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Complete List of Authors:	Efstratiadis, Andreas; National Technical University of Athens, Department of Water Resources and Environmental Engineering Tegos, Aristotelis; ECOS Consultants S.A., Varveris, Anastasios; ECOS Consultants S.A., Koutsoyiannis, Demetris; National Technical University of Athens, Department of Water Resources and Environmental Engineering
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Assessment of environmental flows under limited data availability – Case study to Acheloos River, Greece

A. Efstratiadis[1], A. Tegos[2], A. Varveris[2] and D. Koutsoyiannis[1]

[1]*Department of Water Resources and Environmental Engineering, National Technical University of Athens, Heroon Polytechneiou 5, GR-157 80, Zographou, Greece*
andreas@itia.ntua.gr
[2]*ECOS Consulting S.A., Makedonon 10, GR-115 21, Athens, Greece*

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Abstract The lower course of Acheloos River is an important hydrosystem of Greece, heavily modified by a cascade of four hydropower dams, which is now being extended by two more dams in the upper course. The design of the dams and hydropower facilities that are in operation has not considered any environmental criteria. However, in the last fifty years, numerous methodologies have been proposed to assess the negative impacts of such projects to both the abiotic and biotic environment, and to provide decision support towards establishing appropriate constraints on their operation, typically in terms of minimum flow requirements. In this study, seeking for a more environmental-friendly operation of the hydrosystem, we investigate the outflow policy from the most downstream dam, examining alternative environmental flow approaches. Accounting for data limitations, we recommend the basic maintenance flow method, which is parsimonious and suitable for Mediterranean rivers, whose flows exhibit significant seasonal variability. We also show that the wetted perimeter – discharge, which is an elementary hydraulic approach, provides consistent results, even without using any flow data. Finally, we examine the adaptation of the proposed flow policy (including artificial flooding) to the real-time hydropower generation schedule, and the management of the resulting conflicts.

Key words modified rivers; hydroelectric dams; reservoir water balance; basic maintenance flow; wetted perimeter – discharge; artificial floods

1. INTRODUCTION

Because of their interventions to the natural morphological and hydrological conditions, large-scale dams may cause significant modifications to the downstream river systems and, consequently, to their ecological status. Indeed, the spatial and temporal regulation of flows caused by large reservoirs may result to major changes to the hydrological regime of the river, which in turn has negative impacts to both the biotic and abiotic river environment (in terms of habitat conditions and structure, biological distributions, etc.). On the other hand, it is far from reasonable to ignore the beneficial and multidimensional role of such projects, in terms of providing water for various water uses (water supply, irrigation, hydroelectric production, navigation, etc.), together with the reduction of flood risk. Another benefit is the formation of an attractive landscape, favouring the touristic development of the areas around the artificial lake. In this respect, it is essential to seek for a balance between the maximization of the socio-economic benefits and the environmental improvement. This challenging task requires a holistic and rational viewpoint to handle the numerous conflicting interests that are involved in the operation of the related reservoir systems (Christofides *et al.* 2005, Efstratiadis and Hadjibiros 2011).

The EU Water Framework Directive (WFD; 2000/60/EU) emphatically promotes the maintenance of a good ecological and chemical status of surface waters. Naturally, attention is paid on heavily modified water bodies, such as regulated rivers

(Acreman *et al.* 2008). For this reason, the water policies in EU have been thoroughly revised to incorporate ecological, environmental and water quality criteria within the design and management of reservoirs towards ensuring (or restoring) natural conditions, to some extent. The most usual practice is the establishment of a specific, either steady or seasonally varying, outflow rate through the reservoir, which is typically called environmental, ecological, minimum or maintenance flow, and aims to guarantee a sufficient level of protection for the downstream aquatic environment (Alcázar *et al.* 2008). In last decades, its assessment has become an issue of continuous research, as indicated from the increased number of papers dealing with this specific topic.

There exist many interpretations of environmental flow assessment (EFA). For instance, Tharne (2003) defines the problem as "*an assessment of how much of the original flow of a river that should continue to flow down it and onto its floodplains in order to maintain specified, valued features of the ecosystem*". Another definition is provided within the so-called Brisbane Declaration (2007), asserting that "*environmental flows describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on them*". While the latter definition is more general, it gives the impression that EFA is rather a theoretical issue, involving the estimation of the water needs of ecosystems under pristine (i.e. unmodified) river conditions. In contrast, the former definition accepts the existence of two flow regimes, an original and a modified one. Nevertheless, any EFA should be accompanied by an operational plan for the management of the water resources. This should compromise the environmental needs with the human ones, under all technical, economical and institutional constraints. In this context, EFA is an essential yet not unique component of a broader study, which requires an integrated and system-wide viewpoint.

EFA has become a major issue in watershed management, for which numerous approaches have been proposed, of all levels of complexity. A short review of the methodologies and the related management practices is provided in next section. The health and sustainability of river ecosystems depends on multiple factors, including flow regime, river hydraulics (e.g. geometry of channel and riparian zone), level of exploitation, presence of physical barriers to connectivity, etc. (Acreman and Dunbar, 2004). It involves a number of biological, geomorphological, physical, and chemical processes in a river that form and maintain aquatic ecosystems (Suen and Eheart 2006). However, an overall evaluation of all the above factors is extremely difficult. Despite the important advances towards understanding the complex eco-hydrological processes and their interactions, the amount and time-length of the required information (in terms of field observations) remains the most important restricting factor. Therefore, in most real-world applications the problem should be handled under significantly limited data availability (e.g., Smakhtin *et al.* 2006). In many cases, this may involve even "trivial" types of information, such as daily discharge data. Theoretically, environmental flows can be calculated only in gauging stations, operating for a quite long time (at least ten years) and under natural flow regimes. In practice, these assumptions are rarely valid, thus making essential to seek for EFA approaches that are as parsimonious as possible, in terms of data requirements.

Another important issue is the adaptation of the management policy of the existing reservoir systems, in order to accomplish the environmental objectives. Typically, the latter are addressed in terms of external constraints to reservoir stages and outflows (e.g., Harman and Stewardson 2005, Suen and Eheart 2006, Suen 2011). The outlines of each policy first depend on the purpose of the project, because different types of dams alter natural flow regimes in different ways (Richter and Thomas 2007). This article puts emphasis on large-scale hydroelectric reservoirs, the role of which is of key importance with regard to scheduling of energy production at the national level. Traditionally, their management is determined thought pre-specified operation rules, with the goal of maximizing energy revenue, while meeting other water uses. In this context, the regulation of outflows is determined by both the long- and the short-term energy demand, the temporal variability of which is radically different to the variability of the natural flows. Obviously, the flexibility of the hydropower generation schedule is restricted when the outflow policy is also determined by environmental constraints. In general, the latter limit the contribution of peak hydropower plants to adapting the power supply to the demand and to providing certain ancillary services to the electrical grid (Pérez-Díaz and Wilhelmi 2010). For this reason, the task of adapting the operation rules of large-scale hydropower systems to account for environmental requirements is far from straightforward. To our knowledge, the practical aspects of this issue, which is a challenging multidisciplinary problem, have gained little attention in the literature. For instance, Jager and Smith (2008) reviewed decision-making efforts and optimization techniques to problems involving both hydropower and environmental criteria. Renöfält *et al.* (2010) investigated the impacts of hydropower generation on freshwater ecosystems and discuss efficient mitigation measures. Beilfuss (2010) developed a simulation model, using a 97-year historical flow series, to assess the trade-offs between environmental flow scenarios and hydropower generation in the Lower Zambezi Basin, Mozambique. A simulation-based approach, using the HEC-5 package, was also employed by Babel *et al.* (2012), in order to improve the operation of the hydropower system of La Nga river basin, Vietnam.

In this study, we review alternative EFA approaches and investigate their implementation within the operation of the hydroelectric scheme of Acheloos River, in Western Greece. Acheloos is the river with the highest runoff in Greece and produces more than 40% of its hydroelectric energy. Moreover, its estuary is of major ecological importance, protected under the Ramsar Convention. In order to estimate the environmental demand at the estuary, we attempted to “reconstruct” the natural flows along the river for a 42-year period, using rather limited hydrological data (i.e. sparse flow measurements and reservoir level and outflow data, on daily basis). Next, we revised the outflow scheduling through the most downstream dam, taking into account the results of the EFA analysis and the real-time management of the related infrastructures (power plants, channels, etc.). The whole methodology can be used as framework for similar studies, involving heavily-modified rivers with significantly variable flows, and where the only available data are daily discharge records.

