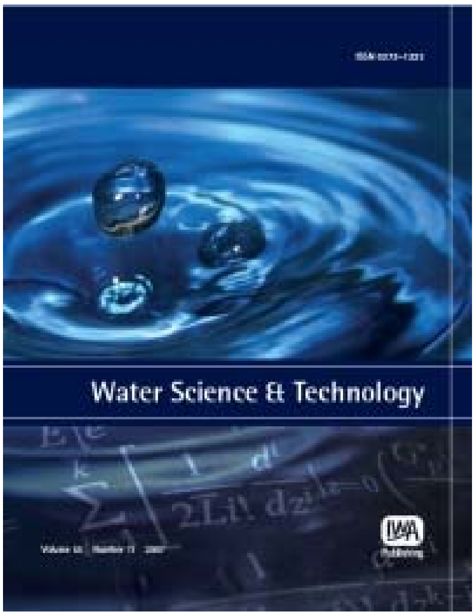
Water Science & Technology

Nutrient-based ecological consideration of a temporary river catchment affected by a reservoir operation to facilitate efficient management

Ourania A. Tzoraki, Gerald Dörflinger, Nicholas Kathijotes and Artemis Kontou

ABSTRACT

The water quality status of the Kouris river in Cyprus was examined in order to fulfil the requirements for ecological quality as defined by the Water Framework Directive-2000/60/EC. Nitrate concentration (mean value) was increased in the Limnatis (2.8 mg L^{-1}) tributary in comparison with the Kryos (2.1 mg L^{-1}) and Kouris (1.0 mg L^{-1}) tributaries depicting the influence of anthropogenic activities. The total maximum daily nutrients loads (TMDLs) based on the flow duration curves approach, showed that nutrients loads exceeded threshold values (33.3–75.6% in all hydrologic condition classes in the Kouris tributary, and 65–78% in the Limnatis tributary) especially under low flow conditions. The TMDL graph is intended to guide the temporal schedule for chemical sampling in all hydrologic classes. Kouris reservoir is an oligotrophic system, strongly influenced by the river's flash-flood character but also by the implemented management practices. Kouris river outflow, which was reduced to one-tenth in the post dam period altered the wetland hydrologic network and contributed to the decrease of aquifer thickness. Continuous evaluation and update of the River Basin Management Plans will be the basis for the sustainable development of the Kouris basin.

Key words | Cyprus, hydrologic regime, Kouris river, measures, reservoir, temporary rivers, TMDLs, water quality

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INTRODUCTION

To date, the dynamic and sustainable aquatic and terrestrial ecosystems are threatened by population, change of land use and the irreversible effects of climate change (CC). Dry and semi-arid regions at mid and low latitudes and especially extended areas of southern Europe are suffering from water stress and desertification. Common practices related to lack of water include dam construction, river abstraction and overexploitation of groundwater (Mimikou *et al.* 2000; Krol *et al.* 2011). Despite the fact that dam construction saves millions of cubic meters of water, the reduction of river flow, creates severe alterations of the river ecosystems in terms of dynamics and quality. In delta ecosystems, downstream of dams, a decrease in biological productivity and in sediment transport is observed. Additionally, an increase in the salinity of delta and agricultural areas and in general ecosystems deterioration is particularly observed in many parts of the Mediterranean region.

Integrated water resources management plans consider the river basin and coastal zone as a unit, aiming to achieve 'good water ecological quality' according to the requirements of the Water Framework Directive (WFD-2000/60/EC). Therefore, the WFD provides clear instructions for the characterization of the hydrological and chemical quality of perennial rivers neglecting intermittent flow rivers (temporary rivers). A river is characterized as intermittent (or temporary) if it ceases to flow every year or at least twice every 5 years (Tzoraki *et al.* 2009). Prolonged no-flow periods are interrupted by intense flood events which initiate transport of sediment and pollution load downstream into the coastal zone. Ecological indexes such as macroinvertebrates and riparian vegetation metrics are affected by flow variability (Bonada *et al.* 2008; Poff & Zimmerman 2010; Munné & Prat 2011). In particular, nutrient fluxes are of major concern in lakes and reservoirs because they are correlated with

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cyanobacteria bloom occurrence (Ye *et al.* 2011). Nutrient fluxes mostly originate from human activity such as cultivated area runoffs, industrial effluents and municipal sewage effluents. Implementation of efficient water resources management plans at intermittent flow river basins requires a high frequency of monitoring in order to identify the spatiotemporal fluctuation of environmental variables.

