Integration of enhanced reservoir operation (*enrop*) into IWRM in association with environmental and ecological aspects

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Introduction & Background

The intrinsic natural variability of the environment plays a central role in the investigation of improved IWRM measures for integrating environmental aspects. According to the Global Water Partnership (GWP, 2000) Integrated Water Resources Management (IWRM) is thereby "*a process promoting the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*".

IWRM aims to meet human water needs without compromising the sustainability of ecosystems, and by this the need to find approaches and solutions for an integration of these aspects arose. This comprises also the provision of the essential quantity and quality of water required to maintain the ecosystems biotic structure. In the past a vast number of methods were developed in order to quantify such certain amount, and denoted by different terms, like *instream flow requirements* (IFR), *environmental flow* (*e-flow*), *environmental water allocation* or *ecological reserve* and so on (van den Berg et al., 2007; Acreman&Dunbar, 2004; Tharme 2003). One of the commonly accepted definition of environmental flow is described by Dyson et al. (2003):

> "*An environmental flow is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated.*"

Most of the existing methods for assessing environmental flow, e. g. hydraulic rating methods, habitat simulation methods, and holistic methodologies (Arthington et al., 2006, Dyson et al. 2003, Tharme 2003), predominantly build on the natural flow paradigm (Poff et al., 1997). As most of these methods were developed according to site specific requirements they lack on a universal transferability to other sites.

Moreover, the trend of last years, towards more holist approaches was gaining in popularity, because these imply a comprehensive flow regime, dynamic over time and with cognisance of the need for natural flow variability (King et al., 1999). The problem of such overarching approaches is that in most countries where e-flows are of high interest (semi arid and arid regions) needed information on the dynamic flow regime are only sparsely available or missing, what is at least not only justified by the fact that mostly rivers running dry (temporary streams) within a certain period of the year.

The discussion of maintaining e-flow includes mainly two aspects, on regards the minimum amount of water needed for ecological conformity and the other one the quality of the flow. With respect to a required amount of water much research was done during the last years and gathered for example in online databases, like the "Environmental Flow Assessment for Aquatic Ecosystems: A Database of Methodologies" (Smakhtin, 2007) but with respect to the downstream quality requirements a lot of investigations focussed on sediment or total dissolved solids (TDS) (Espa et al., 2007). Some considerations regarding the salinity of rivers were done in a recent study carried out by Horrigan et al. (2005). This for example aimed to investigate changes in the macroinvertebrate communities associated with changes in the conductivity (μS cm^{-1}) level in streams and rivers. It has been shown that the most dramatic shift between groups of different salinity tolerance occurs as conductivity reaches 800 - 1000 μS cm^{-1}. This threshold value is lower than the generally accepted value of

1500 µS cm^{-1}, above which freshwater ecosystems are likely to experience salinity related ecological stress (Hart et al. 1991). The authors conclude that variabilities of salinity between ranges of 200 µS cm^{-1} lead to measurable changes in macroinvertebrate communities.

Regulating rivers by dams modifies directly and significantly natural river flow regimes and, since their operating rules and policies determine the amount and timing of releases, they are an important entry point for securing water quality, quantity and environmental sustainability.

In this context, enhanced reservoir operation - *enrop* - provides a first concept for operating reservoirs considering these aspects. The primary aim of the introduced method is to increase the availability of water with the best possible quality. This is achieved by identifying inflow pollution streams and accordingly the adaptation of the inflow and release schedule of the reservoir.

For a sound and environmental compliant management of the reservoir-river-system the integration of ecological and environmental demands is essential. Known water quality and quantity demands, like water level or salinity tolerance of native fish species and aquatic biota, set the targets for the reservoir operation.

The proposed method of *enrop* provides the ability to be embedded into the main key terms of IWRM. According to the relationship proposed by Naiman et al. (2006) the herein described concept can be embedded as shown in Figure 1.
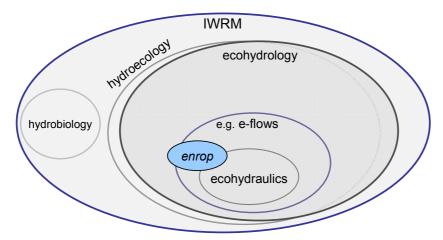

Figure 1. Embedding *enrop* into the relationship between key terms of IWRM (adapted to Naiman et al., 2006)

Ecohydrology considers the functional interrelations between hydrology, aquatic ecosystem processes and their biota. It uses ecosystem processes as tools to meet freshwater resource management goals, such as enhancing natural processes of nutrient retention to avoid harmful algal blooms (Zalewski 2000). As *enrop* is also a tool associated to IWRM it is placed in close connection to the provision of e-flows and ecohydraulics as it impacts directly on these aspects.