2. HISTORY AND CLASSIFICATION OF ENVIRONMENTAL FLOW MODELS

Regulations about minimum river flow requirements are very old and must have been invented based on common sense and empirical criteria. The following example of minimum flow regulation survives owing to epigraphic evidence from the 5th century BC (Davies 1996; see also Koutsoyiannis 2012). It refers to the ancient site Gortyn, crossed by the river Lithaios, today called Mitropolianos, which dominates the valley of Messara, Crete, and starts with an invocation to gods:

> *«Θιοί· τô ποταμô αἴ κα κατὰ τὸ μέττον τὰν ῥοὰν θιθῆι ῥῆν κατὰ το Fὸν αυτô, θιθεμένōι ἄπατον ἤμην. Τὰν δὲ ῥοὰν λείπεν ὅττον κατέκει ἀ ἐπ᾽ ἀγορᾶι δέπυρα ἤ πλίον, μεῖον δὲ μὴ.»*

(Gods. If anyone makes the flow of the river run from the middle of the river towards his own [property], it is without penalty for the person so doing. [He is] to leave the flow as wide as the bridge that the agora holds, or more, but not less.)

However, the concept of EFA, based on the analysis of environmental issues, is very modern and was developed in the last three decades to address the problems created by segmentation of rivers by dams. As reported by Tharne (2003), elementary EFA approaches are found from the end of the 1940s, in the western USA. Yet, the great expansion of environmental flow models (EFMs) was made during the 1970s, as the new environmental and freshwater legislation made essential the quantitative documentation of environmental flow requirements. Outside of the United States, the EFMs gained significant attention in the 1980s. From the 1990s, more integrated approaches have been evolved, focusing on ecological rather than on hydrological aspects of the problem. A comprehensive review of EFA methods is provided by Tharme (2003), Acreman and Dunbar (2004) and Petts (2009).

The number of the existing approaches and their variations is noteworthy. One decade ago, Tharme (2003) listed 207 different methods within 44 countries. In general, EFMs are classified into four main categories, depending on the type, size, quality and availability of the required raw information, the data processing, the methodological assumptions, as well as the time and the cost for shaping the final proposals. The main characteristics of each category are summarized herein.

2.1 Hydrological methods

In this category fall a large variety of methods that use streamflow time series as single input. Quoting Palau and Alcázar (1996), streamflow can be considered as the ‘genetic code of the river’, driving the relationship between the hydrological variability and the physical and biological river structure and dynamics. In fact, the flow regime determines the hydraulic and geomorphologic characteristics of the river (distribution of velocities and depths, bank form, bed width, bed substrate types, sediment transport), which in turn determine both the abiotic structure and the biotic composition of the riverine ecosystems. We remark that in the WFD, the flow regime is not considered a primary quality element to assess water bodies (cf. Acreman and Ferguson 2010), which is, in our opinion, unreasonable.

Hydrology-based EFMs constitute the highest proportion of the overall number of methodologies recorded (about 30%, according to Tharme 2003), and they have been widely employed to establish the outflow policy downstream of existing or new dams. In most of these (also referred to as desktop or lookup table methods), the minimum flow requirements are expressed in terms of percentages of annual flows or percentiles from a flow-duration curve (Acreman and Dunbar 2004). The typical computational procedure presupposes a statistical analysis of the historical discharge data, emphasizing on low-flow periods. Often, pre-processing is essential to obtain the so-called “naturalized” time series, given that after the construction of the dam the flow regime is radically modified. The suggested time resolution of flow data is at least daily, although mean monthly and mean annual flow data are also suitable, for the most elementary approaches.

The level of complexity of hydrological methods ranges from very simple rules-of-thumb to sophisticated procedures, requiring advanced data processing. A characteristic elementary rule is imposed by the French Freshwater Fishing Law of 1984, which requires that residual flows in bypassed sections of a river must be a minimum of 1/40 of the mean annual flow (MAF) for existing schemes and 1/10 of the mean flow for new ones (Acreman *et al.* 2008). Similar standards have been employed in many countries and incorporated in the related environmental legislation. In particular, the minimum average monthly flow has been generally used in Greece to determine the flow to be maintained below dams. In Spain, the 10% of MAF is generally employed, for river basins with limited information, while the routine values in Portugal are 2.5 to 5.0% of MAF (Tharme 2003).

The flow targets are also assessed by considering specific exceedence percentiles of flow duration curves, derived from statistical analysis of daily discharge records (Smakhtin 2001). For instance, the Q_{95} (i.e., the flow which is equalled or exceeded 95% time) is adopted as minimum standard in UK, Australia, Taiwan and Bulgaria, while Canada and Brazil typically use the Q_{90} discharge. On the other hand, some countries consider much less conservative thresholds, such as the Q_{364}, which corresponds to the minimum daily flow of the year, and it is practically estimated as the 99.7% discharge quantile.

While most of the aforementioned approaches are rather empirical, the so-called Tennant (or Montana) Method (Tennant, 1976) is the first one attempting to quantify the correlation between the streamflow regime and the sustainability of fish fauna. Its development required the collection of a huge amount of field habitat, hydraulic and biological data, during a 20 year-period. The method identifies a critical flow rate for the summer and winter months (expressed as percentage of the mean annual discharge), according to the river conditions. For instance, for poor conditions, this percentage should be 10% during the dry and 30% during the wet period.

In the UK, a series of workshops were recently held, at which lead water scientists defined environmental standards for river abstractions, in order to achieve the WFD objectives (Acreman *et al.* 2008). The team of fish ecologists recommended various abstraction thresholds as a percentage of flow on the day in excess of Q_{95}. In this context, the natural Q_{95} is encountered as the lower limit for fish maintenance. The Q_{95} was also proposed by hydrology experts, on the basis of hydraulic data retrieved from 65 sites over UK.

Instead of imposing a time-constant flow constraint, advanced hydrological approaches account for the variability of flows at multiple temporal scales (monthly, seasonal and annual), thus they are purported to be more ecologically relevant. The most representative of them are the basic flow method (BFM; Palau and Alcázar 1996) and the range of variability approach (RVA; Richter *et al.* 1996, 1997).

The BFM was developed and broadly applied in Spain (especially across the Ebro watershed), but in the last years it also gained increasing recognition elsewhere. It is based on the study of irregularities in hydrological series of daily mean flows using the simple moving average model as a tool to extract the relevant information. Its key assumption is that organisms living in a river system are adapted to it, and therefore the biological cycles and ecological requirements are adapted to the seasonal fluctuations of flows. Given that the organisms can afford significantly low flow conditions for limited time periods, the method wishes to determine the average duration and magnitude of such periods, on the basis up to 100-day moving average time series. In reality, the BFM constitutes a complex management proposal, which includes a number of issues affecting the biological functioning of regulated rivers (e.g., flow variability, bankfull flows or varying flow rates), through the establishment of monthly instream flow requirements (Palau and Alcázar 2012). The method is now incorporated within the Spanish regulation, implementing the obligations of the WFD.

The RVA is even more complex, since it uses 32 different hydrological parameters for the description of hydrologic changes, directly related to the quality of ecosystems. The so-called indicators of hydrological alteration (IHA) are grouped into five categories:

(1) The mean monthly flow values, providing a general measure of habitat availability or suitability (e.g. humidity for riparian vegetation, water for land animals);
(2) The magnitude and duration of hydrological extremes (floods and droughts), which are associated with environmental stress and disturbance (e.g., dehydration for animals, anaerobic stress for plants) and also affect the colonization processes;
(3) The timing of annual extreme conditions, associated with the life cycles of various organisms, the reproductive behaviour and the accessibility to specific habitats;
(4) The frequency and the duration of high and low flows, which are associated with the soil moisture regime in the riparian zone, the soil characteristics, the duration and extent of specific seasonal habitats, the river geomorphology, etc.;
(5) The rate and frequency of change in conditions, which describe the abruptness and number of intra-annual cycles of environmental variation and thus provide a measure of the rate and frequency of environmental changes.

In a modified flow regime, the IHA parameters should be maintained within the limits of their natural variability. In the absence of other ecological information, a threshold of one standard deviation from the mean value of each parameter is suggested as a default limit, in order to set the environmental flow targets.

2.2 Hydraulic rating methodologies

Hydraulic rating (also known as habitat retention) approaches assume that hydraulics is the key driver of the river ecosystem integrity. In this context, they evaluate a number of hydraulic, morphological and geometrical characteristics (wetted perimeter, depth, velocity, etc.) and establish links with habitat availability of target biota. Input data are historical flow records and cross-section data. The analysis is implemented in few selected cross-sections, particularly in shallow areas (e.g. riffles) or areas with important ecological characteristics, which are considered as critically limiting biotopes. The obvious assumption is that the protection of the most critical hydraulic areas ensures the maintenance of the entire aquatic ecosystem.