The main objective of this study was to assess the water quality status of the Kouris catchment and Kouris reservoir, to identify the flow thresholds related to excess nutrient loads and to suggest potential measures of improving the ecological status of the river. The total maximum daily nutrients load (TMDL) approach is used as the foundation for recommendation of restoration measures.

In this study, the Kouris catchment was selected as a representative case study of a semi-arid basin of high importance, as it is composed of a dense drainage network of intermittent and episodic flow streams and it flows into the largest drinking water reservoir of Cyprus. The eutrophication risk of the reservoir is assessed based on water quality measurements and the Carlson Index.

METHODS

Study site

Kouris catchment is a typical mountainous area with steep valleys, a drainage area of 357 km^2, with elevations ranging from 0 m at the estuaries up to 1,956 m near the Troodos mountains. Sixty-three percent of Kouris catchment is covered by forest and natural surfaces, 1% by surface water bodies, 31% by agriculture fields and 5% by man-made structures. The geology of the catchment is divided into two main zones; an ophiolite complex in the north and an overlying sedimentary complex in the south (Ragab *et al.* 2010).

The main tributaries of the catchment include the Kouris, Kryos and Limnatis rivers, that flow into the Kouris reservoir (Figure 1). Kouris Dam (34°43′40″N, 32°55′5″E) has a maximum depth of about 90 m and corresponding water volume of 115 Mm^3. Since 1998, an additional water volume of ≈17.1 Mm^3 per year (averaged over 2007–2011) is transferred from another reservoir (Arminou Dam) outside the catchment area via a 14.5 km pipeline to the Kouris Dam. The released water is used primarily for irrigation and domestic water supply (Ma *et al.* 2008). The Kouris delta defines the west boundary of the Akrotiri wetland. The Akrotiri Ramsar site is composed of two distinct areas that are hydrologically connected. The first and largest area is the salt lake, situated in the centre of the Akrotiri peninsula and hosts a range of birds such as the flamingo *Phoenicopterus ruber*. The second distinct area is Phassouri marshes (west marsh, Figure 1) which is made up of a matrix of freshwater habitat types including grazing marsh and reedbeds.

The Akrotiri aquifer (C9), the third largest in Cyprus (49 km^2), is located in the northern part of the peninsula. Kouris Delta aquifer is the western extension of the Akrotiri aquifer and the eastern part covers the area between Trachoni village and the new Limassol harbor. Kouris Delta aquifer is mainly recharged by surface runoff infiltration and the transmission losses of the Kouris river (Milnes 2011).

Monitoring

Water samples were collected on a monthly basis during 2007–2011 from the three tributaries Kryos, Kouris and Limnatis and additionally the reservoir (Figure 1). Water physicochemical parameters, pH, electrical conductivity (EC), and dissolved oxygen (DO) were measured *in situ* using WTW handheld meters with SenTix 41, TetraCon 325 and Cell Ox 325 probes. Water samples were retrieved using a HydroBios Ruttner-type water sampler and were analyzed in the laboratory for nitrate, ammonia, nitrite, dissolved inorganic phophorous (DIP), total phosphorus, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (standard Hach methods). The method detection limits are presented in Table 1 of the Supporting Information (SI), available online at http://www.iwaponline.com/wst/069/783.pdf. Daily flow measurements from the three gauge stations for the period of 2007–2010, and the reservoir water depth for the period of 2000–2010, were provided by the Cyprus Water Division Department (WDD). The water level measurements since 1983 from two irrigation wells in Akrotiri aquifer (wells 1966/028 and 1977/076) were also provided by WDD (WDD 2011).

Finally, aquifer water quality data (nitrate-N, chlorides, sulfated) from 2007 up to 2009 were provided by previous studies (Nikolaidis 2010). Daily precipitation records of the Kouris station (code313) for the period 2000–2010 were provided by Cyprus Meteorological Service.

