Assessment of environmental flows under limited data availability – Case study of Acheloos River, 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 Flow Method, which is parsimonious and suitable for Mediterranean rivers, whose flows exhibit strong variability across seasons. We also show that the wetted perimeter – discharge method, 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 potential impacts on the natural morphological and hydrological conditions, large-scale dams may cause significant modifications to downstream river systems and, consequently, to their ecological status. Indeed, the spatial and temporal regulation of flows caused by large reservoirs may result in major changes to the hydrological regime of the river, which in turn may have negative impacts on both biotic and abiotic river conditions. On the other hand, we cannot ignore the beneficial and multidimensional role of such projects, in terms of providing water for various uses (water supply, irrigation, hydroelectric production, navigation, etc.), together with the reduction of flood risk. Another possible benefit is the formation of an attractive lake landscape, favouring the touristic development of the surrounding area. In this respect, it is essential to seek a compromise between the maximization of the socio-economic benefits and the environmental improvement, which requires a holistic and rational viewpoint to handle the numerous contrasting or even conflicting interests (Christofides *et al.* 2005, Efstratiadis and Hadjibiros 2011).

The Water Framework Directive (WFD; 2000/60/EU) pays particular attention to heavily modified water bodies, for which it aims to ensure a good ecological and water quality status. In this respect, the water policies for regulated rivers have been thoroughly revised to incorporate ecological, environmental and water quality criteria within the design and management of reservoirs towards provision (or reestablishment) of natural conditions, to some extent (Acreman *et al.* 2008). In order to guarantee a sufficient level of protection for the downstream aquatic environment, it is common practice to establish a minimum outflow rate through the reservoir, either temporally steady (static) or variable (dynamic), which is typically called environmental, ecological, minimum or maintenance flow (Alcázar *et al.* 2008).

In recent decades, environmental flow assessment (EFA) has become an issue of continuous research, globally. As reported by Tharme (2003), early approaches are found from the end of the 1940s, in the western USA; in the same article are listed 207 different methods within 44 countries. In fact, regulations of such kind are very old and must have been invented based on common sense and empirical criteria. The following example of flow regulation in Greece 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 (translation by Davies 1996):

> *«Θιοί· τô ποταμô αἴ κα κατὰ τὸ μέττον τὰν ῥοὰν θιθῆι ῥῆν κατὰ το ϝὸν αυτô, θιθεμένōι ἄπατον ἤμην. Τὰν δὲ ῥοὰν λείπεν ὄττον κατέκει ἀ ἐπ' ἀγορᾶι δέπυρα ἤ πλίον, μεῖον δὲ μὴ.»*
>
> *(Gods. If anyone makes the flow 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.)*

EFA has become a major issue in watershed management, for which numerous approaches are in use, of all levels of complexity; in general, these are classified in four categories, referred to as hydrological, hydraulic rating, habitat simulation and holistic. Comprehensive reviews of these methods are provided by Tharme (2003), Acreman and Dunbar (2004) and Petts (2009). There exist many interpretations of EFA. For instance, Tharme (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 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 in defining sustainable river/dam operation rules, which requires an integrated and system-wide viewpoint.

After defining the environmental objectives, the next step is their incorporation into the management policy of the existing reservoir system. Typically, these objectives 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 through 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 that are suitable for areas with limited data availability and investigate their implementation within the operation of the hydroelectric scheme of Acheloos River, which produces more than 40% of the hydroelectric energy in Greece, while 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 a 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 a framework for similar studies, involving heavily-modified Mediterranean rivers, where the only available data are daily discharge records.

2. PARSIMONIOUS ENVIRONMENTAL FLOW MODELS: OVERVIEW

2.1 Problem statement

It is recognized that 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). Thus, it involves a number of biological, geomorphological, physical, and chemical processes in a river that forms and maintains aquatic ecosystems (Suen and Eheart 2006). However, an overall evaluation of all the above factors within an EFA study 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 many real-world applications the problem is normally handled under significantly limited data availability (e.g., Smakhtin *et al.* 2006). In such cases, it is essential to seek parsimonious EFA approaches, in terms of data requirements.

