European Water 58: 535-541, 2017.

Adaptive management of Koronia ecosystem based on external-internal dynamics

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Abstract: Lake Koronia, a Ramsar and Natura site has a prolonged history of degradation to wetland status due to intensive groundwater use. In 2015 Lake Koronia water-level increased due to restoration works and a favorable hydrologic year. Consequently, Lake Koronia has progressed considerably towards autotrophy and distinct open water and littoral ecosystems and is expected to oscillate around autotrophy-heterotrophy and wetland-lake transitions depending on annual water budget. Lake Koronia, as it has been configured following water volume increase, presents ecological status assessment and management challenges. The purpose of this paper is to develop an integrated management approach combining internal and external system dynamics and an indicator detecting spatial and temporal changes. Internal factor management centers around dissolved oxygen, as it reflects primary production based on nutrient concentrations in water and sediment, exchanges at the sediment-water interface and littoral-open water interactions. The development of a dynamic aeration scheme, based on spatial and temporal ecosystem variability and real time earth insitu monitoring is proposed. External factor management focuses on agriculture, as it contributes greatly to nutrient loading and water budget determination. The eco-hydrological model SWAT assesses the impact of spatial and temporal fertilization and irrigation water application using space born geodata. Proposed agricultural practices effectiveness is evaluated. Adaptive management and ecological status assessment is based on the proposed indicator, which integrates near real time monitoring, developed protocol, and appropriate layers of Earth observation geodata. This indicator addresses water column, littoral zone, sediment and watershed loading, while complimenting the European Water Framework Directive 2000/60/EC.

Key words: ecosystem management, watershed interactions, ecosystem functions, integrated indicators, earth observation, WFD

1. INTRODUCTION

Lake Koronia, a Ramsar and Natura 2000 site is located in Northern Greece at approximately 75 m a.s.l. The watershed is drained by five creeks, extents to about 350 km^2, is inhabited by 45,000 people. Lake Koronia had maximum depth >5 m and was eutrophic in 1970s prior to the intensification of irrigation and fertilization agricultural practices. Industrialization in the 1980s and 1990s accelerated groundwater use and wastewater addition to the lake. Consequently, water-level declined progressively from about 4 m in mid-1980s to <1 m in 1995 (Mitraki et al. 2004). Concomitant water quality deterioration led to hypertrophy, aquatic trophic web collapse and massive fish and waterfowl deaths.

Despite gradual loss of industry in the watershed after 2000, water-level in Lake Koronia fluctuated from 0-1 m with periodic complete desiccation. During this low water-level period of approximately twenty years, the flocculent sediments of the lake were either permanently or periodically exposed and subjected to progressive dessication, oxidation and compaction. Ultimately wetland soils were established. Phragmites littoral vegetation expanded lakeward displacing open water areas by dense stands (Crisman et al. 2014), while communities of both wetland and upland plants were established on permanently exposed areas, and opportunistic plants invaded periodically exposed sediments (Alexandridis et al. 2014). Thus, Lake Koronia developed

all three characteristics of wetland ecosystems: minimal water-level fluctuating hydroperiod, intermittently saturated soils and hydric vegetation. Overall ecosystem metabolism shifted to heterotrophy, a characteristic of wetlands and hypertrophic lakes, at a lake depth of 1.5-2.5m (Mitraki et al. 2004). Wetland characteristics, however, supported avian fauna diversity and abundance increase. The deterioration of Lake Koronia led to a comprehensive restoration plan (Zalidis et al. 2004) that has been partially implemented.

In spring 2015, water-level increased in Lake Koronia, as a result of restoration actions and a wet hydrologic year. Since then, maximum depth has been consistently maintained >2.5 m resulting in the formation of an open water area. Water quality improved, and trophic state declined considerably, while the deepest part of the lake shifted to increased autotrophy. However, a considerable part of the lake has remained below the autotrophy threshold water-level of 1.5 m and has been experiencing prolonged diel anoxia especially during summer. Lake Koronia is predicted to oscillate between autotropy-hetrotrophy and wetland-lake transitions, as a function of annual water budget, which reflects both fluctuations in annual precipitation and groundwater use in the watershed.

The purpose of the Water Framework Directive 2000/60/EC (WFD) is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters, and groundwater. Emphasis is placed on prevention of further deterioration, protection, and enhancement of the status of aquatic ecosystems; promotion of sustainable water use; reduction of priority substances discharges; reduction of groundwater pollution; and mitigation of flood and drought events. This Directive dictates integrated river basin management purposed to achieve "good water status" for both surface water bodies and groundwater. Ecological status is assessed based on biological, hydromorphological, and physicochemical elements. No wetland definition is provided by WFD, but their functionality is recognized both at the level of water body - adjacent wetland interaction and as a part of the hydrological cycle of a river basin.