RESULTS AND DISCUSSION

Basin hydrological status

The estimated mean annual precipitation is 463 mm (2000–2010). Potential evapotranspiration is estimated to be

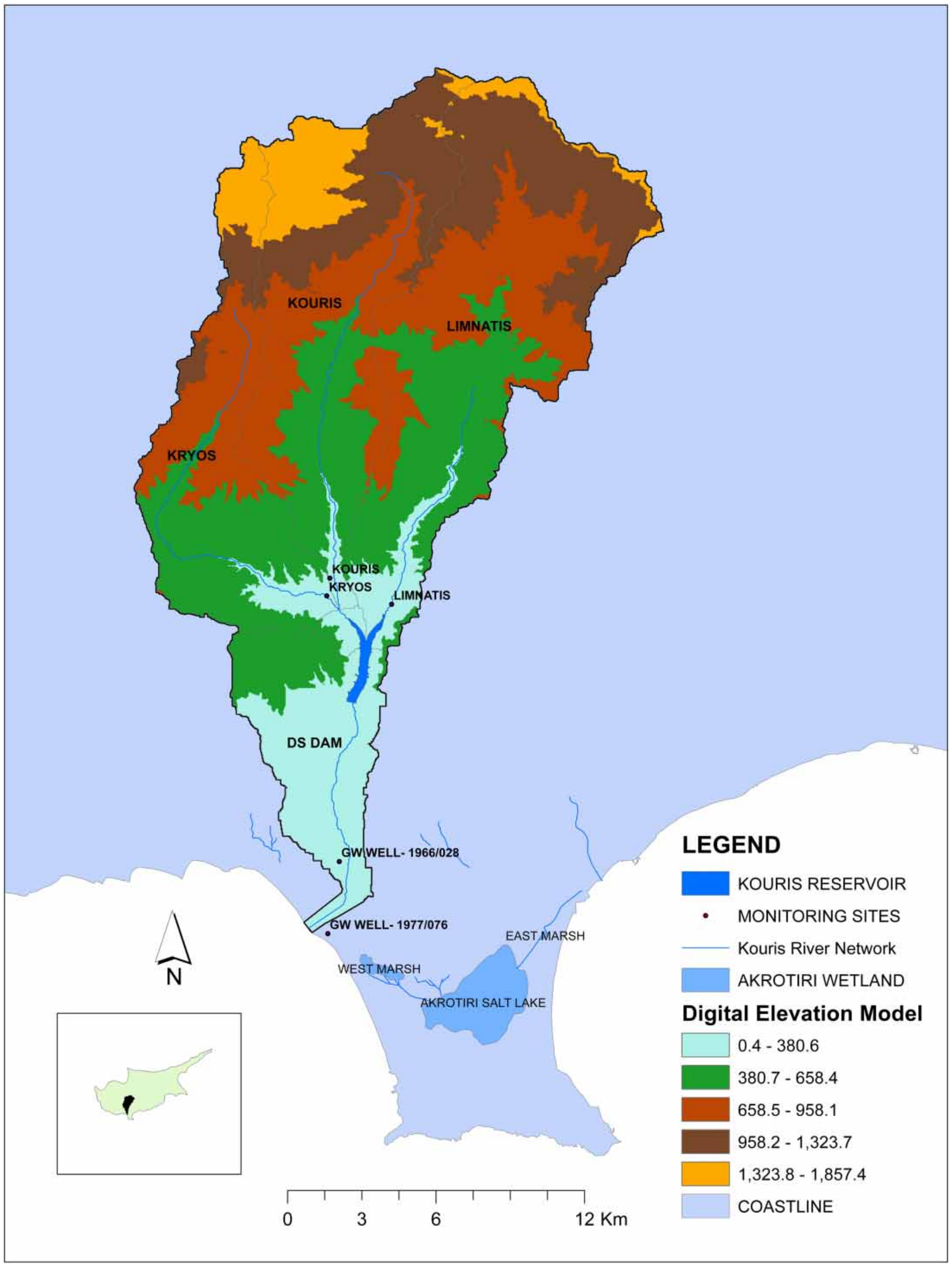

Figure 1 | Kouris river basin stream network, Akrotiri wetland and current drainage network.