Among the various methodologies that are available in the literature, the most parsimonious ones are the so-called hydrological and hydraulic rating approaches. In the former category fall a large variety of methods, from very simple rules-of-thumb to more sophisticated procedures, all of which use streamflow time series as a 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. This is a rather straightforward task, when such data are available in gauging stations operating for quite a long time (15-20 years) and under natural flow regimes (Richter *et al.* 1997, Alcázar *et al.* 2008, Kennard *et al.* 2010). Yet, in case of regulated rivers a pre-processing is essential to obtain the so-called “naturalized” time series, since 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 data are also suitable, for some simple methods.

On the other hand, hydraulic rating 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 (particularly, the wetted perimeter) and establish links with habitat availability of target biota.

2.2 Elementary hydrological methods

In elementary hydrological approaches, also referred to as desktop or lookup-table methods, the critical minimum flow is expressed in terms of statistical indices, such as percentages of annual flows or percentiles from a flow-duration curve (Acreman and Dunbar 2004). A characteristic index-based approach is imposed by the French Freshwater Fishing Law of 1984, which requires that residual flows in bypassed sections of a river must be at least 1/40 of the mean annual flow (MAF) for existing schemes and 1/10 of MAF 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).

While most of the aforementioned standards are rather empirical, the Tennant (1976) method (also known as Montana method) is the first one attempting to quantify a correlation between the streamflow regime and the resilience 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 MAF), according to the river conditions. For the dry period, the proposed ratios are 10% for poor to fair quality (survival), 20% for good habitat and 30% for excellent habitat, while for the wet period the corresponding ratios are 30%, 40% and 50%, respectively.

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 a 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. Specifically, the UK standard, i.e. Q_{95}, was recently specified by a multidisciplinary team of lead water scientists and competent authorities, who are responsible for implementing the WFD (Acreman *et al.* 2008). In this context, the team of fish ecologists recommended various abstraction thresholds as a percentage of flow on the day in excess of the natural Q_{95}, which 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.

2.3 Advanced hydrological methods

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) and 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 recent years it has 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 withstand significantly low flow conditions for limited time periods, the method wishes to determine the average duration and magnitude of such periods, on the basis of up to 100-day moving average time series (since in Mediterranean rivers, the low-flow period lasts about three months). Summarizing Palau and Alcázar (2012), the computational procedure is the following: First, we identify the so-called basic flow Q_b, which is the absolutely minimum discharge that should be maintained along the river. In this respect, we calculate the moving averages of daily flows, from one-day to 100-day intervals, for at least ten years. For each year i and each interval k we extract the minimum flow value q_i^k, accounting for an annual period starting in April, i.e. the so-called “hydrobiological” year. Next, we calculate the relative increment between each pair of consecutive minima as follows:

$$b_i^k = (q_i^k - q_i^{k-1}) \,/\, q_i^{k-1} \tag{1}$$

For each year i, we select the moving average flow q_i^{kmax} with the largest relative increment; the mean value of all q_i^{kmax} represents the basic flow Q_b.

In order to maintain the river ecosystem as close as possible to the natural conditions, it is also important to represent the temporal variability in the proposed regulated flow regime. In this context, for each month j we estimate the so-called basic maintenance flow by the formula:

$$\mathrm{BMF}_j = Q_b \, (Q_{\mathrm{mean},\,j} \,/\, Q_{\mathrm{min},\,j})^{0.50} \tag{2}$$

where $Q_{\mathrm{mean},\,j}$ and $Q_{\mathrm{min},\,j}$ are the mean and minimum discharge of month j.

In reality, the BFM constitutes a broad management proposal, including a number of issues affecting the biological functioning of regulated rivers. Thus, apart from a monthly schedule of minimum maintenance flows, it 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 1.5 year flood (this is a generally accepted value, although a wider range of estimates of the corresponding return period have been reported in the literature, particularly in semi-arid climates; cf. Shamir *et al.* 2013), as well as the “maximum flow”, estimated as the 25-year flood. 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 parameters to describe the hydrologic changes that are 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.

2.4 Hydraulic rating methodologies

Input data for hydraulic rating approaches (also known as habitat retention methods) are both historical flow records and cross-section data. Since the available aquatic habitat, for given flow conditions, is by definition determined by the wetted perimeter of the channel, most of these approaches use the above geometrical characteristic as basic tool for ecological evaluation. The rationale 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 employed 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. The analysis should be 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.