The WFD dictates protection and enhancement of status, both ecological and chemical, of inland surface waters. Although ecological status is defined in article 2 as "an expression of the quality of the structure and functioning of aquatic ecosystems associated with surface waters", quantification of this expression is based largely on taxonomy and ecosystem structure metrics. Contemporary freshwater and terrestrial ecosystem research, however, concludes that anthropogenic stressors influence both structure and function, or either one (Sandin and Solimini 2009; Crisman et al. 2004). Consequently, effective ecosystem management considers both structure and function. However, this approach is only applied to wetlands. The expansion of the functional indicator concept to rivers and lakes led to the conclusion that ecosystem functions serve the purpose and objectives of the European Framework Directive (Barker et al. 2009). Such an approach is particularly appropriate in shallow lakes, where interactions with littoral and adjacent wetlands are prevalent compared to stratifying lakes.

Traditional lake management approaches focus on water column and water-sediment processes. This is usually sufficient in deep stratifying lakes, where the hypolimnion functions as nutrient sink and predator refugium. In shallow non-stratifying lakes, however, hypolimnion is functionally replaced by the littoral zone, which is usually managed for structure. Crisman et al. (2004) recognized that ecosystem structure does not imply function and proposed that traditional vertical water column-sediment management approaches be integrated with horizontal management plans based on plant-sediment and littoral-open water interactions to enhance functions performed by shallow lakes. To separate littoral function and structure, vegetated littoral areas were divided into lakeward littoral wetlands and landward adjacent, core wetlands. The core wetland receives runoff and outflow water from the watershed, functions as a sediment and nutrient sink, is heterotrophic and predominantly anoxic, and interacts with open water only during extreme weather phenomena. The littoral wetland interacts intensively with open water, receiving dissolved oxygen by wave action, while functioning as a source of carbon and faunal predation refugium. The littoral wetland is mostly well oxygenated and autotrophic (Crisman et al. 2004). This functional optimization management approach is integrated with external dynamics, as the watershed functions as a source

of nutrients and suspended solids to the lake ecosystem. Different land uses have distinct impacts on the export of nutrients, chemicals, and sediment to the lake. Thus, integrated management for ecosystem function can be expanded to watershed and the land-core wetland interface.

The purpose of this article is to develop: a) an integrated long-term management approach for Lake Koronia combining internal (ecosystem) and external (watershed) system dynamics; and b) a system of indicators for management and ecological status assessment addressing both ecosystem structure and functions. Indicators are based on in-situ and satellite borne earth observation. These purposes support Social Benefit Areas (SBA) of the Group of Earth Observations (GEO). Focus is placed on the SBAs of biodiversity and ecosystem sustainability, food security and sustainable agriculture, and water resources management. Moreover, this project supports the GEO-Glows Initiative, which is intended to facilitate the use of Earth observation assets to contribute to mitigating water shortages, excesses and degraded quality arising from population growth, climate change, and industrial development.

2. METHODS

Data collection for proposed indicators follow protocols developed by the Global Earth Observation System of Systems (GEOSS) and the Open Geospatial Consortium (OGS). Thus data are of identified quality and provenance, interoperable supporting tool development, and readily accessible to multiple public and private users. Proposed indicators are based on both in-situ measurements and spaceborne images analysis. Indicator estimation at the watershed level is performed by the ecohydrological model SWAT using both in-situ and spaceborne data.

Frequency of data collection and analyses frequency varies. Telemetric stations record values hourly, water sample collection is monthly, and sediment sampling occurs approximately at five year intervals. Satellite images analyses, and watershed contribution estimations and predictions by ecological monitoring is performed annually.

3. LAKE KORONIA MANAGEMENT

Lake Koronia management objectives are determined in the restoration plan: habitat diversity, food-web support, water quality and trophic state improvement, and increased water retention capacity (Zalidis et al. 2004). This approach includes structural, and mostly functional components. It calls for a shallow lake with littoral and open water phases and sustainable land uses and agricultural practices in the watershed.