693 mm using the Thornthwaite method. The three tributaries of Kouris reservoir (Kouris, Limnatis and Kryos) have a total outflow of 31.7 $Mm^3\,yr^{-1}$ (mean value of 1965/66–2008/09 hydrologic years). The mean annual flow is 0.35 $m^3\,s^{-1}$ for Kouris stream, 0.31 $m^3\,s^{-1}$ for Limnatis and 0.49 $m^3\,s^{-1}$ for Kryos stream (mean values of 2000–2010; Figure 1 SI (available online at http://www.iwaponline.com/wst/069/783.pdf)). Reservoir volume reached 113 Mm^3 in 2003 and became almost zero (0.7 Mm^3) in 2008 (Figure 1 SI). In the post dam period, no regulation to maintain river ecological flow was applied. Thus river outflow decreased to 3.8 Mm^3 annually (mean value of 1990–2008 hydrologic years), almost one-tenth of its previous flow (Figure 2 SI, available online at http://www.iwaponline.com/wst/069/783.pdf). Consequently in the natural recharge mode of Akrotiri aquifer a decreasing thickness was observed (Figure 2).

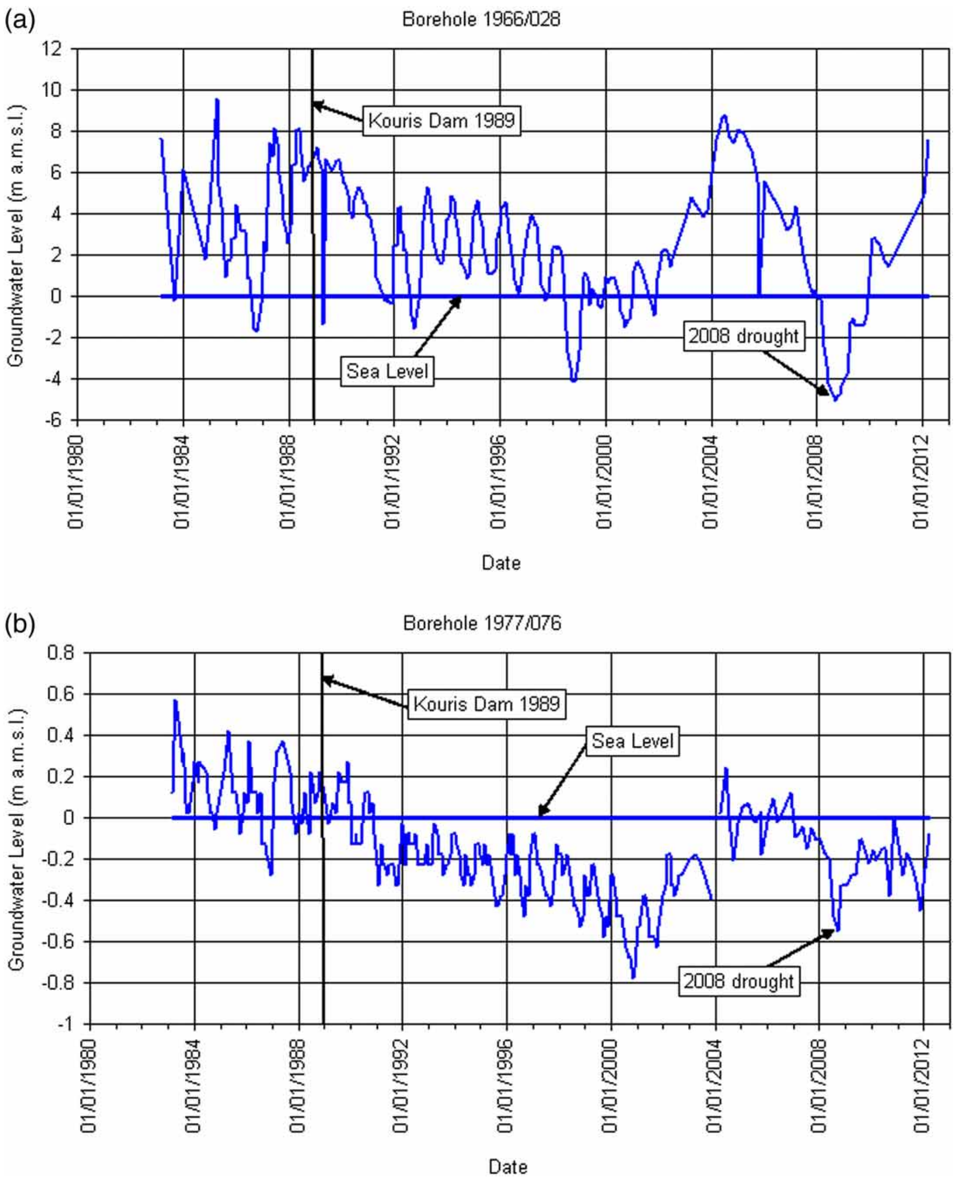

Figure 2 | (a) Water level fluctuation 1983–2012 of groundwater in borehole 1966/028, Akrotiri aquifer. (b) Water level fluctuation 1983–2012 of groundwater in borehole 1977/076, Akrotiri aquifer.