3. CASE STUDY

3.1 The river Acheloos and its hydroelectric reservoir system

The case study involves the assessment of environmental flows of the Acheloos River and their implementation within an operational management plan. The Acheloos River is located in Central Western Greece, and 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 5027 km^2. 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, which corresponds to an equivalent 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 for irrigation and water supply, also taking advantage of an exceptional hydraulic head, ranging from 561 to 577 m. 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 reservoir, 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 energy production, the system provides water for domestic supply and irrigation, as well as 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, have been operationally ready for more than a decade, but, the reservoir is kept empty and the project is out of function due to opposition by ecologists and local communities. The interbasin transfer tunnel is also almost complete, while the dam at Sykia at the beginning of the tunnel is under construction 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 also been 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 flood phenomena were very rare during the last four decades. The substantial differences between the natural and modified hydrological conditions are illustrated in Fig. 2, which compares, on a monthly basis, the main statistical characteristics of historical outflows from the most downstream dam (Stratos) and the “naturalized” flows. The latter are estimated according to the methodology described in section 4.3. The data refer to the period 1990-2008, i.e. after the completion of Stratos works (1989).

The hydrological changes were also accompanied by major changes in the land management practices in the Aetoloacarnania plain, due 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 were specified in the mid-1990’s within the environmental impact assessment study (EIA) of the upper Acheloos project (Hydroexygiantiki 1995). This was one of the first studies in Greece dealing with the estimation of environmental flows. Among other things, it envisaged the maintenance of a seasonally constant minimum flow of 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 the dams of the interbasin transport plan (Fig. 1).

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 (ECOS Consultants 2009; see also Varveris *et al.* 2010) 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 in 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.

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 one. Modern approaches on environmental flow assessment suggest using flow records of daily or finer time resolution, and of length of 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 installation 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; the unique flow gauge (Avlaki) is located in the upper course of the river, 45 km upstream of the Kremasta dam, and controls only 27% of the total basin, i.e. 1358 out of 5027 km^2 (Fig. 1). However, even if a flow record near the outlet 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 Avlaki station, which drains 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 also been 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 a daily basis. In particular, the inflow i_t was computed by accounting for the storage fluctuation during each day, $s_t - s_{t-1}$, the amounts of water used in energy production r_t and the spill losses w_t, i.e.

$$i_t = s_t - s_{t-1} + r_t + w_t \quad (3)$$

The rest of water balance components, i.e. areal rainfall p_t and water losses due to evaporation e_t and leakage l_t were neglected. However, this approach resulted in systematic underestimations of inflows, especially during the summer period. In particular, the minimum inflow value was found to be 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 not realistic.

The reason for these inconsistencies is the ignorance of term $e_t + l_t - p_t$ in the water balance equation, together with measurement errors and other uncertainties (e.g. in the stage-storage relationship). 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 (i.e. added) 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. As shown in Fig. 3, the updated flow-duration curves are substantially different from the original estimates. The key statistical characteristics of the naturalized flows are given in Table 2. In particular, the mean annual 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 other sites of interest

The next reservoir, Kastraki, has been in operation since 1969. It receives the outflows of Kremasta and the runoff of the intermediate sub-basin, which covers an area of 548 km^2. Since no abstractions exist in the river course between the two dams, and in order to estimate the naturalized flows at Kastraki we add the daily runoff of the aforesaid sub-basin to the naturalized flows at Kremasta.

In theory, the runoff generated by the intermediate basin can be estimated by extracting the outflows from Kremasta (i.e. water releases for energy production, abstractions for water supply and spill losses) from the regulated inflows to Kastraki, which in turn are estimated by solving the daily water balance equation of the reservoir. However, within the daily time interval, the level fluctuations of Kastraki are not accurately represented, thus leading to major errors is the computation of its inflows. For instance, about 25% of inflow 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 approximate approach, using monthly water balance data, which are more accurate since the measurement errors decrease as the temporal scale increases (in particular, at the monthly time scale the level fluctuations are more distinguishable than at the daily one, and therefore the calculations of the storage variations, $s_t - s_{t-1}$, are more accurate). Starting from the monthly inflows to Kastraki, we estimated the monthly runoff of the intermediate sub-basin and the naturalized runoff of the whole sub-basin. Next, for each month of the study period 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 (this assumption is reasonable, given that summer flows are not significantly affected by local flood events). Finally, we multiplied the daily flows at Kremasta by the related ratio, to obtain the naturalized flows at Kastraki. On a mean monthly basis, their values range from 1.06 to 1.17 (the highest values exceed 1.50), while the ratio of the two catchment areas is 1.15. By employing different values for each month (504 values, in total) we accounted for the spatial heterogeneity of runoff, as much as possible. The results are summarized in Table 2. As shown, 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 has been in operation since 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, in the specific reservoir the historical data (lake level and outflows) are highly uncertain, thus the establishment of a consistent water balance was impossible, even at the monthly time scale. In the absence of any other type of hydrological information, we estimated the daily naturalized flows at the dam site by simply increasing the daily 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. The two aforementioned ratios were estimated by taking into account the area of the upstream basins and their mean annual precipitation, thus (inevitably) assuming a homogenous response of the two basins to rainfall. In addition, we made the empirical assumption that the equivalent runoff depth in the lower Acheloos basin is 350 mm, on a mean annual basis. 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). We remark that the heavily modified system downstream of Stratos is very poorly monitored. In fact, there are no systematic data with regard to agricultural abstractions from the river, which could be very helpful for improving our estimations at the estuary, especially during the low-flow period.