Reflooding and subsequent formation of open water phase re-introduced vertical management challenges in Lake Koronia. Overall system metabolism shifted towards autotrophy, as sediment decomposition impact to dissolved oxygen concentration was reduced. Additionally, sediment became more inorganic through repeated cycles of atmospheric exposure and flocculent material consolidation to the deepest part of the lake basin (Crisman et al. 2004). However, the extent of the well oxygenated open water areas varies seasonally with water-level. Moreover, extensive littoral wetlands rely on open water for oxygen input, while remaining below the autotrophy water-level threshold. Consequently, oxygen regime within the open water-littoral wetland areas periodically reach hypoxia and even anoxia. Anoxic periods are more likely to occur or be more pronounced during summer, because oxygen solubility is a function of water temperature; and nighttime, if nocturnal respiration surpasses daytime oxygen input in the water column. Thus, anoxic conditions posing threats to the survival of fish communities may occur either occasionally during periods of increased autotrophy (water-level >2.5 m) or daily at times of heterotrophy (water-level <2.5m). Mechanical aeration is proposed for preventing dissolved oxygen depletion in the water column, while maintaining heterotrophic metabolism in core wetlands. The mechanical aeration scheme needs to be based on a predictive oxygen regime model based on water-level, water temperature and biotic community needs.

Littoral areas are a substantial part of an integrated management plan. Prior to degradation, Lake Koronia had a minimal littoral zone with negligible contribution to lake metabolism (Crisman et al. 2004). However, gradual water-level decline allowed aggressive aerial expansion of dense Phragmites stands at the rate of 29% annually. Phragmites habitats followed slowly water-level contours, but lakeward margin progression was far greater than landward margin retreat (Crisman et al. 2014). Despite being native in Europe, Phragmites is a invasive nuisance species in many North-European lakes displacing indigenous plant communities. The effect of Lake Koronia reflooding on Phragmites cover is not yet fully measured and understood due to delayed Phragmites response to water-level changes. Although Phragmites habitats might be structurally similar throughout, functionally stands are divided into core and littoral wetlands (Crisman et al. 2004). Unruly expansion of either wetland habitat may compromise functionality of remaining habitats, especially open water ones. Consequently, ecosystem maintenance requires sufficient water-level and suitable littoral:open water area ratio. Such a ratio can be maintained with Phragmites harvesting, which also contributes to nutrient removal from water and sediment. The harvesting scheme needs to include proper biomass disposal, especially if Phragmites analyses indicate heavy metal uptake from sediments.

Lake Koronia restoration and management plans were designed at the watershed level, where ecosystem degradation causes lie. Proposed actions in the restoration Masterplan were introduction of sustainable agriculture practices and groundwater recharge enhancement (Zalidis et al. 2004). Ecohydrological model SWAT applications in Koronia watershed showed that if low input sustainable agriculture practices, providing water and fertilizer to plants only where and when needed, replaced conventional practices at watershed level, annual nutrient input to Lake Koronia would be reduced by 3.8%. However, saved water would contribute to groundwater recharge instead of stream flow, which would increase several years later. Additionally, production increase with crop redistribution according to soil quality characteristics would result to reduced nutrient input to the lake, only if combined with low input sustainable agriculture practices. Besides being the prevalent land use in the watershed, agriculture is the economic activity of greatest groundwater demand. It also adds considerable nutrient load to Lake Koronia. Proposed management practices are low input sustainable agriculture and crop redistribution according to soil quality characteristics.

4. ECOLOGICAL STATUS INDICATORS

In accordance with the WFD the indicator system proposed for Lake Koronia addresses both adaptive management and ecological status assessment and integrates ecosystem structure, function, and watershed interactions (Table 1). These three components were considered in the determination of Lake Koronia ideotype, restoration plan, and ongoing management (Management Body of Lakes Koronia and Volvi 2009; Zalidis et al. 2004).

Proposed indicators of biological elements compatible with WFD describe littoral and open water aquatic communities. Indicators chosen are littoral extent, littoral:open water areas ratio, and planktonic community abundance and diversity (Table 1). Littoral extent corresponds to the function of floodwater detention, because intermittently inundated mostly core wetlands provide space for water storage, absorb water in unsaturated parts of the sediment and reduce incoming water velocity by means of hydrophyte resistance to flow. Littoral extent is also an indicator of groundwater recharge/discharge, as groundwater exchange between lakes and aquifers occurs predominantly in littoral areas. These areas are also critical for nutrient retention, because nutrients are commonly immobilized and/or metabolized in wetland plants and soil. Littoral:open water area ratio addresses conservation of open water habitats, which are threatened by water-level reduction and/or lakeward littoral zone expansion. Consequently, this ratio pertains to the ecological functions of ecosystem maintenance ensuring multiple habitat existence, and food-web support providing multiple primary producers growth (vegetation and phytoplankton) and thus supporting consumers diversity. Additionally, littoral:open water ratio describes in-situ carbon retention, as long-term carbon storage occurs in highly organic sediments in both littoral and open water areas,