According to Tharme (2003), these methods represent about 11% of EFMs and can be viewed as preliminary appearances of habitat simulation or even holistic approaches. Since the available aquatic habitat, for given flow conditions, is by definition determined by the wetted perimeter of the channel, a number of approaches have been proposed aiming to use the above geometrical characteristic as basic tool for ecological evaluation. Their key idea is that the wetted perimeter of shallow and wide rivers is more sensitive against flow changes, in comparison to narrow and deep ones (Acreman and Dunbar 2004). In particular, the wetted perimeter–discharge breakpoint has been extensively used to define optimum or minimum flows for fish rearing in the USA from the middle 70s. The breakpoint (also referred to as inflection point) is the point where the slope of the stage-discharge curve changes (decreases), so that a large increase of flow results in a small increase of perimeter. The lowest breakpoint in the curve is taken to represent a critical discharge below which habitat conditions for aquatic organisms rapidly become unfavourable (Gippel and Stewardson 1998). In the absence of in situ hydrometric data, the Manning's equation is generally used to identify the stage-discharge relationship, in which the detection of the breakpoint can be made either graphically or analytically.

Today, the use of the wetted perimeter as the unique indicator of the river health and the means for determining ecological flows is limited. Nevertheless, hydraulic approaches are usually employed only in conjunction with other techniques.

2.3 Habitat simulation methods

Habitat simulation methods are the most popular after the hydrological ones. In general, they assess the environmental flow requirements on the basis of detailed analyses of the quantity and suitability of instream physical habitat, particularly target species or assemblages (mainly fish), observed under different flow regimes. The models use hydrological, hydraulic and biological data, to represent the habitat conditions within hydraulic simulation tools, thus allowing for the establishment of a direct link between habitat and discharge.

A well-known approach of this category is the instream flow incremental methodology (IFIM; Stalnaker *et al.* 1995), which has been considered by some practitioners as the most scientifically and legally defensible methodology available for assessing environmental flows (Tharme 2003). IFIM was designed to address a number of ecological components (including flow regime, physical habitat structure, water quality, and energy fluxes) in the context of management decisions concerning instream flow. It also comprises mechanisms for analysing the institutional aspects of water resource issues. The IFIM framework has been implemented within decision support systems, among which the Physical Habitat Simulation (PHABSIM) software, developed by the USGS (Waddle 2001).

2.4 Holistic approaches

Holistic methods are essentially processes that allow aquatic scientists from many disciplines to integrate data and knowledge (King *et al.* 2003), thus indicating a shift from prescriptive to interactive approaches (Tharme 2003). Obviously, these are much more demanding, in terms of data requirements as well as human and time resources. Their objective is to address the requirements of the entire riverine ecosystem, comprising instream and groundwater systems, floodplains and downstream receiving waters (Arthington *et al*. 1992). In fact, they do not provide explicit ecological targets but rather focus on determining the effects of water resources management scenarios, thus being suitable for related studies and master plans.

The term "holistic" was first proposed by Arthington *et al*. (1992). In the last two decades, a wide range of such methodologies has been developed and applied, initially in Australia and South Africa, and more recently in the UK. The most recognized are the building block methodology (King and Tharme 1994, King and Louw 1998), developed in South Africa, the so-called DRIFT (downstream response to imposed flow transformations) framework (King *et al.* 2003), and the benchmarking method (Arthington and Zalucki 1998, Arthington and Pusey 2003). The latter is the only tool specifically designed to assess the risk of environmental impacts due to river regulation, at the basin scale.

3. CASE STUDY

3.1 The river Acheloos and its hydroelectric reservoir system

The case study involves the assessment of environmental flows of river Acheloos and their implementation within an operational management plan. Acheloos is located in Central Western Greece, and it is the largest river of the country in terms of flow and the second one in terms of length (~220 km). Its river basin, depicted in Fig. 1, covers an area of about 5000 km^2, and it is enormously rich in water resources. The mean annual precipitation reaches 1350 mm and the mean annual (naturalized) discharge at the estuary is estimated to be 136.9 m^3/s (see section 4), which corresponds to an equivalent runoff depth of more than 850 mm and a runoff coefficient of 63%. In the mountainous areas, due to the domination of low permeability formations (flysch), the mean annual runoff exceeds 1000 mm and the runoff coefficient is around 70% – an outstanding percentage for Mediterranean catchments.

From the early 1960s, the Public Power Corporation (PPC) constructed four major dams and interconnected hydropower stations in the middle and lower course of the river. Their characteristics are summarized in Table 1. The system hosts 43% of the installed hydropower capacity of the country, i.e. 1302 out of 3060 MW, and today produces 42% of the annual hydroelectric energy, i.e. 1880 out of 4500 GWh (official data by the PCC; Argirakis 2009). The oldest dam (Plastiras) is located on a tributary of Acheloos (Tavropos), and diverts the entire runoff of its upstream basin (161 km^2) to the adjacent plain of Thessaly, taking advantage of an exceptional hydraulic head, ranging from 561 to 577 m. After passing through the turbines, the water is used for irrigation and water supply. The other three dams (Kremasta, Kastraki, Stratos) form a cascade along the main river course. In particular, the Kremasta dam, with a height of 160 m, is the highest earth dam in Europe. The artificial lake, with total storage capacity of 4500 hm^3, extends up to 80 km^2 and it is the largest in Greece, while the hydropower station, with installed capacity of 160 MW, is also the largest in Greece. Apart from the production of hydroelectric energy, the reservoir system provides water for domestic supply and irrigation, and also provides flood control to the downstream areas (Aetoloacarnania plain).

Future configurations of the system have been also studied, involving the interbasin transport of part of the upstream flows of Acheloos to Thessaly. Some components of this system are completed. In particular, the dam and the hydropower plant of Mesochora, in the upper Acheloos course, are ready for operation since more than a decade, but, the reservoir is not allowed to fill due to opposition from ecologists and local communities. The diversion tunnel is also almost ready, while the diversion dam at Sykia, downstream of Mesochora, is auctioned and some of the preliminary works are completed. Critical assessments of the situation have been provided by Koutsoyiannis (2011) and Fourniotis (2012).

3.2 The Acheloos estuary and its ecological importance

The environmental value of the entire river basin of Acheloos is indisputable. For instance, the riverine ecosystems in the upper and middle course have been identified as important habitats for many threatened species of freshwater fish and birds. Fortunately, this part of the basin is only slightly influenced by human interventions. Yet, the most important and sensitive ecosystems are hosted in the estuary, extended areas of which belong to the NATURA 2000 sites, while the Acheloos Delta is protected by the Ramsar Convention (Varveris *et al.* 2010).

The geomorphological and hydrodynamic conditions of the estuary (e.g. distribution of brackish and freshwater) favoured the development of important wetlands, such as lagoons, coastal salt lacustrine and freshwater marshes, with remarkable biological diversity (Fourniotis 2012). In particular, in the lower course and the estuary, three main types of riparian forests grow, i.e. riparian forests with Salix alba and Populus nigra as dominant species, a forest of Fraxinus angustifolia, and clusters with Tamarix parviflora and Vitex agnus-castus. Regarding fish fauna, 41 species have been identified, including Endangered Sturgeon (Acipencer Sturio), Barbus Albanicus, Barbus Peloponnesius, Trichonovelonitsa (Cobitis Trichonica), Greek Dromitsa (Rutilus Ylikiensis), as well as the unique European species of Silurus Aristotelis. Birds are the largest group of vertebrates, recording 259 species (Fulica Atra, Larus Genei, Egretta Alba, Phalacrocorax Carbo, Aythya ferina, Anas Penelope, etc.). For this reason, the Acheloos Delta has been also included in the Special Bird Areas list. Finally, there exist at least 20 species of reptiles and amphibians that are protected at international level. For analytical information on the flora and fauna of the broader area, the reader is referred to the Filotis website, a database for the natural environment of Greece (http://filotis.itia.ntua.gr/).

3.3 The actual management policy

The actual operation of the hydrosystem is mainly determined by the energy demand (usually, for peak energy production); the irrigation demand during the summer period is of less importance. The management of these uses requires large-scale regulations and abstractions (including the diversion of the sum of runoff of the upstream Tavropos basin), which radically changed the former flow regime of the river, particularly in the lower course and the estuary. In fact, the temporal variability of flows became much smoother and not any severe flood phenomenon was observed during the last decades. The substantial differences between the natural and modified hydrological conditions are illustrated in Fig. 2, in which are compared, on mean monthly basis, the historical outflows from the most downstream dam (Stratos) and the "naturalized" flows. Both refer to period 1990-2008, i.e. after the completion of the Stratos works (1989).