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. ESTIMATION OF ENVIRONMENTAL FLOWS

For the estimation of the ecological requirements downstream of Stratos we employed various EFA approaches, based on the naturalized discharge time series, averaged at the daily, monthly and annual time scales. All calculations herein refer to the dam site. In order to "transfer" the results to the Acheloos estuary, the corresponding flow values at Stratos should be simply increased by 5%, in order to roughly account for the runoff generated by the local sub-basin.

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 (Oct. 1966 to Sep. 2008). 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

We evaluated a number of indices, which are summarized in Table 5, using the following approaches of section 2.2:

(a) **Tennant method**: Since the river is heavily modified, we applied the MAF ratios that correspond to poor quality conditions, i.e. 10% for the dry period and 30% for the wet one. Given that the mean annual naturalized discharge in Stratos is 130.3 m^3/s, the critical flow values are 13.0 and 39.1 m^3/s, respectively.

(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.

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

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

(e) **Indices based on flow-duration analysis**: From the flow-duration curves at Stratos, we calculated two typical flow indices, specifically the Q_{90} (21.8 m^3/s) and the Q_{364} (11.3 m^3/s).

5.3 Basic flow method

As mentioned in section 2.3, the BFM 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. Following the typical procedure by Palau and Alcázar (2012), we calculated the moving averages of the naturalized daily flows at Stratos, from one-day to 100-day intervals (Fig. 5) and extracted the minimum flow value (Fig. 6). In the specific case, the flow with the largest relative increment is the one-day moving average minimum. The average of all daily minima, i.e. the basic flow, for the considered study period (42 years) is 13.3 m^3/s, while the BMF values, which are calculated from eq. (1), range from 16.8 m^3/s (July) to 32.5 m^3/s (January), following the seasonal variability of the naturalized flows (Fig. 7). Finally, the other two characteristic flows ("bankfull" and "maximum") were estimated using different return periods from the originally proposed. In particular, in order to establish an artificial flooding plan through Stratos (section 6.3) we estimated the maximum daily flow for return periods 2 and 5 years.

5.4 Range of variability approach

We used the IHA/RVA software (version 7.0), developed by the Nature Conservancy (2009), to evaluate the 32 indicators of hydrological alteration in the two sites of interest (Stratos and estuary). The most important 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

We selected five representative cross-sections along the lower course of Acheloos, with different geometrical shapes (triangular, rectangular), where we employed the maximum curvature approach 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. ESTABLISHMENT 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, which are characterized by 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 that are not realistic to implement.

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).

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. Therefore, in an operational context, the implementation of the environmental flow only affects the outflow policy of the most downstream reservoir. Yet, the monthly time step is too rough to represent all aspects of the real-time operation of the reservoir, i.e. the current scheduling of outflows through the power plant and the technical constraints imposed by the related hydraulic works. For this reason, it is essential to investigate the adaptation of the minimum flow constraint at finer 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 inflows 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 recent 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, which are thoroughly revised by Petts and Gurnell (2005). 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 have not seen 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 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. Their establishment 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). It is interesting to remark that although such standards are clearly expressed in terms of discharge, 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.

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 (apparently, it also increases with river 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. In this respect, the collection of systematic biological data is an essential task, in order to provide more comprehensive environmental flow standards. However, such data, if ever obtained, will be usable only on the long run. A promising solution for such data-scarce areas, as proposed by Arthington *et al.* (2006), is to take advantage of flow – ecological response relationships, obtained by calibrating the flow standards with biological data in well-monitored rivers, which could be classified in terms of some characteristic hydrological indices. In this context, the assessment of environmental flows will be based not on the hydrological data themselves but on the hydrological classification of each specific river.

