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# Phragmites distribution relative to progressive water level decline in Lake Koronia, Greece

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## ABSTRACT

Lake Koronia is a hypertrophic Ramsar site in northern Greece. Water level dropped progressively from approximately 6 m in the mid 1980's to 0.8 m in 2001 associated with over extraction of groundwater for agriculture. The resulting annual water level loss of 0.25-0.30 m/yr was accompanied by expansion of *Phragmites australis* from a littoral fringe to dominance of exposed lake bottom areas from 97 ha in 1977 to 785 ha in 2005. The aim of this work was to apply an ecohydrological approach using remote sensing and GIS to examine the movement of *Phragmites* relative to the water level retreat and to basin morphometry. Aerial expansion of *Phragmites* averaged 11-32 ha/yr during the period of progressive water level decline, but increased to 38-116 ha/yr during a brief period of water level increase (2001-2003) as the plant colonized reflooded portions of the basin. The total area of *Phragmites* expanded 29% per annum during 1977-2005. Landward and lakeward margins of the *Phragmites* area followed water level retreat, moving 55 m and 129 m, respectively, during the long period of progressive water level decline. Aerial movements of *Phragmites* in Lake Koronia are some of the highest reported in the literature. Mean water level within the *Phragmites* bed varied from 0.5 m to 2.0 m during the period covered by this study. Very minor changes in basin slope, however, affected plant colonization rates, as evidenced by 200-250 ha/0.5 m water level drop at 0.18% basin slope to 360-1360 ha/0.5 m water level drop at 0.029% slope.

**Keywords:** *Phragmites australis*, reedbed, ecohydrology, water level, wetland, remote sensing, GIS

## INTRODUCTION

Management of the emergent macrophyte, *Phragmites australis*, is of concern throughout Europe. Cultural eutrophication in several Swedish lakes has been accompanied by expansion of *Phragmites* in shallow littoral zones (Andersson, 2001), while many German and Swiss lakes undergoing eutrophication have lost *Phragmites* zones (Ostendorp *et al.,* 1995; Kubin & Melzer, 1997). The extent of *Phragmites* wetlands has been reduced significantly in eastern Europe, including the Balkans, via drainage for agriculture, and it is likely that such reductions will increase as the direct result of altered hydrological regimes associated with climate change and the increased opportunity such environmental change will afford for further agricultural expansion into previously marginal areas (Hartig *et al.,* 1997).

Loss of *Phragmites* during cultural eutrophication has been attributed both to ancillary human activities including bank erosion, mechanical damage to reeds and recreational activities (Ostendorp *et al.,* 1995) and to environmental constraints of the plant. Variables governing the distribution of *Phragmites* in lakes include basin slope, substrate characteristics, trophic state, and two hydrological components, water level and hydroperiod. Although Andersson (2001) suggested that slope was a major determinant of *Phragmites*' distributions in Swedish lakes, Fensham *et al.* (2004) felt it was of little importance in Australia, possibly reflecting vastly different ranges of basin configurations between the two regions. *Phragmites* appears to prefer inorganic sediments (Pelechaty, 2004) with slow accumulation rates (Pyke & Havens, 1999), although accumulation of plant litter appears to be more important than total sediment organic content (Lenssen *et al.,* 1999). Highly organic and flocculent sediments do not favor growth of *Phragmites*. *Phragmites'* photosynthetic rate and other physiologic activities decreased at high water and salinity stress in a pot culture experiment (Yang *et al.,*, 2013).

The relationship with trophic state is complicated. Although generally thought indicative of higher trophic state, Pelechaty (2004) found that *Phragmites*-dominated macrophyte communities were more representative of low rather than high trophic state lakes in Poland. It is likely that methanogenesis (Sorrell *et al.,* 1997) and reduced toxic compounds, such as ferrous iron (Weisner, 1996), in highly organic sediments with an overlying, oxygen depleted water column, regardless of trophic state, negatively affect *Phragmites* distributions.

Increasingly, hydrology, especially stage and its timing and duration, is recognized as the overarching factor controlling how *Phragmites* interacts with other environmental variables. Inundation frequency influences vegetation community distribution of a shallow lake of south China, where reed communities are more suitable for regions with low inundation frequency (Deng *et al.*,, 2013). *Phragmites* in deep water produces a lower number of shoots and allocates proportionately less to below than above ground biomass to compensate for difficulties in oxygen transport to its roots (Vretare *et al.,* 2001; Hayball & Pearce, 2004). Deep water rhizomes tend to be shorter and closer to the sediment surface than in shallow water (Weisner & Strand, 1996), but this adaptation to oxygen transport makes deep water plants less able to withstand physical removal by wave action (Coops *et al.,* 1994). Furthermore, deep water plants may not be able to adjust their morphology quickly during periods of rapid water level change and thus are eliminated from the system (Weisner & Strand, 1996). Nevertheless, Chessman *et al.* (2008) found no evidence that water abstraction from streams has an effect on the abundance of macrophytes, including *Phragmites*, in southeast Australia.