The hydrological changes were also accompanied by major changes in the land management practices in the Aetoloacarnania plain, grace to the release of extended fertile areas. Even the floodplains of Acheloos, very close to the main course, have been occupied by agricultural activities and temporary settlements. This practice, apart from being illegal and dangerous (since the flood risk is reduced but not eliminated), further contributes to the environmental degradation of the lower course areas. Moreover, the PCC is obliged to adjust its control policy of the reservoirs, in order to avoid conflicts with local society in case of damages due to inundations. In this context, the outflow downstream of Stratos is not allowed to exceed the discharge capacity of the penstocks, while the spillway remains – except for very rare cases – out of use (Koutsoyiannis *et al.* 2012). However, this requires keeping empty storage in the reservoirs, which is actually inefficient in terms of hydroelectric energy management.

3.4 Update of the environmental terms of Acheloos hydrosystem

The environmental terms for the operation of the reservoir system have been specified in the middle 90's, within the environmental impact assessment study (EIA) of the upper Acheloos project (Hydroexygiantiki 1995). We highlight that this was the first study in Greece dealing with the estimation of environmental flows. Among others, it envisaged the maintenance of a seasonally constant minimum flow 21.3 m^3/s, downstream of the Stratos dam. The above constraint was determined through statistical analysis of the mean monthly naturalized discharges of the drier month (August). The proposed value equals the 5-year minimum discharge, i.e. the discharge with 80% exceedance probability. The study also determined the ecological flow downstream of the rest of dams of the interbasin transport plan (two in Acheloos and two in Thessaly basin).

The environmental terms involving the existing scheme of works (i.e. Kremasta, Kastraki and Stratos) were incorporated within the related legislation only in 2007. In 2009, the PCC appointed a new study to investigate two key issues: (a) the suitability of the formerly proposed environmental flow, taking into account the most recent hydrological data as well as the advances on the field, and (b) the adaptation of the management practices and the design of the related hydraulic works (if necessary), to implement the proposed environmental policy. The results of this study (elaborated by ECOS Consultants 2009; see also Varveris *et al.* 2010), are summarized below.

4. HYDROLOGICAL ANALYSIS

4.1 Outline of methodology

The investigation of the flow regime of the river is a key step of any environmental flow assessment method, from the simplest to the most sophisticated ones. The former estimation of environmental flows was based on monthly runoff data, which is yet inconsistent with the requirements of the majority of EFA procedures worldwide. As recommended, the time resolution of flow records should be daily or finer, while their time length should be at least 10 to 20 years, in order to extract reliable statistical conclusions (Hughes and Smakhtin 1996, Palau and Alcázar 2012). Moreover, the flow time series should correspond to unmodified conditions. If the river regime is modified (e.g. due to the interpolation of large-scale hydraulic structures), the data have to be adjusted, by "removing" all regulation effects (water storage, abstractions, water losses, etc.). This procedure is commonly referred to as "naturalization", since the adjusted flows are assumed identical to the flows under natural conditions.

Unfortunately, no hydrometric station exists close to the Acheloos estuary, to extract the required flow time series at the exact point of interest. However, even if such a record was available, it would be necessary to correct its data, taking into account the operation of the upstream reservoirs. Therefore, in order to evaluate the flow regime at the estuary, it is essential to extract the naturalized flows at each dam site, by proceeding from upstream to downstream (in particular, from Kremasta, next to Kastraki, next to Stratos, and finally to the estuary). In this context, all available hydrological information was considered, aiming to provide as much reliable estimates as possible. Apart from the flow time series, outputs of the hydrological analysis were the flow-duration curves at all points of interest, which allowed for estimating characteristic quantities on a probabilistic setting.

4.2 Reproduction of naturalized flows at Kremasta dam

Kremasta reservoir is the key regulator of the hydrosystem, due to its great storage capacity. In order to estimate the naturalized runoff of the upstream sub-basin, two types of data were used: (a) daily inflow volumes for years 1965-2008, and (b) instantaneous discharge measurements at the hydrometric station of Avlaki. The latter is located in the outlet of the upper course of the river, 45 km upstream of Kremasta dam, and controls about 40% of the sub-basin of interest (1358 out of 3570 km^2). The available record covers 30 years (1965-1994), and contains about 900 discharge values, non-uniformly distributed over time. Sparse flow measurements close to the Kremasta have been also employed before the construction of the dam (1965), yet these were not accessible.

The reservoir inflows were directly provided by the PCC. These have been estimated from the water balance equation of the reservoir, on daily basis. In particular, the inflow was computed by accounting for the storage fluctuation during each day, the amounts of water used in energy production and the spill losses. The rest of water balance components, i.e. areal rainfall and water losses due to evaporation and leakage, were neglected. However, this approach resulted in systematic underestimations of inflows, especially during the summer period. In particular, the minimum inflow value was found just 1.0 m^3/s, while the minimum observed value before the construction of the dam was 18.5 m^3/s. The inconsistency of the estimated inflows is easily proved, by comparing them with the measured flows at Avlaki. The comparison is made is statistical terms, i.e. by contrasting the two empirical flow duration curves. As shown in Fig. 3, their shapes exhibit significant differences in the low-flow area, which is of key importance for the assessment of the environmental needs. Moreover, about 11% of the flow values at Kremasta are lower than the corresponding measurements at Avlaki, which is evidently out of sense.

The reason of these inconsistencies is the negligence of the three aforementioned components and the uncertainties and errors in the reservoir balance. In fact, during the summer period, the evaporation losses may be as much as 10 mm, which corresponds to 7.0 m^3/s of additional inflow, taking into account the large extent of the lake (40 to 75 km^2). Moreover, the reservoir losses due to leakages are important, since they are estimated to be 6.0 m^3/s, approximately (seasonal variations are neglected). This value is to be also considered in the naturalized flows. Finally, the rain falling over the lake should be considered, although its contribution during the summer months is rather minor.

According to the above assumptions, we recalculated the water balance equation of Kremasta, to obtain a consistent time series of daily inflows for the years 1965-2008. The final record was extracted by adding the upstream flows of Tavropos tributary, which are diverted through the Plastiras dam. Fig. 3 depicts the updated flow-duration curves, which are substantially different from the formerly estimated ones. The key statistical characteristics are given in Table 2. In particular, the mean annual naturalized discharge is 114.3 m^3/s, the mean monthly discharge of the driest month (August) is 24.1 m^3/s, and the overall minimum value is 7.5 m^3/s.

4.3 Estimation of naturalized flows at the rest sites of interest

The next reservoir, Kastraki, operates since 1969. It receives the outflows of Kremasta and the runoff of the intermediate sub-basin, which covers an area of 548 km^2. Therefore, to estimate the naturalized flows at the dam site we should add to the naturalized flows at Kremasta the daily runoff of the aforesaid sub-basin.

In theory, the inflows to Kastraki can be trivially estimated by solving the daily water balance equation of the reservoir, similarly to the case of Kremasta. However, within the daily time interval, the reservoir level fluctuations cannot be accurately represented, thus leading to major errors is the inflow estimations. For instance, about 25% of the flow values appear to be negative. Moreover, the correlation of the summer flows with the corresponding flows at Kremasta is as low as 10%, which is totally unrealistic given that during the dry period, the dominant runoff process is baseflow. For this reason, we employed an alternative approach, based on the monthly water balance of Kastraki, which is satisfactorily accurate. Initially, we estimated the monthly runoff of the intermediate sub-basin and, by adding the monthly runoff upstream of Kremasta, we obtained the naturalized runoff of the whole sub-basin. Next, for each month, we calculated the ratios of the two runoff values (i.e. Kastraki runoff / Kremasta runoff), which was assumed representative of the fraction of the corresponding daily flows. Finally, we multiplied the daily flows at Kremasta by the related runoff ratio, to obtain the naturalized flows at Kastraki. As shown in Table 2, the mean annual naturalized discharge at the dam site is 125.4 m^3/s, and the mean monthly discharge of August is 27.8 m^3/s.

The most downstream reservoir of Stratos, which operates from 1989, drains a local sub-basin of 202 km^2, the contribution of which is minor, if compared to the whole upstream basin of 4320 km^2. Unfortunately, the establishment of a consistent water balance for the estimation of reservoir inflows during its operation was impossible, even at the monthly time scale. Therefore, due to the absence of any other type of hydrological information, we estimated the daily naturalized flows at the dam site by increasing the flow time series at Kastraki by 4%. Finally, we employed an additional 5% increase to obtain the daily flow sample at the estuary, with total drainage area 5027 km^2. This was based on the empirical evidence that the equivalent runoff depth in the lower Acheloos basin is 350 mm. Under this hypothesis, the mean annual naturalized discharge in Stratos is 130.3 m^3/s (136.9 m^3/s at the estuary), and the mean monthly discharge of August is 29.0 m^3/s (30.4 m^3/s at the estuary).