Wetland hydrological status

The river and Akrotiri wetland are connected through the Phasouri marsh. The Phasouri plantation is located in the north-west part of the wetland and covers an area of 60 ha of flat land lying below sea level. The marshy depressions are inundated during the rainy season both by direct precipitation and by runoff from the surrounding areas. Groundwater flows towards the salt lake rather than the coast, with a recharge rate around 2.0 Mm^3/yr (Ragab *et al.* 2010). A decrease of the lake water below sea level due to high evaporation rates enhancing groundwater flow towards the lake was verified (Figure 3 SI). In the past, water from the river was also transferred to the Phassouri plantation, and to the marshes, by a complex system of man-made diversion canals (Figure 4 SI). The water was conveyed over several kilometers southward and eastward. During the field survey of 2010, a registration of the ephemeral and temporary streams, north-west of the wetland and the open channel that serves the drainage system of the new harbor (Figure 5 SI), took place. No available flow data of the temporary streams and the recently man-made open channel network exist. (Figures 3–5 SI are available online at http://www.iwaponline.com/wst/069/783.pdf.)

Akrotiri aquifer hydrological status

The eastern part of Akrotiri aquifer is recharged by direct precipitation and excess runoff during rain events and by the transmission losses of the Kouris river. The water levels follow a seasonal variation pattern. This pattern is characterized by a decrease in water level during the dry months, as a result of over-extraction (Milnes 2011) and an increase during the winter when the natural precipitation recharge occurs. For instance the water level in the well 1966/028 (Figure 2(a)) ranged between 8.8 and −5 meters above mean sea level over the period 1983–2011 and from +0.6 up to −0.8 in the well 1977/076 (Figure 2(b)) over the period 1983–2011. Both figures clearly show the gradual decline of water levels over the period 1995/96–2000/01 below the average. The replenishment of the aquifer over the period 2001/02–2003/04 can also be seen. It shows values above-average rainfall, and the low water level due to the exceptional drought of 2008. The latter was caused by increased pumping that was practiced to compensate for the lack of surface water during the drought. The operation of many wells (more than 400) in the Akrotiri region that pump more than 2.5 $Mm^3\,yr^{-1}$ modifies the aquifer water levels. The combination of increased salinity together with the contamination by nitrates, phosphates and pesticides limit the aquifer capacity as a source of potable water. Therefore, an even higher decline of aquifer volume is expected, since CC scenarios predict a surface water reduction of about 17% and a recharge reduction of Akrotiri aquifer of about 20% up to 2050 (Ragab *et al*. 2010).

Water quality status evaluation

Four sites were selected in order to assess the water quality of the basin (Figure 1):

- Site 1 Limnatis river upstream of Kouris reservoir reflects the domestic and agricultural pressures of a semi-mountainous forested area.
- Site 2 (Kouris–Alassa) reflects mainly agricultural pressures.
- Site 3 (Kryos upstream of Diarizos diversion tunnel outlet) which is minimally affected by anthropogenic activities due to the mountainous catchment area, the considerable distance between the site selected and the pressures that are located in the upper part of the Kryos' catchment.
- Site 4 Kouris reservoir.