This paper is a first contribution towards linking technical and environmental aspects of a water resources management and aims to bridge technical measures to the IWRM and connected conceptions like the '*ecohydrology*', which supports research on bringing together different sectors. The approach makes to its business to care about the spatial diversification of the hydrological characteristics of aquatic ecosystems. Thereby, reservoirs provide an important factor as the spatial variation of the retention time can have a great influence on nutrient recirculation through biota and therefore on water quality (Zalewski et al., 1997).

Against past trends it will used existing and simpler methods, feasible to be applied in practice rather than developing a further complex approach, which cannot be used for the purpose needed. The innovation of this study lies in the establishment of interrelations between engineering and environment as well as implicating specific technical aspects (*enrop*) to the context of ecology.

Under the umbrella of this overall aim, the study discusses the application of enhanced reservoir operation (*enrop*) as a management theory supporting the improvement of IWRM in water deficient regions. The development of operation schemes by adapting reservoir inflow and release patterns address the future provision of downstream water supply and ecological requirements. The Lac model was used to simulate the changing status (quality and quantity) of the reservoir, mainly focussing on the reservoir salinity and subsequently the designated information on the release water quality. The introduced methodology was further applied on the reservoir system of the Medjerda catchment in Tunisia. Suitable reservoir operation schemes for the Sidi Salem reservoir were identified. The results show a considerable improvement of the reservoir water quality and thereby an enhancement of the conditions for the downstream environment.

Failing suitable data on ecological and environmental studies and data, the investigations herein are limited only to one important water quality parameter - the salinity - and its corresponding changes related to the water releases due to the application of *enrop*.

Methods and Approaches

Timing and volumes of waters flowing in the river network are strongly modified by the presence of dams and their management schemes as well as general water translocation plans. In these cases the reservoir operation became the key factor linking and tuning the human pressure on the fluvial environment. Physical and biological information on river habitat and environment downriver of dams is one of the most relevant information needed for linking ecological aspects to the operation of reservoirs influencing on it vice versa. The conceptualised approach herein applied is described in Figure 2.
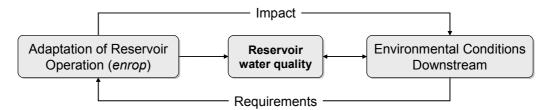

Figure 2. Relation between *enrop* and environmental flow requirements (Bauer et al., 2008)

Reservoir operation influences the downstream environmental condition mainly through the modulation of the releases. Environmental flow requirements in turn make demands on reservoir management by requiring specific release conditions such as water quality, flow magnitude, or specific water levels.

Contributing to this basic methodology, *enrop* aims to increase the availability of water with the best possible quality of a reservoirs water body. For this, main steps are

- analysis and processing available inflow, reservoir and release data,

- simulation of adapted operation schemes using the 1D reservoir water quality model *Lac*, and

- the valuation of the changed quality status of the reservoir and accordingly the releases by the criterion '*Water Volume by Class'* (WVC) (Bauer, 2006)

As mostly in water deficit regions, where a practical implementation of IWRM is required, data on river flow and reservoir storage volumes are only sparsely or not available at all. So side-step-methods are defined, able to provide the needed information. This was done for example by case specific approaches in connection with simplified calculation methods developed using generally known software (e.g. MS Excel).

Subsequently, the processed data are used as input for the simulation of reservoir operation rules within the identified 'operation periods', using the model *Lac*. It is a dynamic, deterministic model and

permits the simulation of time-dependent and depth dependent changes of relevant quality processes within reservoirs and lakes (Froebrich, 2000). The special characteristic of the model is the detailed collection of hydraulic, hydrothermal, and biological processes, enabling, amongst other things, a reliable investigation of density stratification and its influence on salinity dynamics. The model has two main components: (i) different sub-models enabling the hydrophysical simulation and (ii) the water quality sub-model for simulating the variation of hydrochemical constituents and biological variables, where time and depth dependent changes of state variables were calculated by using an explicit difference scheme. Equations incorporated in the *Lac* model for calculation of heat and radiation balance at the water surface are adapted from Hurley Octavio et al. (1977). Advection is simulated using an approach from Schwerdhelm (1992). For each time step, the mass flux through the layer boundaries is calculated by the water balance in each layer, starting from the bottom. If inflow and outflow for a given layer are not balanced, positive or negative flows across the layer boundaries are assumed accordingly.

