organisation
NeWater	*qualification : -- / - / + / ++*							
		+	+			+		--
	Scenario oriented model	+	+			+		--
	Large basin scale modelisation	++	++			+		+
	Results sharing	++	+	-	-	-	++	-
	Open modelling architecture	++	-	-	-	-	-	-

Table 5: Decision support system characteristics

5 Conclusion

This report presents a first step in the development of buffering capacity concept:

- The first part highlighted essential components of buffering capacity providing a possible structure for further developments,
- The second part suggested examples of buffering capacity,
- The last part identified tools to implement buffering capacity assessment in the selected case studies.

Buffering capacity is still a new and open concept that will evolve ion the course of the project.

Buffering capacity covers many different aspects, scales and issues, hence it can be used to bridge gaps between water management disciplines. Buffering capacity is by nature an “adaptive” concept because it measures the degree of freedom offered to water managers.

The next steps to reach work package 1.5 objectives are the followings:

- Launch active interactions with stakeholders to integrate their preoccupations and objectives,
- Initiate analysis of selected case study basins and start the application of buffering capacity assessment methodologies.

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