Based on the naturalized time series of daily discharge, we implemented a flow-duration analysis, at all sites of interest. Table 3 gives the flow values for characteristic exceedance probabilities, corresponding to specific time percentiles.

5. ASSESSMENT OF ENVIRONMENTAL FLOWS

For the estimation of the ecological requirements downstream of Stratos we employed various EFA approaches, based on the available hydrological data, i.e. the naturalized discharge time series, averaged at the daily, monthly and annual time scales. We remind that for the assessment of the environmental flows at the Acheloos estuary, the corresponding magnitudes at Stratos should be simply increased by 5%, in order to account for the runoff generated by the local sub-basin. All calculations herein refer to the dam site.

5.1 Estimation of minimum 5-year discharge of the driest month

As mentioned in section 3.4, this approach was adopted in the EIA study of 1995, within the investigations of the operation of the Acheloos diversion scheme. In the present study, we repeated the calculations, on the basis of the updated monthly discharge time series downstream of Stratos dam, which extend over a period of 42 hydrological years (1966-67 to 2007-08). First, we picked up the minimum average monthly discharge of each year (typically, the lowest flow appears in August and occasionally in September), thus formulating a sample of 42 values. Next, we fitted a theoretical statistical distribution to the sample, in particular the normal one (as shown in Fig. 4, paradoxically it looks suitable), on the basis of which we estimated the discharge value that corresponds to a 5-year return period (i.e. 80% exceedence probability). The 5-year low flow of the driest month is 21.1 m^3/s, which is almost identical to the legislative flow constraint (21.3 m^3/s), which was proposed within the EIA study. This value is equal to 16.2% of the mean annual discharge.

5.2 Calculation of typical hydrological indices

Many countries employ elementary hydrological approaches, expressing the critical minimum flow in terms of percentiles and other indices. By implementing some of the most representative methods, we obtained the following results:

(a) **Tennant method**: This method specifies percentages of mean flow that provide different river quality habitats, i.e. 10% for poor quality (survival), 30% for moderate habitat and 60% for excellent habitat (the ratios refer to the dry period). Given that the mean annual naturalized discharge in Stratos is 130.3 m^3/s, the corresponding critical flow values are 13.0, 39.1 and 78.2 m^3/s. The lower value is adopted, because the system is heavily modified. During the wet period, for poor conditions, the recommended percentage increases to 30% of MAF (39.1 m^3/s).

(b) **French freshwater fishing law**: Since Stratos dam is an existing project, the minimum flow to leave downstream should be 1/40 (2.5%) of the naturalized mean annual discharge, which is 3.3 m^3/s (Table 3).

(c) **U.K. standards for achieving Good Ecological Status**: According to the outcomes of the flow-duration analysis, the Q_{95} value in Stratos is 18.0 m^3/s.

(d) **Typical practices in Mediterranean countries**: In Italy, Spain and Portugal standard percentages of the mean annual flow are used, such as 2.5, 5.0 and 10%, which correspond to 3.3, 6.5 and 13.0 m^3/s.

(e) **Other approaches based on flow-duration analysis**: On the basis of the flow-duration curves at Stratos, we calculated other typical indices, such as the Q_{90} (21.8 m^3/s) and the Q_{364} (11.3 m^3/s).

5.3 Basic maintenance flow method

The BFM method has been widely employed for the assessment of environmental flows of river Ebro, Spain, the hydrological regime of which is expected to have similarities with Acheloos. We applied the computational procedure described by Palau and Alcázar (2012), as follows:

Initially, we calculated the moving averages of the naturalized daily flows at Stratos, from one-day to 100-day intervals (Fig. 5). For each year and each interval, we extracted the minimum flow value (Fig. 6), accounting for an annual period starting in April, i.e. the so-called "hydrobiological" year. This is an important assumption, allowing for a consistent estimation of the basic flow (if we used the typical hydrological year, starting in October, the basic flow would be significantly underestimated). Next, we calculated the relative increment between each pair of consecutive minima, and selected the flow with the largest relative increment (in the specific case, the one-day moving average minimum). The average of all daily minima for the considered study period (42 years), which is 13.3 m^3/s, represents the so-called basic flow (Q_b), namely the absolutely minimum discharge that should be maintained along the river. On the basis of Q_b, we estimated the basic maintenance flow (BMF) of each month, i.e.:

$$\mathrm{BMF}_j = Q_\mathrm{b}\,(Q_{\mathrm{mean},j} / \mathrm{Q}_{\mathrm{min},j})^{0.50} \qquad (1)$$

where $Q_{\mathrm{mean},j}$ and $\mathrm{Q}_{\mathrm{min},j}$ are the mean and minimum discharge of the corresponding month j. As shown in Fig. 7, the proposed BFM values range from 16.8 m^3/s (July) to 32.5 m^3/s (January), following the seasonal variability of the naturalized flows.

Apart from the monthly schedule of the minimum maintenance flows, the method also accounts for the so-called "bankfull flow", which represents the dominant discharge in channels at dynamic equilibrium and it is usually calculated as the 1.58–2.33 year flood, and the "maximum flow", estimated as the 25-year flood (Palau and Alcázar 2012). For the case of Acheloos, we used different return periods, in particular 2 and 5 years, in the context of establishing an artificial flooding plan through Stratos (section 6.3).

5.4 Range of variability approach

In section 2.1 we briefly discussed the outline of the RVA, which requires the evaluation of 32 indicators of hydrological alteration (IHA). For the implementation of the method in the two sites of interest (Stratos and estuary) we used the IHA/RVA software (version 7.0), developed by the Nature Conservancy (2009). The most important indices are the 25 and 75% quantiles of monthly discharge, which are shown in Fig. 8, and they are used to specify the desirable range of monthly outflows through the Stratos reservoir. Other characteristic indicators, related to extreme hydrological conditions, are given in Table 4.

5.5 Wetted perimeter - discharge method

In this method, the wetted perimeter–discharge breakpoint at characteristic cross-sections is typically used as indicator of the corresponding critical flow. In this context, we selected five representative river cross-sections along the lower course of Acheloos, with different geometrical shapes (e.g. triangular, rectangular). Next, we employed the maximum curvature approach proposed by Gippel and Stewardson (1998) to define the lower breakpoint of each rating curve, on the basis of the Manning equation. The critical flow over the five cross-sections ranges from 13.1 to 20.4 m^3/s. These values are reasonable, and within the range of most of the hydrology-based approaches. This is a very important conclusion, since the method only uses cross-section geometry, and does not require any hydrological information.

6. ESTABLISHING OF ENVIRONMENTAL FLOW REQUIREMENTS

6.1 Evaluation of EFM approaches

The results of each method, in terms of minimum flow targets at the two sites of interest are summarized in Table 5. The already established constant minimum flow of 21.3 m^3/s exceeds the critical values obtained by almost all variants of the most representative hydrology-based approaches, as well as the wetted perimeter – discharge method, employed at five cross-sections downstream of Stratos. This value is very close to the 5-year minimum monthly discharge and the Q_{90} daily discharge, which provide quite conservative estimations.

However, the assumption of a constant flow constraint may not be suitable for Mediterranean rivers, the flow regime of which exhibits significant seasonal variability, due to the substantially different hydroclimatic conditions between the wet and dry period of the year. For this reason, we suggest revising the current environmental terms of the reservoir operation, in order to account for the seasonality of flows. In this context, we recommend to employ the BFM approach, which is well-documented for the river Ebro, Spain. As already mentioned, Ebro and Acheloos have many similarities, with regard to hydroclimatic regime, man-made interventions, environmental value and importance to national economy. A key advantage of BFM is its parsimony, both in terms of data requirements and computations. Moreover, the outcome of the method, i.e. a specific minimum maintenance flow for each month of the year, is easy to understand and incorporate within an environmental policy. On the contrary, the RVA method provides a wide range of acceptable flows, as well as a number of hydrological indicators, the practical interpretation of which is difficult.

6.2 Adaptation of Stratos outflow policy

Until any new environmental flow policy is adopted, it is essential to ensure that the current standard of 21.3 m^3/s can be technically implemented. Given that all projects were constructed in past decades, without any provision for environmental flows, this is a non-trivial engineering problem that requires a technically appropriate and economically efficient solution. Given that the three cascade reservoirs (Kremasta, Kastraki, Stratos) serve multiple and conflicting water uses, the incorporation of any new constraint obviously increases the complexity of their combined management. In addition, any modification to the actual operation policy requires an agreement between all involved stakeholders (PPC, farmers and local authorities).