For the valuation of the proposed adapted regulation a tool is needed able to give an indication of the modified water quality of the releases. Here, the criterion *Water Volume by Class* (WVC) provides a method to quantify the effects of different reservoir operation schemes on the water supply and ecosystems protection in the downstream area. Each single class represents the provided water volume associated to a defined concentration range of a selected water quality parameter (C_r to C_{r+a}). By this, it integrates the aspects of water quality and quantity (Bauer, 2006).

$$WVC\ (i) = \sum_{t=t_0}^{t_e}(Volume_X(\Delta t)) \qquad \Big| if \quad C_r\,(i) \leq C_X\,(\Delta t) < C_{r+a}\,(i)$$

Where
	WVC	:	Water Volume by Class (m³)
	i	:	Number of Class
	t_0, t_e	:	Start / End date of the investigation period
	$Volume_X(\Delta t)$	:	Volume of parameter x at current time step (m³)
	$C_r(i)$	:	Lower boundary of concentration range (mg l^{-1})
	$C_{r+a}(i)$	:	Upper boundary of concentration range (mg l^{-1})
	$C_x(\Delta t)$	:	Concentration of parameter x at current time step (mg l^{-1})

The total concentration range, C_r to C_{r+a}, should be selected according to the sensitivity of the system or to the level of protection to be guaranteed. Established increments between the single WVC reflect the effects of the modified operation (changes in quality) on the investigated parameter, and provides important information for the respective sector of supply.

Case study application

Hydrology

The area of Tunisia extends over 164,150 km² (Figure 3). Characteristic for the country is the significant spatiotemporal variability of rainfall and temperature. In the North, the climate benefit from the Mediterranean, with characteristic hot and dry summers, and mild and relatively rainy winters.

A semi arid climate, with high temperatures and a limited rainfall potential. About 1500 mm yr^{-1} is basically received in the northwest, between 150 and 400 mm year^{-1} specify the Central Part of Tunisia and dropped to less than 50 mm yr^{-1} in the southern desert zone resulting in a wide spatial variability (Table 1) (Louati et al., 2005). Similarly, the annual evaporation varies between 1,300 mm in the North to about 2,500 mm and even more in the South (Bahri, 2000)

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	Salinity	Unit	North	Centre	South	Total
Area of the region		%	17	32	61	100
Rainfall		%	41	29	30	100
Surface water		Mm³	2,190	320	190	2,700
		%	78	38	19	58
Shallow aquifers		Mm³	395	222	103	720
		%	14	26	10	15
Deep aquifers		Mm³	216	306	728	1,250
		%	8	36	71	27
Total water resources		Mm³	2,801	848	1,020	4,670
		%	60	18	22	100
Resources	$< 1.5\ g\ l^{-1}$	Mm³	1,796	153	6	1,955
		%	82	48	3	72
Resources	$> 3.0\ g\ l^{-1}$	%	37	49	86	
Shallow aquifers	$< 1.5\ g\ l^{-1}$	%				3
Deep aquifers		%				22
Shallow aquifers	$1.5 - 3.0\ g\ l^{-1}$	%				11
Deep aquifers		%				57
Shallow aquifers	$3.0 - 5.0\ g\ l^{-1}$	%				27
Deep aquifers		%				16
Shallow aquifers	$5.0 - 7.5\ g\ l^{-1}$	%				59
Deep aquifers		%				5

Table 1. Water resources distribution and quality in Tunisia (DGRE, 1990)

Tunisia is submitted to drought periods that could be restricted for one or some regions and could be generalized. The drought duration could be one season or one year and more, but with variable intensity.

Water resources

Tunisia can be considered as one of the Mediterranean countries, which has probably the lowest level of water resources. For example in 1995, Tunisian water resources were evaluated to 528 m³ capita^{-1} year^{-1}. According to the definition of the Word Meteorological Organization (WMO), Tunisia can be therefore classified as a country of (hydrological) water stress (Labane, 2002), although it is only a quantitative consideration.