At present, a constant flow is established for the Acheloos River, 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 desirable. However, it is feasible to fulfil the environmental and irrigation demand at the daily scale, through an effective scheduling of outflows. Preliminary hydraulic analysis indicated that it is possible to take advantage of the storage capacity of the channel downstream of the dam, in order to regulate the outflows and ensure the desirable continuous flow in the estuary.

The 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.

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TABLES

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

	Plastiras	**Kremasta**	**Kastraki**	**Stratos**	**Mesohora**
First 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

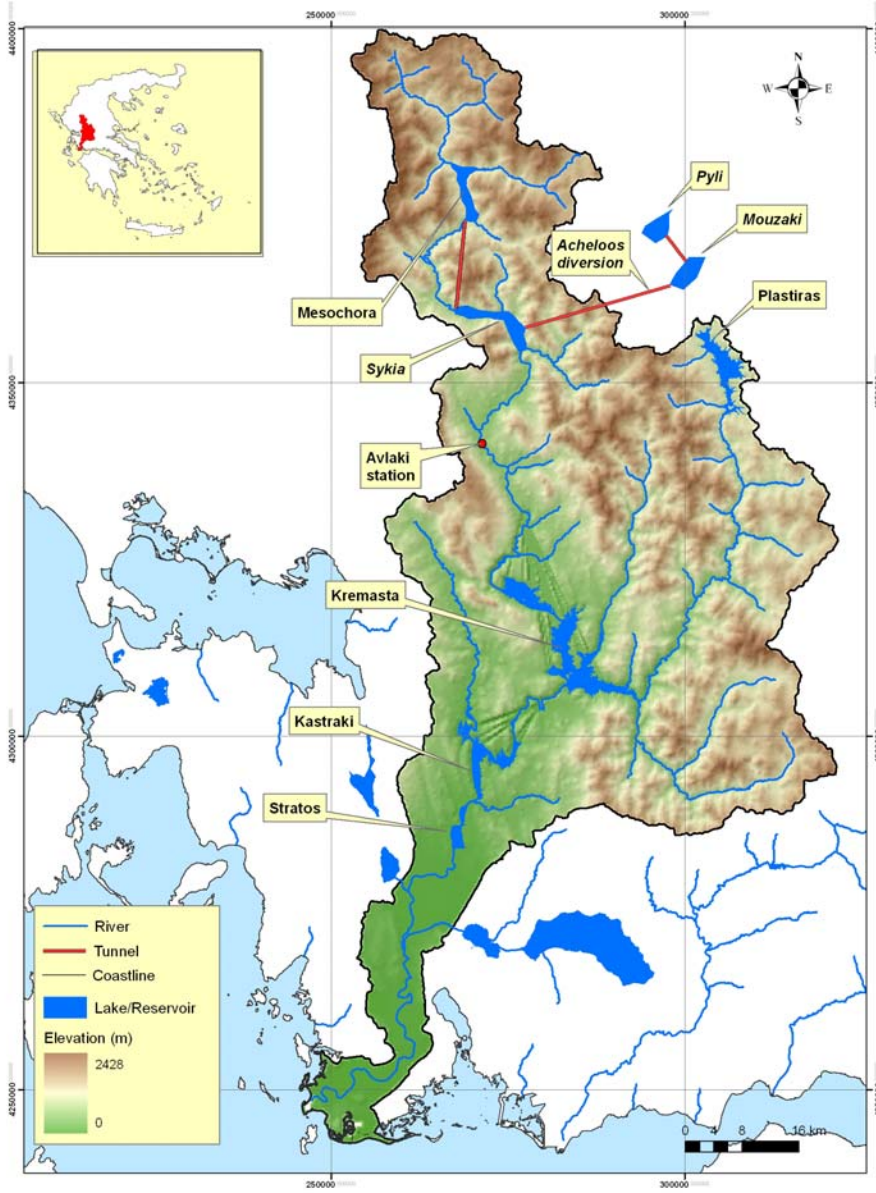
Table 5: Summary of environmental flow requirements at Stratos dam and Acheloos estuary (flow values in m^3/s), estimated by different methods.