Table 1 shows the average and standard deviation of 12 basic water quality parameters for the monitoring period of 2007–2011 All nitrate dissolved forms (mean values) are higher in Limnatis stream (2.8 $mg\,L^{-1}$N-NO_3, 0.009 $mg\,L^{-1}$N-NO_2, 0.079 $mg\,L^{-1}$N-NH_4) than in Kryos

Table 1 | Average (mean) values and standard deviation (SD) of common parameters of water quality in four sites of Kouris river during the sampling period 2007–2010

Variables	Units	Site 1 Limnatis		Site 2 Kouris–Alassa		Site 3 Kryos		Site 4 Kouris reservoir	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
pH		8.5	0.1	8.6	0.1	7.8	0.6	8.8	0.6
DO	$mg\,L^{-1}$	10.2	1.7	10.0	1.3	9.5	1.0	8.4	2.1
T	C	13.9	4.1	14.4	4.8	14.6	4.0	20.0	4.9
Conductivity	$\mu s\,cm^{-1}$	721.9	144.6	1225.4	239.5	600.7	92.8	708.5	213.7
COD	$mgO_2\,L^{-1}$	<lod	–	<lod	–	<lod	–	9.4	4.5
BOD	$mgO_2\,L^{-1}$	<lod	–	<lod	–	<lod	–	<lod	–
N-NH_4	$mg\,L^{-1}$	0.079	0.086	0.070	0.075	<lod	–	0.099	0.122
N-NO_2	$mg\,L^{-1}$	0.009	0.005	0.006	0.005	0.034	0.025	0.013	0.018
N-NO_3	$mg\,L^{-1}$	2.8	1.4	2.1	1.1	1.0	0.6	0.3	0.4
N-Total	$mg\,L^{-1}$	3.2	1.7	2.7	1.8	NM	–	2.2	5.0
P-PO_4	$mg\,L^{-1}$	0.028	0.040	0.011	0.016	NM	–	0.009	0.008
P-Total	$mg\,L^{-1}$	0.070	0.087	0.022	0.049	NM	–	0.013	0.014

lod = limit of detection; SD = standard deviation in parentheses; NM not measured.

(1.0 mg L^{-1}N-NO_3, 0.034 mg L^{-1}N-NO_2) and closer to Kouris stream (2.1 mg L^{-1}N-NO_3, 0.006 mg L^{-1}N-NO_2, 0.070 mg L^{-1}N-NH_4). The N-NO_3 value in Limnatis is higher than the reference conditions for eutrophication (Brunel *et al.* 1997). N-NH_4 on the contrary, is in the low range for eutrophication both in Limnatis and Kouris (Table 2 SI, available online at http://www.iwaponline.com/wst/069/783.pdf). The slightly increased nutrient values can be attributed to agricultural land use and to domestic effluents. Annually nutrient emissions by point and diffuse sources in the catchment have been estimated to reach 6.6 ton P and 210 ton N (Tzoraki *et al.* 2013). The mean value of total phosphorus concentration (0.013–0.070 mg L^{-1}) is lower than the threshold value of 0.15 mg L^{-1}. This value is critical for eutrophication problems in European rivers (Karaouzas *et al.* 2011) and in the low range of French rivers (Brunel *et al.* 1997). All sites showed very low COD (<lod (limit of detection)–9.4 mgO_2 L^{-1}) and BOD (<lod) concentrations. The pH varied in the range of 7.8–8.8 with no significant fluctuation within all sites. The high DO concentration (8.4–10.2 mgO_2 L^{-1}) indicates a rich oxygenated river system. The highest EC was observed at Site 2 (1,225 μS cm^{-1}) and is assumed to be due to the dissolution of minerals in Troodos complex geologic substrate.

Kouris reservoir (Table 1 – Site 4) appears to have a very low content of nutrients which satisfies the drinking water criteria and freshwater eutrophication criteria (Table 2 SI). For the sampling period of 11/2007–12/2011 the nitrate-N concentration was 0.283 (±0.382) mg L^{-1}, the nitrite-N 0.013 (±0.018) mg L^{-1}, ammonia-N 0.096 (±0.126) mg L^{-1}, total N 0.070 (±0.601) mg L^{-1} and total P 0.085 (±0.341) mg L^{-1}. In the studied periods the reservoir water had an oligotrophic status according to the Carlson trophic state index and had phosphorus as a limiting factor according to Redfield number examination.

Aquifer nutrient concentrations followed an increasing trend for the period 2007–2009. Mean nitrate-N concentration in the aquifer for the sampling period was 12.3(±8.6) mg L^{-1}, chloride was 179.9 (±82.36) mg L^{-1} and sulfate was 276.4 (±391.9) mg L^{-1}. The mean nitrate was slightly higher than the threshold value of 11.3 mg L^{-1} defined by the groundwater directive 98/83/EE. The dissolution of sulfate-rich soils in groundwater resulted in higher sulfate concentrations than the threshold of 250 mg L^{-1} (Nikolaidis 2010). Seawater intrusion by adding chloride into the system, and increased concentrations of nutrients originating from agricultural activities, degraded the water quality.