Tunisia is rapidly approaching full utilisation of its available water resources. The scarcity of water resources is even more acute as the possibilities of developing new sources are limited and their costs are increasing (Bahri, 2000).

About 25% of the Tunisian population are associated with the agricultural sector with 40% depending directly or indirectly on it. As agriculture is traditionally and predominantly rain-fed, it is consequently influenced by a high annual variability (Bahri, 2000). This is also a reason for the disproportional high agricultural water demand. With estimated 2,115 Mm³ in 1996, for example, it represents 84% of the total annual demand (Table 2).

Sectoral water demand	1996 Mm³	1996 % of Total	2010 Mm³	2010 % of Total	2020 Mm³	2020 % of Total	2030 Mm³	2030 % of Total
Domestic (Urban + Rural)	290	11	381	14	438	16	491	18
Tourism	19	1	31	1	36	1	41	1
Industry	104	4	136	5	164	6	203	7
Agriculture	2,115	84	2,141	80	2,082	77	2,035	73
Total	**2,528**		**2,689**		**2,720**		**2,770**	

Table 2. Past and predicted water demand of Tunisia (Mm³ yr^{-1}) (Ministère de l'Agriculture, 1998)

The Medjerda catchment in North Tunisia encompasses a reservoir system consisting of 22 reservoirs. The Sidi Salem reservoir is the largest in-stream dam of the system and the main water source for the Tunisian water supply. It is located about 70 km southwest from the capital Tunis and has a maximum surface area of 7,225 ha at a maximum depth about 33.5 m. With its manageable storage volume about 762 Mm³ Sidi Salem provides water for about 50% of the population in Tunisia as well as for the large irrigation areas. Sidi Salem plays a decisive role for the water supply of Northern Tunisia as well as for the remaining country as the reservoirs are integrated into a complex hydraulic system of pipelines, canals and pumping stations and serve also for the drinking water supply of the coastal cities and for the preservation of agricultural regions such as the Cap Bon (Bahri, 2000).
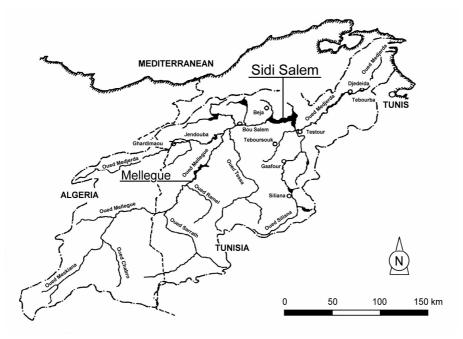

Figure 3. Medjerda catchment with the main reservoir Sidi Salem (after Kretzschmer and Schoppmann, 1985)

The salinities of Tunisian inland waters, not only lakes, but also rivers, cause some concern to water management authorities. The combined effects of evaporation, dissolution of geological formations (triassic gypsum) and salt in canals and reservoirs is increasing the water salinity, thus causing problems for the water supply and irrigation. As the Sidi Salem reservoir, was partly built on Triassic rock, experts had calculated that, for example from March to August 1982, some 45 000 tons of salt were dissolved into the water, causing an increase in salinity of 0.187 g l^{-1}. However, no information is available on how long this transfer of salt into the river may last (Kraiem and Pattee, 1988). Kallel (1995) indicates that the salt concentration of surface waters ranges in general between 500 and 4,500 mg l^{-1} (780 and 7000 µS cm^{-1}).

The important role of Sidi Salem within the Tunisian water supply stresses the relevance of an acceptable quality of the provided water. Analysing existing salinity data of the reservoir, the results

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indicate a high seasonal dynamic of the reservoir quality state, with maximum salinity values about 2600 µS cm^{-1} (ca. 1660 mg l^{-1}). Inflowing water quality ranges from 700 to 5700 µS cm^{-1} between 1990 and 1994. One of the main drivers for the high salinity levels could be identified in the tributary Mellegue. Data of this even show higher values (1,150 to 7,300 µS cm^{-1}). Especially for the Tunisian site as a multi-reservoir system an application of the concept of enhanced reservoir operation is therefore of high relevance.