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, also containing future works of the Acheloos interbasin transfer (diversion) plan, which are annotated in italics (map by A. Koukouvinos).
Figure 2: Comparison of statistics (left: mean values; right: standard deviations) of outflows through Stratos dam (regulated flows) and 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 BFM.
Figure 6: Mean annual daily minima for various time intervals, used for the estimation of the basic flow in the context of the BFM.
Figure 7: Logarithmic plot of mean and minimum monthly naturalized flows at Stratos vs. basic and basic maintenance flows, estimated through the BFM.
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.
Figure 9: Overview of the area around Stratos dam (source: Hellenic Cadastre).

FIGURES



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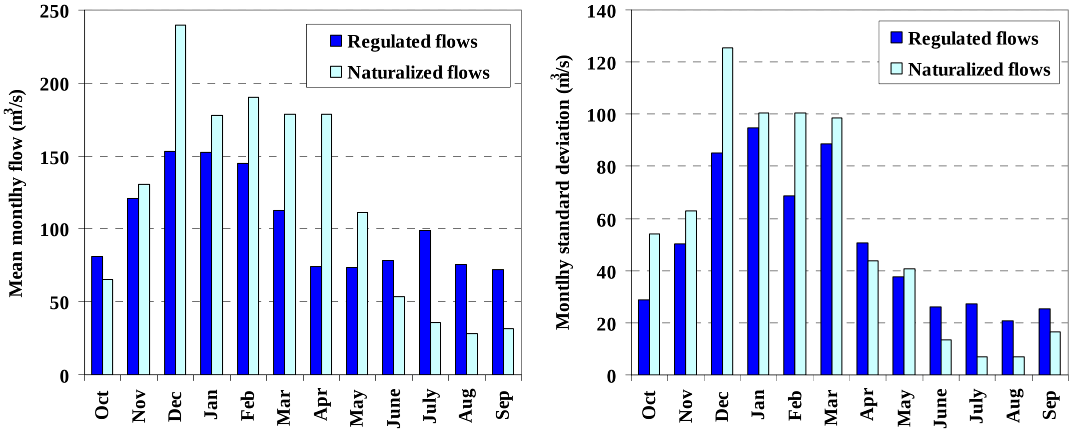

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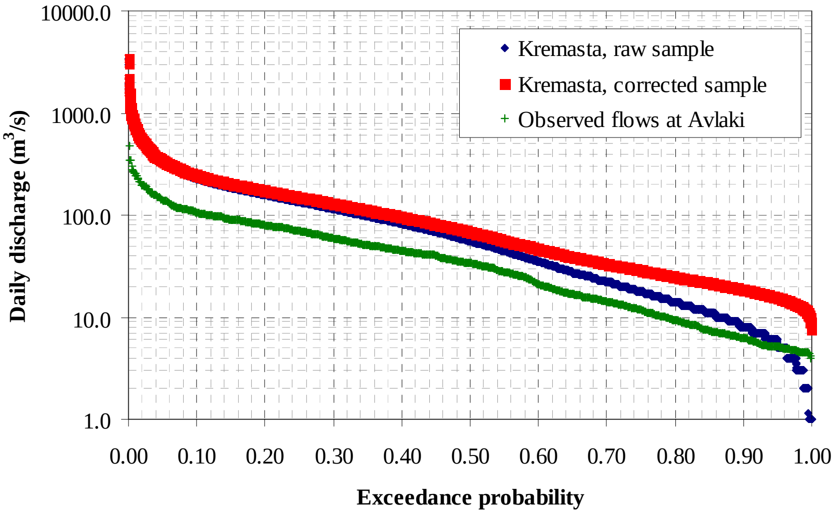