In practice, the implementation of the environmental flow affects the outflow policy of merely the most downstream reservoir (Stratos). For convenience, the legislative minimum flow constraint for the Acheloos estuary refers to the location just downstream of Stratos, given that during the summer period the surface runoff generated over the lower course basin is minor (and it may be further reduced due to agricultural abstractions). Previous studies, using advanced simulation models (Koutsoyiannis *et al.* 2002), proved that the application of the aforementioned constraint, expressed by means of constant monthly abstraction from Stratos, is certainly feasible and can be achieved with negligible risk. Yet, the monthly time step is too rough to represent the technical and other constraints that are involved in the real-time operation of the system. For this reason, it is essential to investigate the current scheduling of outflows through the power plant and the constraints imposed by of the related hydraulic works, working in fine time steps (e.g. hourly). Emphasis is given to the summer period, when three conflicting water uses arise, namely the production of hydroelectric energy, the fulfilment of the downstream irrigation demand and the maintenance of the desirable flow target at the estuary.

The area of interest downstream of Stratos dam is shown in Fig. 9. The system comprises two hydropower plants. The major one (Stratos I), with total installed capacity of 150 MW (2 × 75 MW), is located at the right abutment and its discharge capacity is 480 m^3/s. After passing through the turbines, the water is conveyed to a tunnel and a trapezoid channel of about 7 km length, before reaching the natural river course. The small plant (Stratos II), with total installed capacity of 6.7 MW (2 × 3.35 MW), is constructed at the left abutment and its maximum discharge is 45 m^3/s. During summer, the power plants are put in operation only during the peak energy demand period, typically for 2 hours in the morning and 2.5 hours in the afternoon. The time of operation is also restricted because, for higher efficiency, it is necessary to operate each turbine as close as possible to its discharge capacity. The outflow scheduling from each plant is determined such as to satisfy the daily irrigation demand (4 100 000 m^3) and the daily environmental demand (1 840 000 m^3). Details are specified in the technical study (ECOS 2009).

Under this premise, it is impossible to maintain a steady environmental flow for the entire 24-hour period, without additional provisions. In practice, two large-scale water releases are made, one in the morning and one in the afternoon, which are propagated along the lower course of Acheloos. Evidently, during their travel, the hydrographs are attenuated before arriving at the estuary. However, preliminary hydraulic simulations indicated that, without additional provisions, extended parts of the river course remain periodically dry, given that the input flow conditions are intermittent.

To ensure the continuous flow constraint of 21.3 m^3/s along the entire river course, it is essential to ensure a time-regulation of the upstream hydrograph, using a suitable storage facility to be constructed downstream of the dam. The most obvious option is the utilization of the storage in the conveyance channel at the end of Stratos I plant, by means of sluice gates downstream. Hydraulic simulations showed that the storage capacity attained by this technique is sufficient. In this manner, ensuring the environmental flow becomes almost independent of the time schedule of the power production and environmental benefits from the improved ecosystem functioning are gained without any reduction of the economic value of produced energy. Other technical options were also examined, including the construction of a small regulating reservoir or the exploitation of the neighbouring lake Ozeros, but they were found to be substantially more costly.

6.3 Artificial flooding

In the last years, artificial flooding downstream of dams have gained significant attention. It is expected that the periodic release of large amounts of water (much larger than the usual releases) may help to reverse some of the negative impacts caused due to the interruption of the natural flow regime. Apart from the physical demarcation of the river, artificial flooding has beneficial effects on the river geomorphology, the sediment transport, the water quality and the ecosystem's revitalization. In addition, it discourages illegal occupation and change of use of the wider river bed, which has become very common as, after the dam operation, people do not see it inundated by water for years (Koutsoyiannis *et al.* 2012).

In the present study, in addition to the implementation of the minimum flow constraint, we also aimed to establish a plan for artificial flooding through Stratos dam. In this context, we estimated the maximum daily flows for two characteristic return periods, namely two and five years, which are 1400 and 2000 m^3/s, respectively (both values refer to the annual maximum discharge at the estuary). We propose to apply the aforementioned flow values once per one and five years, respectively.

7. SYNOPSIS AND DISCUSSION

Regulated river systems are a typical field for application of environmental flow assessment (EFA) approaches. Yet, despite of the significant progress made towards a holistic overview of the problem and the development of a large variety of sophisticated eco-hydrological tools, their applicability is significantly restricted in cases of limited data availability and quality. In such cases, hydrological approaches, which typically seek for a critical flow to be maintained along the river, offer the advantage of parsimony in terms of data requirements and computations. Indeed, the most elementary of these methods only make use of the mean annual discharge, while the more advanced ones employ analyses of daily flow time series. The simplicity of their outcomes is also desirable, given that the latter are to be incorporated within existing water management policies.

In many countries, the flow standards implied by hydrological approaches have been incorporated within environmental legislation. The establishment of those standards depends on local hydroclimatic conditions but it is also a political issue. Some countries adopt quite conservative standards (e.g. Q_{90}), while other ones apply much more relaxed values (e.g. 1/40 of MAF, in France).

In Greece, the assessment and implementation of environmental flows is a very difficult task, due to data scarcity as well as due to lack of standards. Often, even the most essential hydrological information is hardly available and its quality is many times questionable. The case study of Acheloos offers valuable lessons, on dealing with real-world systems of high complexity, under the aforementioned limitations.

Most of papers found in the literature handle EFA as a theoretical problem, in which the engineering point-of-view is missing. A plausible explanation is that the technical aspects of the problem, including the extraction and processing of hydrological data, are regarded rather trivial. The case of Acheloos proved that this is far from reality. The hardest part of the study was the estimation of the naturalized time series along the river. A key step was the estimation of the reservoir inflows, by solving the water balance equation in daily basis, which was only possible for the most upstream reservoir at Kremasta. In Kastraki reservoir, this method provided realistic results only at the monthly time scale, while in the small reservoir of Stratos it proved impossible to extract a consistent water balance. Therefore, the reliability of the water balance approach (which should be the rule, in case of regulated rivers) strongly depends on scale – it increases with reservoir scale and decreases with time scale. Moreover, as we focus on low flows, it is important to carefully account for the loss components of the reservoir balance, such as evaporation and leakage, the contribution of which may be crucial. In general, within any EFA study, the engineering experience and the empirical evidence are of major importance, in order to get consistent estimations of the required hydrological magnitudes.

The most representative hydrology-based approaches, as well as the wetted perimeter – discharge method, were employed to assess the environmental flows at the two sites of interest (Stratos dam and Acheloos estuary). These provided a wide range of results, in terms of critical flows or allowable range of them. In the absence of standards, based on the systematic observation of biological parameters under different flow conditions, it is impossible to make a proper evaluation of them.

At present, a constant flow is established, which fits the outcomes of the most conservative approaches. For the future, we recommend imposing a seasonally-varying flow, which can better preserve the eco-hydrological regime of the river. Among two well-known methods accounting for seasonal variability, i.e. the basic flow maintenance (BFM) and the range of variability approach (RVA), the former seems more suitable. For, BFM is well-tested in Ebro, i.e. a large-scale, heavily-modified Mediterranean river, with many similarities with Acheloos. The method also provides guidance for artificial flooding, which is a new dimension in modern environmental policy. On the other hand, the RVA is quite complex, difficult to interpret and thus difficult to implement in practice.

The wetted perimeter – discharge method, which was employed at five representative cross-sections, provided reasonable results, within the range of most of hydrological approaches. This is a very positive conclusion, given that such an elementary hydraulic method can be used for a preliminary assessment of the environmental requirements, in areas with total absence of hydrological data.

The implementation of the legislative restriction of minimum flow within the actual management policy of the Acheloos reservoir system also was a challenging engineering task. The system was designed and operated for more than 50 years without any provision for environmental protection. The flow constraint should be streamlined with the existing technical and operational constraints that are involved in the real-time operation of the system. Given that the primary objective is the production of peak hydroelectric energy, the maintenance of a continuous discharge downstream of Stratos is not feasible. On the other hand, it is feasible to fulfil the environmental and irrigation demand at the daily scale, through an effective scheduling of the outflows by the two hydropower plants. Preliminary hydraulic analysis indicated that it is possible to take advantage of the storage capacity of the channel downstream of the power plant, in order to regulate the outflows and ensure the desirable continuous flow in the estuary.

Next research step will be the optimization of the overall water resource system, including the complex irrigation network in the lower course of Acheloos. At least two levels of analysis should be adopted, i.e. a strategic one, for the derivation of the long-term management policy, and an operational one, for the real-time control of the system. The outcomes of this effort will be reported in due course.

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TABLES

Table 1: Characteristic data of Acheloos reservoir system (existing development scheme).