As the Medjerda is a transboundary river, the water quality of the water discharged from the Algerian part would be of high interest but due to the lack of reliable data only small indications of the salinity portion could be made but these lead to the assumption that the contributing is smaller than this by the tributary Mellegue. Needed information on biological and physical requirements of native aquatic biota (fish species, macroinvertebrates) are neither available for the Medjerda River nor for the Sidi Salem reservoir (Vanden Bossche and Bernacsek, 1991), therefore this case study focuses on water quality and quantity considerations, in terms of water volumes and salinity levels.

In the past, the water management gave highest priority to the drinking water supply. For covering the registered weekly irrigation demand the releases of the reservoirs are adapted accordingly. Conventionally, the operation of the Sidi Salem reservoir directed to quantitative aspects, i.e. each inflowing water volume reaching the reservoir is stored, independently of its quality (Bauer, 2006).

Results and discussion

The important role of Sidi Salem within the Tunisian water supply stresses the relevance of an acceptable quality of the delivered water. The reservoir salinity of Sidi Salem is among others subject of high temporal variations. Depending on the climatic situation and the inflow constitution the reservoir storage volume arises to periods of acceptable and unacceptable quality.

Therefore, different regulation modes were developed in order to enhance the availability of high-quality water of the water storage.

Simulating these, the changes of the reservoir body with regard to water quantity and quality aspects for a subsequent period of four years are calculated, resulting in an increase of the available water with accepted quality. Comparably, the water release quality is enhanced positively affecting not only the downstream water supply but as well as the riparian area, the conditions for aquatic biota and the ecological environment.

The *enrop* concept basically starts with processing the reservoir inflow data and identifying periods of flow with comparatively high salt loads, which mark subsequently the temporal frame of operation enhancement and regulation periods accordingly. Within these so-called 'operation periods' (Figure 4) the main approach pursued is not impounding the inflowing water but moreover bypassing or using it in upstream areas for purposes requiring less water quality, e.g. agriculture. Options for alternative uses of such partial inflow streams can be establish, with setting different operation scenarios according to given conditions (reservoir storage level, inflow, quality of water body).
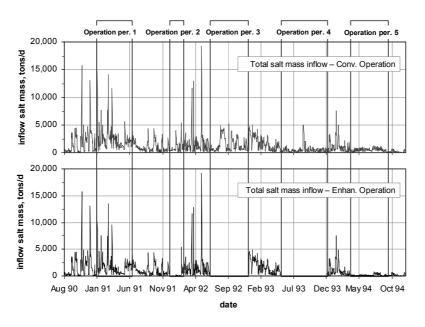
Figure 4. Modified inflow regime of Sidi Salem, based on defined operation periods

The simulation of this adapted operation scheme was done by using the reservoir water quality model Lac. The outcomes indicate the quality improvement of the reservoir water body and the releases accordingly (Figure 5 and Figure 6).

The visualised results of the model show a time-depths plot related to the main parameter investigated the salinity (μS cm^{-1}) for the conventional as for the enhanced operation. Comparing both schemes, it is obvious that the state of the reservoir water body quality improved by applying the proposed concept.
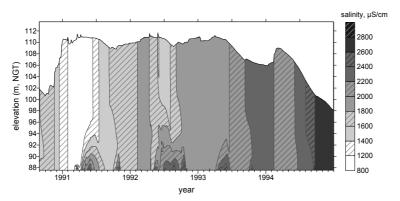

Figure 5. Simulated salinity for Sidi Salem reservoir under conventional reservoir management, time-depths plot for the period 1990 to 1994
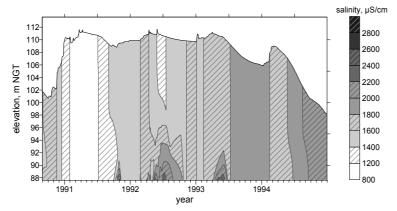

Figure 6. Simulated salinity of Sidi Salem reservoir under enhanced reservoir operation, time-depths plot for the period 1990 to 1994

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The simulation results for a period of four years (1990 to 1994) indicated a substantial increase of high-quality water within the reservoir. An average reduction of about 13% of the salt load at the end of the simulation period was achieved. This is a synonym for a total decrease about 52,000 tons of salt in the reservoir (equally to a reduction of the salinity in December 1994 by 535 μS cm^{-1} (from 2780 μS cm^{-1} to 2245 μS cm^{-1}), as well as for the release volume assuming a totally mixed reactor. Reducing the salt mass of a yearly average about 13,000 tons, contributes significantly for the enhancement of the downstream habitat.