accumulated dead littoral plants, and woody littoral vegetation. Both above mentioned indicators are monitored with satellite image analyses at the peak of littoral vegetation growth in late summer (Alexandridis et al. 2014). Additional analyses during the wet season (spring) is also informative. The biological indicator of planktonic community corresponds to food-web support, as a major determinant of energy and carbon flow in open water communities.

Hydromorphological WFD elements monitored are hydrology and sediment characteristics. Hydrology is described by water-level (Table 1), which is of upmost importance in Lake Koronia. Water-level describes the hydrological functions of floodwater detention, as it is directly connected to water storing ability; groundwater/discharge, as it is a determining factor of inflow/outflow equilibrium; and ecosystem maintenance, because it controls open water aerial extent. Water-level is monitored telemetrically and best interpreted in conjunction with meteorological parameters particularly precipitation.

Table 1. Proposed indicators integrating WFD elements, wetland functions, and watershed processes in Lake Koronia

Wetland functions	**WFD elements**				**Watershed**
	Biological	**Hydromorfological**		**Physicochemical**	
	Aquatic Communities	**Hydrology**	**Sediment**	**Water Quality**	**Land Use**
Hydrological					
Floodwater Retention/Water storage	Littoral Extent	Water-Level			Land Use/Agricultural Practices Changes
Groundwater Recharge/Discharge	Littoral Extent	Water-Level			Groundwater Budget, Water table
Sediment Retention	Littoral Extent		TOC, TC:TN	Transparency, Conductance, TOC, TSS	Suspended Solids Inflow
Biogeochemical					
Nutrient Retention	Littoral Extent		TN, TP	TN, TP	TN, TP Lake Input
Nutrient Export			TN , TP	TN, TP	
In-situ Carbon Retention	Littoral: Open Water Ratio		TOC		
Trace Element Storage			Priority Substances	Priority Substances	Land Use/Agricultural Practices Changes
Ecological					
Ecosystem Maintenance	Littoral: Open Water Ratio	Water-Level	TOC, TC:TN, Substrate Structure	Transparency, Conductance, pH	Land Use Changes
Food-Web Support	Littoral: Open Water Ratio, Planktonic Community		TOC, Substrate Structure	Dissolved Oxygen Regime, TN, TP, TOC	

Open water sediment characteristics pertain to total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), priority substances and sediment substrate (Table 1). Although some functions can be assessed by a single chemical variable, multiple sediment attribute synthesis enhances functional ecosystem assessment. Sediment TOC, TN, TP, and TC:TN integrates both external (watershed) and internal (littoral, water column) processes and overall ecosystem metabolism, although calculating contributions of individual processes may not be possible. Allochthonous material not retained in the littoral zone carry both inorganic and organic particles, thus reducing TOC content and changing TC:TN in comparison to sediments of water column origin. Littoral debris contributes also carbon reach plant material, while phytoplankton decomposition contributes low TC:TN organic matter to the sediment. Also, nutrient recycling processes in both water and sediment are reflected in sediment chemistry. Consequently, TOC, TN and TP relate to the functions of sediment and nutrient retention, nutrient export (to the atmosphere and harvested plants), in-situ carbon retention, ecosystem maintenance and food-web support. The last two functions also depend on substrate structure, because the latter creates habitat for benthic

invertebrates, which are in turn primary and secondary consumers passing energy to higher foodweb levels. Trace element storage is monitored with priority substances sampling, which in the case of Koronia are mostly heavy metals of possible industrial origin. Sediment attributes change very slowly depending on sedimentation rates and sediment-water interactions, so sampling frequency should be about five years and adjusted according to results. Most sediment biotic and abiotic processes happen in the top 10 cm, but deeper layers are needed for reference. Total phosphorus fractionation provides additional information about water and sediment procedures. Substrate structure is inferred from gravimetric analyses; and secondarily by visual core inspection of surface flocculent material.