	Plastiras	Kremasta	Kastraki	Stratos	Mesohora
Year of operation	1959	1966	1969	1989	–
Dam height (m)	83.0	160.3	95.7	26.0	135.0
Total drainage area (km^2)	161	3570	4118	4320	633
Total storage capacity (hm^3)	362	4500	800	70	358
Useful storage capacity (hm^3)	286	3500	50	10	225
Maximum level (m)	792.0	282.0	144.2	68.6	770.0
Intake level (m)	776.0	227.0	142.0	67.0	731.0
Maximum reservoir area (km^2)	24.0	79.0	24.4	7.4	7.8
Spillway capacity (m^3/s)	460	3000	3700	4000	3300
Installed capacity (MW)	130	436	420	156	160
Maximum head (m)	577	136	76	37	220
Annual energy production (GWh)	198	848	598	237	–

Note: The sum of runoff upstream of Plastiras dam is diverted to the adjacent plain of Thessaly.

Table 2: Mean monthly naturalized flows across the Acheloos river basin (m^3/s).

	Plastiras	Kremasta	Kastraki	Stratos	Estuary
Oct.	2.5	52.4	59.7	62.1	65.2
Nov.	5.2	121.2	135.4	140.8	147.8
Dec.	10.0	216.7	239.7	249.3	261.8
Jan.	7.8	182.2	201.2	209.2	219.7
Feb.	9.5	192.6	215.4	224.0	235.2
Mar.	9.6	181.8	197.2	205.1	215.4
Apr.	8.6	179.5	190.3	197.9	207.8
May	5.1	112.6	118.7	123.4	129.6
June	1.8	53.2	57.4	59.7	62.6
July	1.1	32.5	35.9	37.4	39.3
Aug.	0.8	25.0	27.9	29.0	30.4
Sep.	0.6	25.7	29.4	30.6	32.1
Year	5.3	114.3	125.3	130.3	136.9

Table 3: Daily flows for various exceedance probability values (m^3/s).

Exceedence probability	Avlaki	Kremasta	Kastraki	Stratos	Estuary
0.99	4.5	11.6	13.2	13.7	14.4
0.98	4.6	13.0	14.4	15.0	15.8
0.96	4.9	14.6	16.4	17.1	17.9
0.95	5.1	15.4	17.3	18.0	18.9
0.90	6.2	18.6	20.9	21.8	22.8
0.80	9.4	24.7	27.8	29.0	30.4
0.70	14.2	33.0	37.0	38.5	40.4
0.60	21.1	46.4	51.3	53.4	56.1
0.50	33.8	68.2	74.0	77.0	80.9
0.40	44.6	95.3	102.9	107.0	112.3
0.30	58.9	129.4	140.2	145.8	153.1
0.20	79.3	173.3	188.2	195.7	205.5
0.10	104.8	244.6	267.4	278.1	292.0
0.05	139.4	343.1	378.3	393.5	413.1
0.02	195.8	537.3	593.3	617.1	647.9
0.01	246.3	734.4	814.9	847.5	889.8

Table 4: Characteristic daily flow values at Stratos (m^3/s), calculated within the RVA method.

	Mean value	Lower limit	Upper limit
1-day minimum	13.1	10.6	15.6
3-day minimum	15.9	12.8	18.9
7-day minimum	17.8	14.1	21.4
30-day minimum	22.5	17.4	27.6
90-day minimum	29.1	23.0	35.1
1-day maximum	1503.1	814.8	2191.3
3-day maximum	1025.5	615.9	1435.1
7-day maximum	698.0	440.2	955.8
30-day maximum	378.1	262.2	494.0
90-day maximum	272.5	192.8	352.1

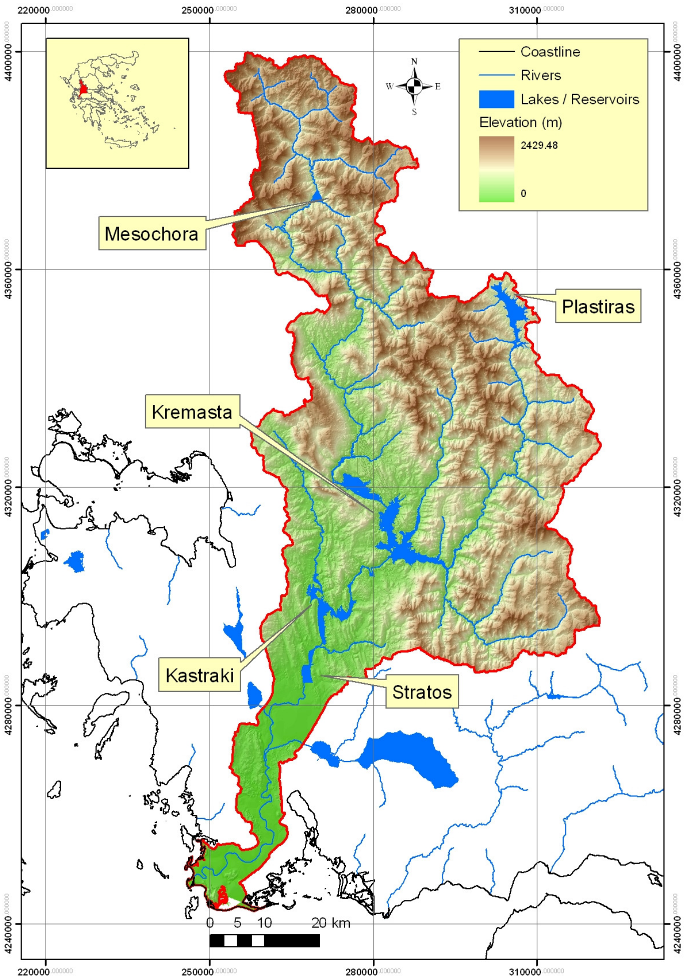
Table 5: Summary of environmental flow requirements at Stratos dam and Acheloos estuary (flow values in m^3/s), estimated by different methods.

Method	**Stratos**	**Estuary**	**Remarks**
5-year minimum monthly flow (EIA study, 1995)	–	21.3	Legislative constraint, incorporated within outflow policy of Stratos reservoir
5-year minimum monthly flow (updated data)	21.1	22.2	Statistical analysis of annual minimum monthly flows (1965-2008)
Tennant method (10-30% MAF, for dry/wet months)	13.0 – 39.1	13.7 – 41.1	Poor conditions are assumed since the river system is heavily modified
French freshwater fishing law (2.5% MAF)	3.3	3.5	1/40 of mean annual flow is assumed for existing works
U.K. standards (Q_{95})	18.0	18.9	Estimated on the basis of empirical flow-duration curves of daily flow data
Q_{90}	21.8	22.9	
Q_{364}	11.3	11.9	
BFM, basic flow (Q_b)	13.3	14.0	Estimated through statistical analysis of daily to up to 100-day moving average flow time series
BFM, basic maintenance flow, seasonally varying	16.8 – 32.5	17.6 – 34.1	
RVA, 25% quantile of monthly discharge	14.6 – 135.3	15.3 – 142.1	Main indicators of hydrological alteration, computed by the IHA/RVA 7.0 package
RVA, 75% quantile of monthly discharge	35.3 – 390.1	37.1 – 409.6	
Wetted perimeter – discharge	13.1 – 20.4		Breakpoint analysis at five characteristic cross-sections, between Stratos and estuary

FIGURE CAPTIONS

Figure 1: The Acheloos river basin and its reservoir system (map by A. Koukouvinos).
Figure 2: Comparison of mean monthly outflows through Stratos dam (regulated flows) and mean monthly naturalized flows, for period 1990-2008.
Figure 3: Empirical flow-duration curves at Kremasta dam (raw and corrected sample of mean daily discharges) and Avlaki station (discharge measurements).
Figure 4: Normal probability plot of minimum monthly flows of Acheloos estuary (dots: empirical probability obtained using the Weibull plotting position; line: fitted normal distribution).
Figure 5: Logarithmic plot of daily and 100-day moving average time series of Acheloos discharge at Stratos, used within the BMF method.
Figure 6: Mean annual daily minima for various time intervals, used for the estimation of the basic flow in the context of the BMF method.
Figure 7: Logarithmic plot of mean and minimum monthly naturalized flows at Stratos vs. basic and basic maintenance flows, estimated through the BMF method.
Figure 8: Logarithmic plot of mean and minimum monthly naturalized flows at Stratos vs. desirable low and high flow limits, estimated through by the RVA method.
Figure 9: Overview of the area around Stratos dam (source: Hellenic Cadastre).