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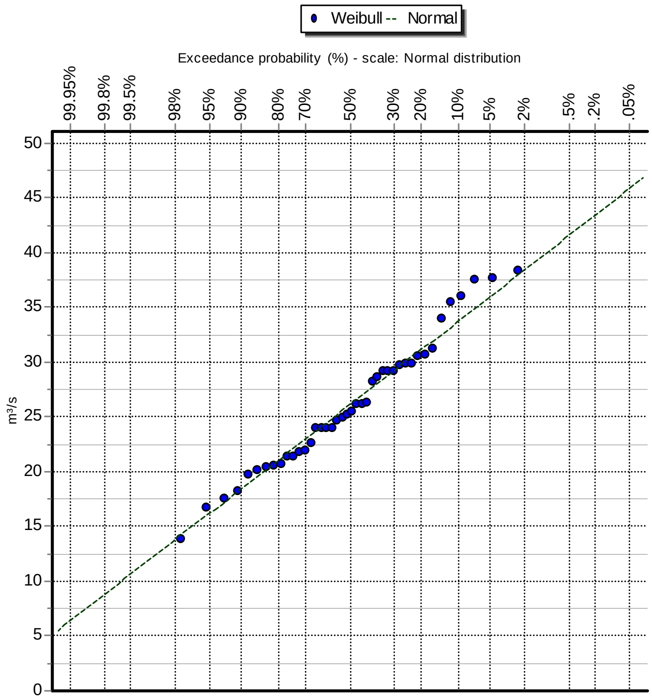

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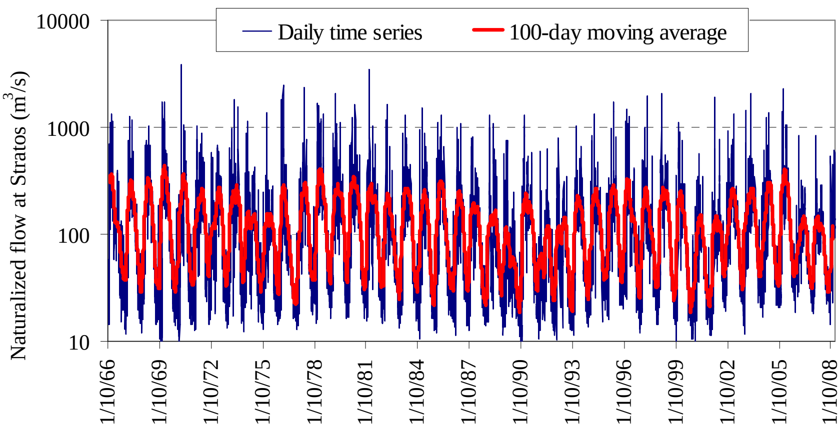

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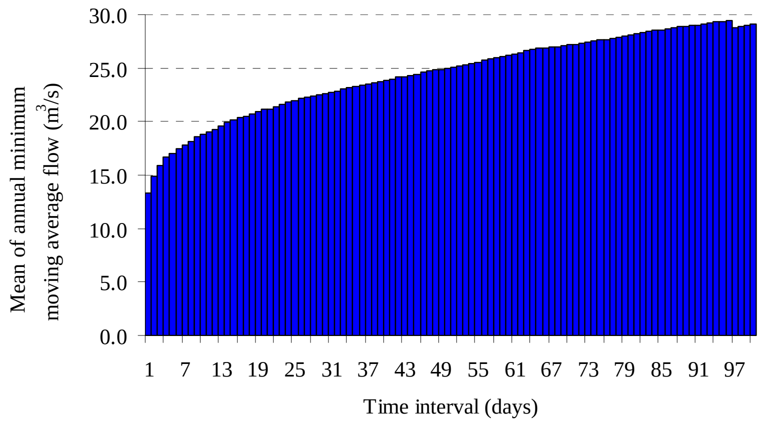

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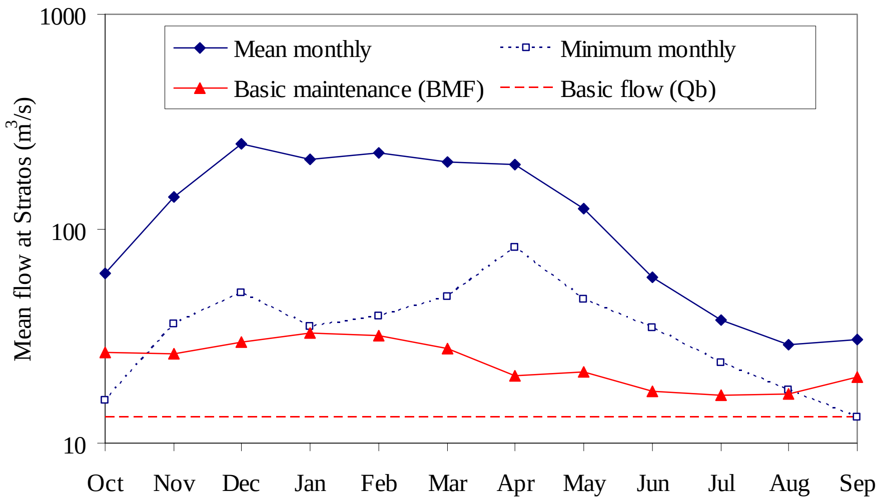


Figure 7: Logarithmic plot of mean and minimum monthly naturalized flows at Stratos vs. basic and basic maintenance flows, estimated through the BFM.