*Phragmites* can expand its distribution rapidly under favorable conditions, with colonization of constructed wetlands in Virginia exceeding 5 ha/yr (Havens *et al.,* 2003). Vegetative growth of rhizomes accounted for annual increases in total plant area of 18% along a Canadian river (Hudon *et al.,* 2005) and 25% in a French marsh (Alvarez *et al.,* 2005). The latter translated into lateral movement of *Phragmites*' distribution of 40 m annually. Greatest rate of expansion in Canada was noted when water level of the previous year was low and flooding did not exceed 100 days, while in France, rapid spread was facilitated in years with stable water levels or spring drawdown periods. Although maximum expansion was attributed to seeds in the former, their importance in the latter was considered minimal. Very high annual expansion of 135% was noted in a restored brackish marsh of southeast Louisiana based on a small test site of < 1 ha (Howard and Turluck, 2013).

Seed germination of *Phragmites* is facilitated by water level fluctuation with an extended period of drawdown during summer (Coops & van der Velde, 1995; Coops *et* *al.,* 2004) and wide temperature fluctuations (Ekstam & Forseby, 1999). Survival of young plants depends on growth being sufficient during drawdown and shallow water periods to have significant biomass above the water surface during subsequent flooding (Weisner & Ekstam, 1993; Mauchamp *et al.,* 2001).

Lathrop *et al.* (2003) identified three patterns for *Phragmites* expansion in brackish tidal marshes of the eastern United States: colonization (new patches), linear clonal growth (along a preferred axis) and circular clonal patches (non-directional, random spread). They noted that patch distributions were dynamic, showing establishment, spread, coalescence and disappearance over time. Bodensteiner & Gabriel (2003) found that larger *Phragmites* patches in a Wisconsin lake tended to have higher stem densities, wider range of water depths, greater historical stability and lower areal fragmentation than small patches. Smaller, more "ragged" patches were characterized by lower maximum depths and restricted water level ranges.

While trophic state and hydrology appear to be the two most important variables controlling colonization and spread of *Phragmites*, the relationship between their interactions and plant success is poorly known. Lake Koronia, Greece provides a unique opportunity to examine historical changes in the distribution of *Phragmites* across a synchronized chronology of profound water level decline and increasing cultural eutrophication. The present study takes an ecohydrological approach using remote sensing and GIS to examine the relative stability of the landward and lakeward extents of *Phragmites* relative to both the amount and rate of progressive water level retreat and how short term reversals of water level, basin morphometry and progressive cultural eutrophication affect long term trends.

## METHODS

### Site description

Lake Koronia (N40°41', E23°09'), northern Greece, is listed as a wetland of international importance by Ramsar (Figure 1). It has a watershed of approximately 350 km$^2$ with a single discharge downstream to Lake Volvi that rarely flows. Watershed land use is primarily agricultural with some industrial activity along the western shore of the lake.

Once the fourth largest lake in Greece (4620 ha), water level in Lake Koronia declined progressively from a maximum of 6 m during the mid 1980's to 0.8 m in 2001, a volumetric and aerial reduction of 90 and 25%, respectively (Mitraki *et al.,* 2004). Such water level reduction can not be ascribed to climatic factors, but reflects a steady decline in levels of the shallow aquifer (0-50 m) in the western part of the watershed during 1969-1981 associated with major expansion in irrigated agriculture near the lake. Agricultural extraction of groundwater (40 x $10^6$ $m^3$) was over three times greater than that of local industries (European Commission, 1999). Given high hydraulic connectivity, depletion of the shallow aquifer was directly reflected in reduced lake level (Zalidis *et al.,* 2004).

Lake Koronia became progressively more eutrophic concurrent with the period of water level decline, especially after the early 1990's, and currently is hypertrophic (Mitraki *et al.,* 2004). Total phosphorus values remained < 200 µg/L from 1977 to 1989, then rose rapidly to >1,000 µg/L by 1996. Phytoplankton have always dominated the autotrophic community, with chlorophyll values >200 mg/$m^3$ reported in the 1990's. Although not extensive in the early 1970's, the emergent macrophyte community, clearly dominated by *Phragmites*, expanded during the period of water level decline. Although the greatest increase was along the western margin of the lake, by the 1980's, reeds gradually appeared and expanded around the entire lake perimeter, forming continuous several meters in width (Zalidis *et al.,* 2004).

[Figure 1 about here]

**Remote sensing database**

In addition to a lakewide assessment of *Phragmites* distribution, a 4,364 m transect was established at the western end of the basin from the historical maximum landward extent of lake area to deep water (Figure 1). A 30 year time series of satellite images was utilized for assessing lake level and *Phragmites* extent and relied on the following satellite sensors: Landsat 2 MSS (08/22/1977), Landsat 5 TM (09/24/1985, 07/19/1987, 08/09/1989, 07/26/1998), SPOT XS (08/24/1994), Landsat 7 ETM+ (07/28/1999, 08/24/2000, 05/30/2001, 08/05/2002), Terra/ASTER (07/16/2003), and IKONOS MSI

(08/07/2005). Although they had variable spectral characteristics, all recorded reflected radiation in visible and near-infrared spectra, essential for monitoring vegetation and water parameters. Because spatial resolution (ground sampling distance) was highly variable, 4m for IKONOS MSI to 79m for Landsat 2 MSS, a data scale represented by 95% of the range, ≤30m (equivalent to 1:60,000) was considered the nominal spatial accuracy for this study.