FIGURES



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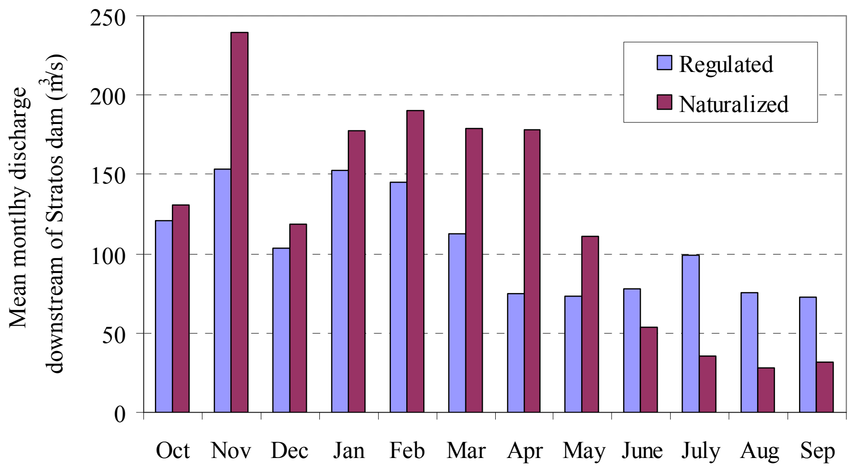

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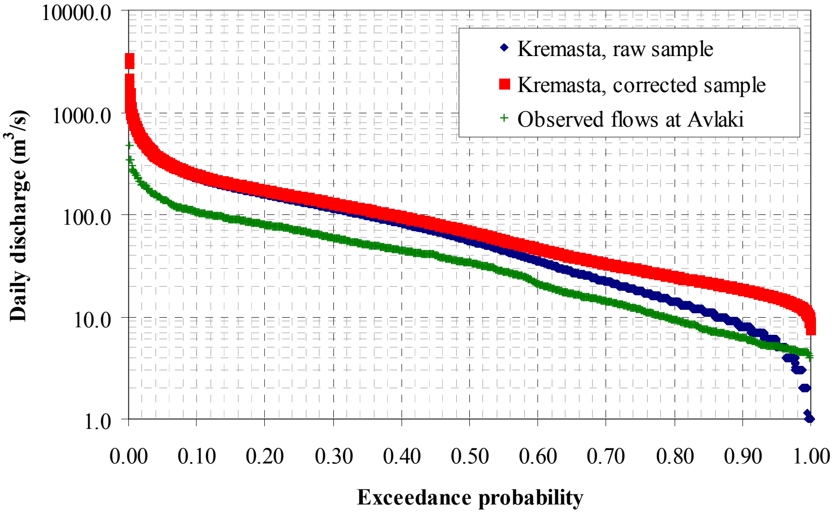

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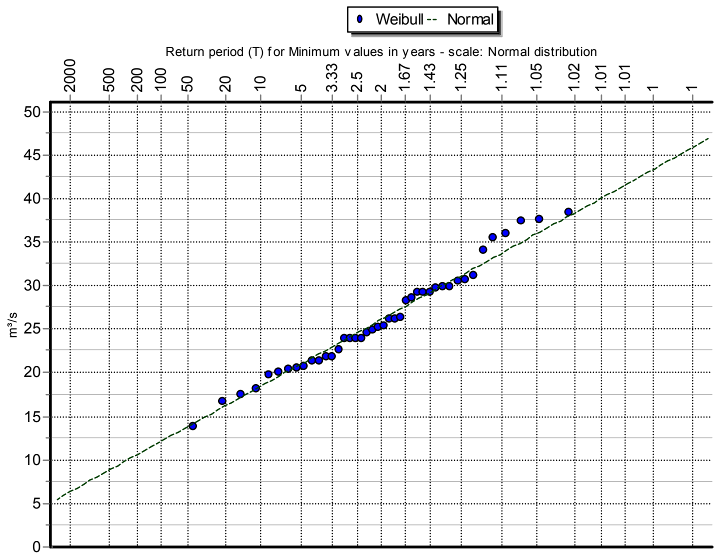

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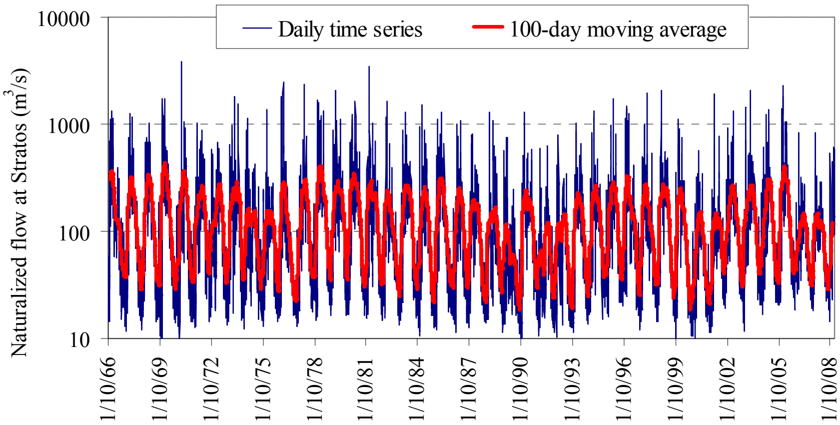

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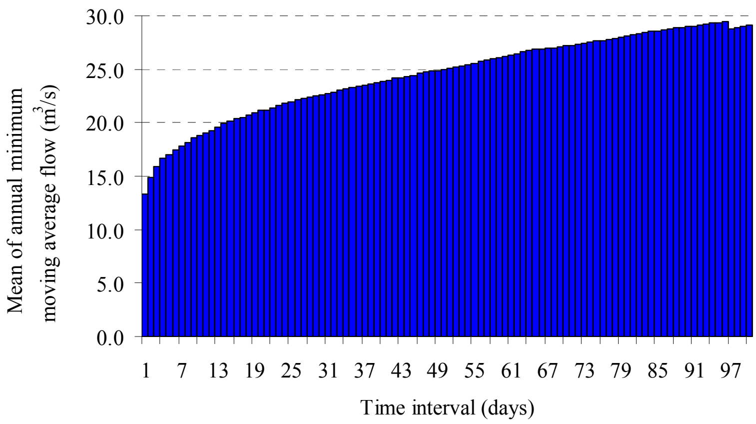

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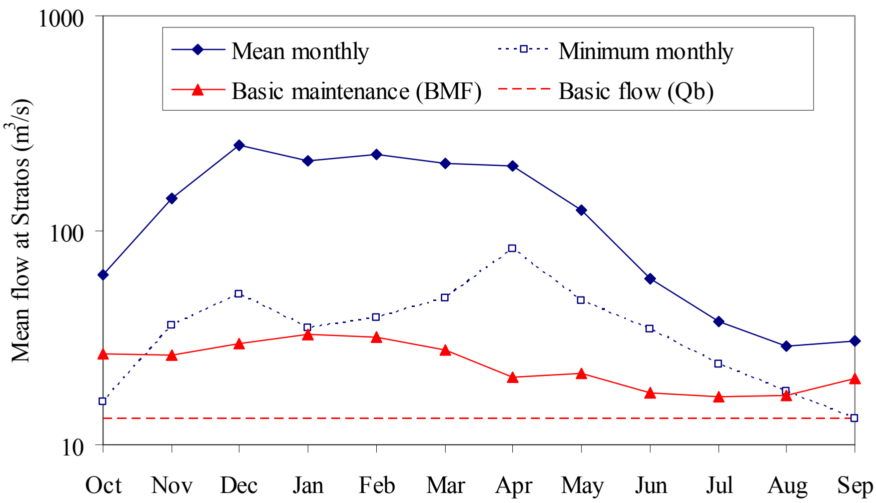

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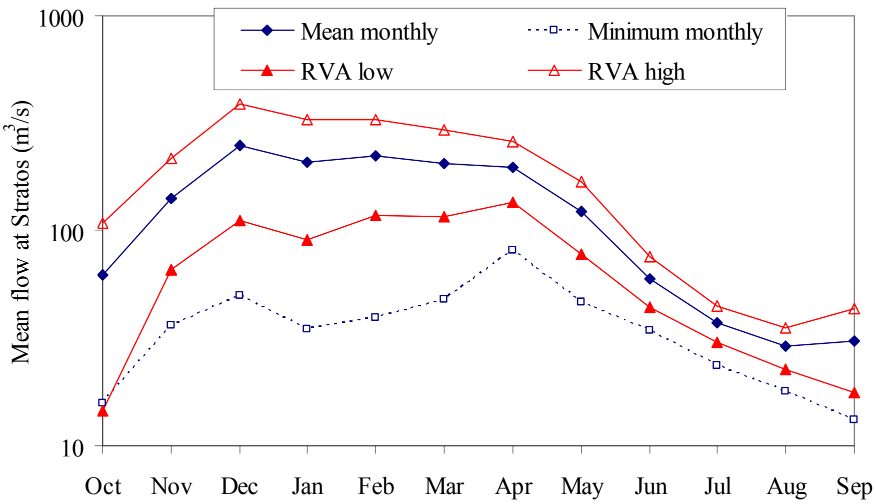

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