Water quality indicators follow closely physicochemical properties described in WFD (Table 1). The hydrological function of sediment retention occurs primarily in the littoral zone. Low retention efficiency is reflected in the water quality indicators of transparency (Secchi disk depth, and turbidity), electric conductance, TOC and total suspended solids (TSS). TN and TP concentrations are anticipated to increase, when the functions of nutrient retention and export are not performed sufficiently in littoral areas and open water sediments. Priority substances concentrations in the water column are directly related to trace element storage and metabolism in sediments, and woody or accumulated dead littoral vegetation. However, metabolism of some toxic organic substances also occurs in the water column. All above mentioned water quality indicators are integrated in the functions of ecosystem maintenance and foodweb support. Transparency, conductance, and pH determine habitat suitability for organisms and correspond to the function of ecosystem maintenance. TN and TP determine autotrophic production and TOC provides food to heterotrophic organisms, thus supporting foodwebs. Dissolved oxygen regime is an important physicochemical component in all lakes. It determines ecosystem ability to support both producers and consumers, and shapes habitats especially at the water-sediment interface and in hypolimnia. However, dissolved oxygen regime is of critical consequence in Lake Koronia, where autotrophy/heterotrophy gradients vary both spatially (littoral vs. water), daily (daytime vs. nighttime), annually (winter vs. summer), and interannually, as a function of annual water budget. Consequently, dissolved oxygen needs to be monitored telemetrically, so mechanical aeration can be designed and applied effectively. Conductance, pH, and turbidity are also measured telemetrically, while water sampling for remaining variables is proposed to be monthly.

Direct interactions among natural and anthropogenic processes in the watershed, wetland functions, and elements determining ecological status according to the WFD are widely recognized. However, proposing indicators for watershed procedures and practices supporting ecosystem functions is a novel approach (Table 1). Land use changes and cultivation practices affect greatly ecosystem floodwater retention, as they determine water flow velocity, temporary floodwater storage and infiltration rate to groundwater. Industrial and residential uses increase impervious surfaces, while irrigation, tillage, and soil cover determine soil porosity and water infiltration rates. Land uses and practices also affect indirectly priority substances storage in the ecosystem, as industrial operations may contribute heavy metals, and agricultural practices may add pesticides to the ecosystem. Additionally, agricultural land has been expanding in littoral areas impacting ecosystem maintenance. Groundwater management is a priority in the watershed of Koronia. However, the functions of groundwater recharge and discharge both at the ecosystem and watershed levels can only be assessed by groundwater modeling and water budget calculations based on water table measurements. Suspended solids inflow is determined by agriculture and forestry practices in the watershed. Practices reducing erosion enhance the function of sediment retention in littoral wetlands. Nutrient (TN, TP) input to the lake is directly related to nutrients applied in agricultural lands and wastewater from residential areas and animal raising facilities in the watershed. Fertilizer use reduction and wastewater treatment support nutrient retention in Lake Koronia. Most watershed indicators (land use/agricultural practices changes, sediment inflow, TN, TP inputs) derive from hydrological models, such as SWAT, which use data from statistical surveys and satellite image analyses. However, these models need to be calibrated with actual nutrient and suspended solids inflow measurements. The importance of water-level in ecosystem maintenance dictates the need

for groundwater modeling for accurate estimation of irrigation effects to lake water volume especially during dry years.

5. CONCLUSIONS

Ecological status assessment in the context of the WFD and adaptive water body management purposed to protect, conserve, and enhance ecosystem status need to be based on ecosystem properties and processes quantification. Measurements of structural ecosystem components can rely on readily available biological and chemical protocols that provide accurate, and reliable data, comparable among different water bodies. Data with these characteristics are greatly appreciated by aquatic scientists and managers. However, ecosystem structure does not necessarily imply function, as exemplified by littoral and core wetlands adjacent to lakes. Although they both are structurally similar, the former functions as a nutrient and carbon source, while the latter as a nutrient and carbon sink. Integrated ecosystem assessment addressing both functional and structural aspects enhances ecosystem status description and management plan efficiency, while serving the purposes of the WFD.

The WFD places water body management at the river basin level recognizing the importance of interactions between aquatic systems and their watersheds. Integration of these interactions in indicators enables adaptive management based on feedback provided by the indicators. Integrated indicators also need to address water body uniqueness. Shallow lakes present intensive interactions between open water and littoral zone compared to deep stratifying lakes. Lake Koronia is a shallow lake, where water-level and groundwater properties define aquatic structure and function. A system of indicators for ecological status assessment and adaptive management integrates structural and functional ecosystem aspects, interactions between water body and watershed and interactions among aquatic ecosystem components. These integrated indicators combine in-situ (telemetry and field sampling) and spaceborne earth observation, and ecohydrological modeling.

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