The enhanced operation leads especially within range of 1,400 to 1,600 μS cm^{-1} to a considerable increase of available water (of higher quality) about 362%, equally to 151 Mm³, i.e. after applying *enrop* more water of the reservoir storage and correspondingly releases having salinity values of this range is available.

Relating the studies outcomes to the conclusions found by Horrigan et al. (2005), a reduction of releases salinity by approximately 535 μS cm^{-1} would have a great effect of the living conditions for the downstream river habitat. Salt sensitive communities can be resettled, connected to a probable reduction of salt tolerant taxa and leading to a more balanced distribution of different species increasing the diversity of the aquatic biota.

Furthermore, setting the results into the context of the existing salinity categories, e.g. given in the median range guidelines for surface water conductivity (DEH and NR&M, 1999) downstream runoff changes the category from 'brackish' to 'marginal 'water.

Conclusions and Outlook

There is the pressuring need of improving water resources management in order to secure water quality, quantity and environmental sustainability. Enhanced reservoir operation allows environmental aspects to be incorporated into water management by optimising reservoir storage in terms of quantity and quality. Combining such operational measures with important issues concerning water resource management the proposed method is a first step towards incorporating environmental aspects into a technical context, but implying the understanding of downstream ecosystem needs.

This is indicated in detail by the results of the Tunisian case study, where the *enrop* concept highly contribute to an improvement of the important sectors of drinking and agricultural water supply but moreover the equally important maintenance and restoration of the river habitat is supported very well. By this, the study develops an exemplary link between a technical method and related ecology and environmental aspects.

From the water quantity point of view, studies carried out in regulated streams mostly come to the conclusion that the optimal flow regime should be correspond nearly to the natural flow of the river. In contrast to these, the alteration of the natural flow regime variability by dams cannot be reconditioned completely, particularly for temporary streams because of their high temporal variability. Therefore, models should be used for estimating in-stream flow requirements as a certain percentage of the mean annual natural runoff.

Furthermore, without required qualitatively information on biological, chemical and physical requirements, for example nutrient concentration, salt tolerance or water level, of native aquatic biota, the relation to the provided water by reservoirs would be not possible. Therefore, future studies must be directed to gaining the knowledge on ecological and environmental information in order to be able to adapt the regulation of reservoirs accordingly within the maximum technical range possible.

Such extended understanding of interactions between specific reservoir operations and the provided water quality and quantity will support satisfying the potential conflicting needs of humans and ecosystems.

The introduced concept further supports decision makers in the overall water management for determining adaptive reservoir operation schemes aiming for an improved water quality and quantity for civil use and aquatic ecosystem protection. For this, a more deepened research on ecological and environmental demands is needed thereby more or less limited to site-specific applications. This in-

turn will limit the transferability of developed method as they cannot be transferred offhand to other regions. Future studies should therefore gain to enhance the knowledge on ecological relations e.g. by extending the monitoring system and data collection.

Although the firstly developed link between technical approaches (*enrop*) exemplarily to the conception of ecohydrology provides an important contribution to building the framework of IWRM, it will not specify the method of incorporating ecosystem processes into management programmes of different levels, as that is necessarily site specific. But by applying new understandings emerging from technical as well as ecohydrological research, water managers can enhance the resilience of freshwater ecosystems to human impacts, thereby capitalizing on ecosystem services and achieving water management goals with minimal engineering inputs and financial investment.

For future developments it is also questionable if the past trend toward holistic approaches should be further pursued because of its limited practical applicability. Maybe for river catchments where a very good data basis exists, holistic methods are more suitable but for most of the developing countries where temporary waters are widespread this is not the case. Here, investigations must start with the development of direct links between the volume of water releases and basic ecological parameters representing downstream requirements (e.g. native fish species), like water level or salinity. Picking up the described coherences, subsequent studies should be aim for approaches, simplified in their application, which are feasible for linking to an evaluation of proposed measures by using indices like the Water Volume by Class (WVC), the Water Quality and Quantity Index (WQQI) (Bauer, 2006) or the Salinity Index (SI) (Horrigan et al., 2005).

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