TMDL approach

Flow duration curves were used for the development of load duration curves (LDC), on which TMDLs can be defined. Flow duration curve intervals can be grouped into several broad classes. These classes correspond to conditions and patterns associated with the flow regime. One class is representing high flows (0–10%), another for moist conditions (10–40%), one covering mid-range flows (40–60%), another for dry conditions (60–90%), and one representing low flows (90–100%) (Table 4 SI, available online at http://www.iwaponline.com/wst/069/783.pdf). This particular approach places the midpoints of the moist, mid-range, and dry zones at the 25th, 50th, and 75th percentiles respectively (i.e., the quartiles). The high zone is centered at the 5th percentile, while the low zone is centered at the 95th percentile. The five zones scheme is assumed to be more appropriate for the Kouris flow regime. The high flows zone pertains to flood events, the moist conditions correspond to the flow state of significant baseflow contribution and high sediment transport capacity. The mid-range zone is a low flow state, dry conditions represent very low flows and finally low flows correspond mostly to zero flows.

The LDC is developed by multiplying stream flow with a water quality criterion and a conversion factor for the pollutant of concern. LDC relates stream flow to loading capacity and allows estimation of TMDLs under various flow conditions. LDC is the graphical tool to link water quality with hydrological processes such as floods, baseflow or only surface flow contribution.

Flow duration curves of the Limnatis stream (period 01/01/2006–30/09/2009) and the Kouris stream (period 01/10/2007–30/09/2009) (Figure 6 SI, available online at http://www.iwaponline.com/wst/069/783.pdf) have served as the foundation for the development of LDC, on which TMDLs could be based. The flash-flow hydrological pattern of the Kryos stream does not allow the creation of LDC. For the estimation of fluxes for the same period, monthly water quality data (nitrate, ammonia, phosphate, total nitrogen and total phosphorus) has been used. The Final Greek River Nutrient Classification System (GR-NCS) has been used (Skoulikidis 2008) for nutrient threshold selection instead of drinking water thresholds (Table 2 SI) since it takes into consideration the impact on stream ecological quality. According to this classification the nitrate – N concentration was selected: 0.89 mg L^{-1} for nitrite-N, 0.016 mg/L for ammonia-N, 0.036 mg L^{-1} for