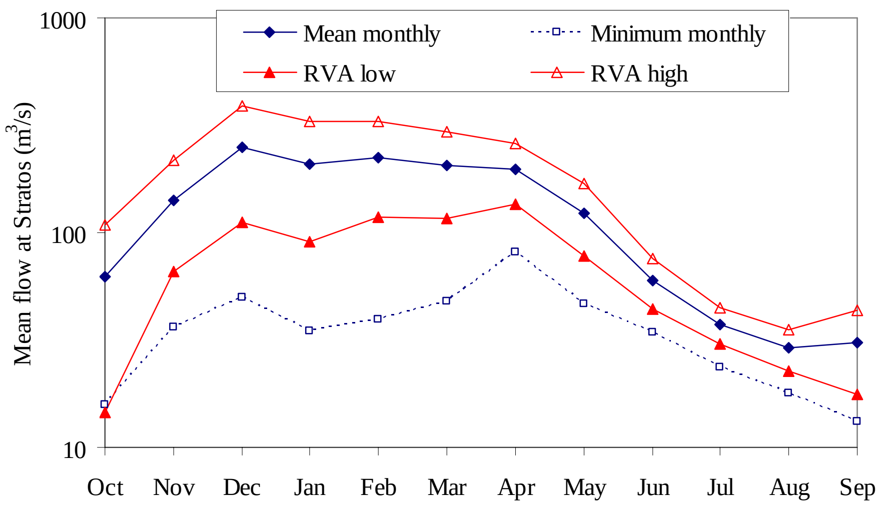
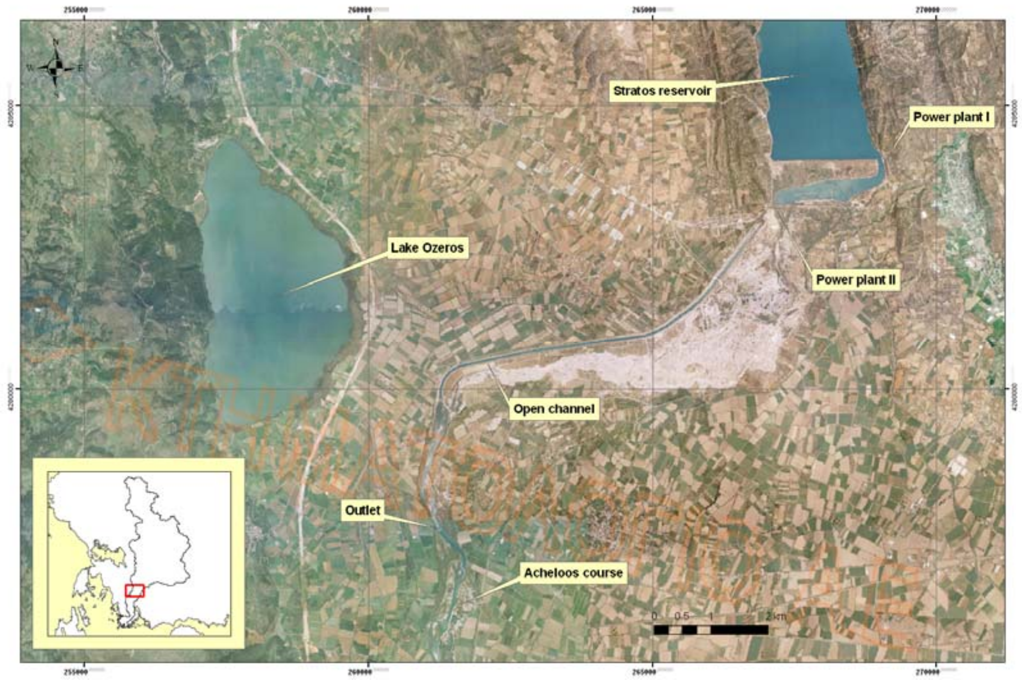


Figure 8: Logarithmic plot of mean and minimum monthly naturalized flows at Stratos vs. desirable low and high flow limits, estimated through by the RVA.



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