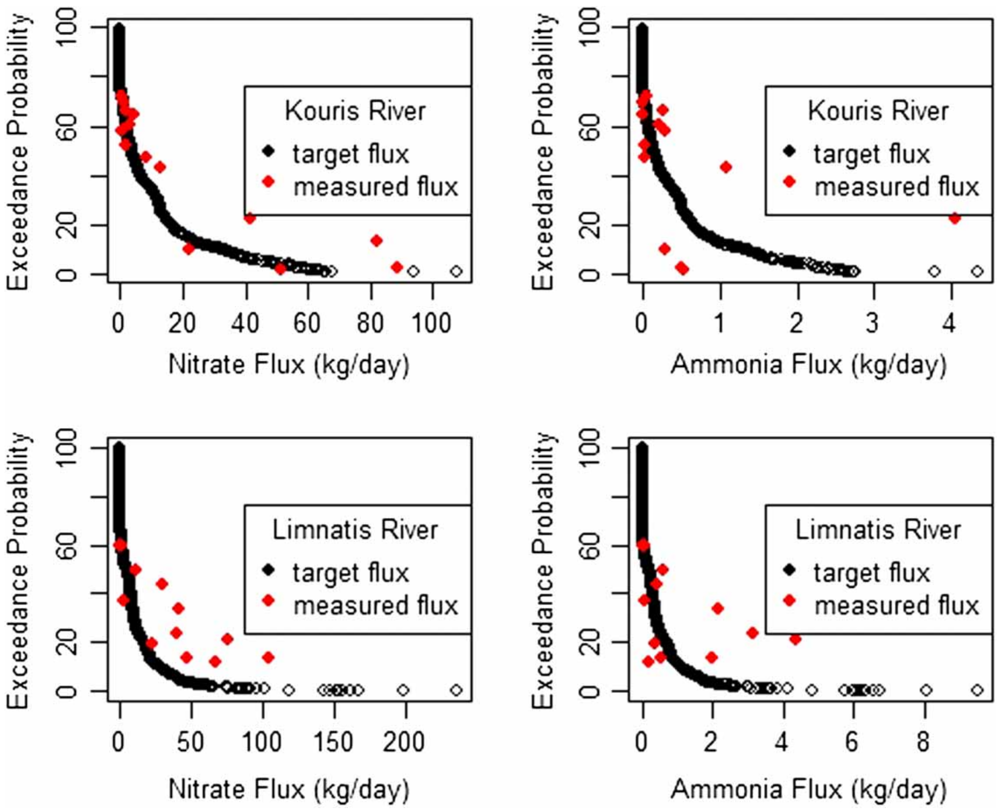

Figure 3 | TMDL approach for (a) ammonia and (b) nitrate fluxes in Limnatis stream; (c) ammonia and (d) nitrate in Kouris.

phosphate-P, 0.028 mg L^{-1} for total N 2.27 mg L^{-1} and 0.084 mg L^{-1} for total P.

As shown in Figure 3 in the Limnatis stream, the current loads exceed the TMDLs in terms of nitrate and ammonia. There are no water quality data available in the high flow class in the Limnatis stream. In moist conditions the nitrate load has to be reduced by 65% to reach the target flux, 78.3% in mid-range and 65.3% in dry conditions. In low flows (70–100%) the river ceases to flow and there is no load transport. Eventually there is no need to reduce the loads. In the mid-range and dry conditions flow classes, ammonia load has to be reduced up to 86.6 and 63.9%, respectively. For the same flow classes it is necessary to reduce the phosphate load by around 65.5 and 35.7%, respectively. Lower load reductions were estimated for the total nitrogen (36.9 and 25.8%) and total phosphorus loads (1.5 and 14.6%) in both mid-range conditions and dry flow conditions.

In the Kouris River, a nitrate-N flux reduction between 67.5 and 73.6% and a total nitrogen flux reduction between 33.3 and 75.6% are required in all flow classes so as not to exceed the TMDLs based on the GR-NCS system. In particular, in the dry conditions flow class, significant load reduction of all examined constituents is suggested. During the dry conditions flow class the most important flow component is the baseflow that constitutes 69–75% of the total streamflow (Boronina *et al.* 2003). Therefore, dissolved nutrients leached by irrigation fields and septic tanks are allowed to flow as baseflow components into the river.

CONCLUSIONS

The measured fluxes exceeded the TMDLs in almost all flow classes. From this analysis, more frequent sampling during high flow is suggested. It is necessary to evaluate the water quality of high flows to determine if the particulates or dissolved nutrients exceed the thresholds. In high flows the highest sediment and washout capacity was observed to generate higher dissolved and particulate nutrient values of the water. Additionally the increase of loads in the dry flow condition class reflected the response of baseflow nutrient transport in the watershed. The TMDL graph is intended to guide the temporal schedule for chemical sampling in all hydrologic classes and to help towards the interpretation of the corresponding results. For instance if nutrients flux exceeds the water quality standard value in the high flow hydrologic condition class, that should signal an alert for actions against the consequences of flash-flood events.

The ecosystem in estuaries of the basin that includes the lower part of the river, the Akrotiri aquifer and the Akrotiri wetland are parts of the Kouris basin that are under high pressure. The Kouris river outflow reduction to one-tenth (3.8 $Mm^3\ yr^{-1}$) in the post dam period caused deterioration of the delta and Akrotiri aquifer ecosystem services. The Akrotiri wetland hydrologic network has been altered due to dam operation. Its thickness is even more decreased by the operation of many private wells in the Akrotiri area.

In the Kouris Dam it is important to minimize the erosion processes and the nutrient input loads. In the Akrotiri aquifer it is essential to maintain the water level by wastewater recharge, thereby helping wetland sustainability. However, preliminary results concerning the proposed measures such as the minimization of pumping volumes from the aquifer have shown positive results. Public dialogue and a continuous evaluation and update of the River Basin Management Plans will be the basis for sustainable development and adaptation measures to new CCs.

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