Image pre-processing included registration to the local projection system using polynomial transformation. The horizontal registration error of less than one pixel for each rectified image provided acceptable positional accuracy. Images were digitally enhanced to increase visual interpretation, and digital image processing techniques, including histogram stretching and linear radiometric enhancement, were used initially to improve contrast, brightness and level of feature distinction, and later to facilitate photo-interpretation and information extraction.

**Water level history**

Dimanidis & Panagiotidis (1999) used a kinematic procedure to develop a bathymetric map (0.5 m contours) for Lake Koronia based on physical measurements of water depth obtained from 109 GPS referenced locations in 1998. Alexandridis *et al.* (2007) interpolated the resulting depth contours to a continuous surface using the ANUDEM algorithm (Hutchinson, 1989) to create a digital depth model (DDM). This procedure performs well with small input datasets and uses a roughness penalty parameter that can be modified to allow the fitted surface to follow the smooth changes of the lake bottom. Visual examination of the original measured points with the bottom surface produced no discrepancies. The mean difference of 0.02m was not statistically significant (t=2.268, DF=258, P=0.024).

Lake water level was recorded from a staff gauge at approximately monthly intervals from September 1982 until May 1999 when water level fell below the calibrated gauge base. Following successful use of various scales of satellite images, including NOAA AVHRR, to measure the extent of open water (Harris, 1994; Birkett, 2000; Bryant & Rainey, 2002) and Landsat TM image to define land-water boundaries (Verdin, 1996, Ward *et al.*,, 2013), a method was developed both to fill in missing water level data for the period of study and to extend the database beyond May 1999 when the staff gauge became exposed and access to the lake became impossible, for dates of available satellite images. The lake shoreline was mapped via photo-interpretation of the time series of available satellite images. Combining this horizontal information with the DDM, estimated water level was determined. Given the mapping accuracy of the images (half pixel) and the basin morphometry of the lake, accuracy of this method ranged from ±0.01 to ±0.29 m for IKONOS and Landsat 2 MSS, respectively, with a mean accuracy of ±0.05 m for 95% of the data. Thus, missing water level could be reconstructed for the dates of acquired satellite images.

Reconstructed water level estimates were validated for the period that physical measurements were also available. The mean difference between estimated and measured water depth was 0.16 m and was not statistically significant ($t=1.561$, $DF=5$, $P=0.1792$). The reconstructed database was then used to calculate intermonthly water level fluctuations as a standard deviation of monthly readings, mean hydroperiod for a series of years, mean depth within the reed bed and the extent of horizontal expansion of lake area relative to incremental changes in water depth.

**History of *Phragmites* distribution**

Spatial data on the extent of *Phragmites* within Lake Koronia were available only for 2004 and 2005, when boundaries of plant distribution were determined via GPS at select locations along the western shore of the lake. Thus, historical photo-interpretations were utilized for reconstruction of the distribution of *Phragmites* for a majority of the study period.

The vegetation community of an Italian wetland, including species richness, was assessed using the spectral variation hypothesis on a multispectral QuickBird image (Rocchini *et al.,* 2004), and wetland boundaries have been delineated elsewhere using computer assisted photo-interpretation of aerial photography (Barrette *et al.,* 2000).

The present study extracted information from remotely sensed images using thresholding of the near-infrared band to discriminate the reed bed from open water, unsupervised spectral classification to identify subtle spectral differences between *Phragmites* and adjacent cultivated crops, raster to vector conversion to delineate features automatically and computer assisted photo-interpretation to correct polygons and produce the final delineation of eco-hydrological parameters. Parameters mapped by these techniques included the aerial extent of *Phragmites*, exposed sediment, and open water. Post-classification change detection was then used to identify changes occurring between consecutive observations by incorporating the mapped parameters into a GIS overlay analysis to estimate change of area and pattern through time.

Using the DDM of the lake basin in a 3-dimensional analysis and simulating water level position, mean water depth within the *Phragmites* bed was estimated for every year of the time series. Values for annual high and low water levels were used to estimate lake surface expansion and contraction. This was repeated for various positions of mean water level to delineate the relationship between water level fluctuation and lake morphometry in Lake Koronia. Finally, interannual rates of expansion and contraction of both the landward and lakeward boundaries of *Phragmites* were estimated via post-classification change detection (Lu *et al.*, 2004).

## RESULTS AND DISCUSSION

### History of water level fluctuation

Based on close agreement between recorded and estimated values during the period of physical measurements (1982-1999), the record of water level was extended earlier (1977) and later (2000-2005) selectively, depending on satellite data availability (Figure 2).

[Figure 2 about here]

While the maximum water level drop between 1977 and 2005 was approximately five meters, resulting in <1 meter depth in the lake at its minimum level (August 2002), the decline was not monotonic but was defined by five distinct periods of water level dynamics (Table 1).

[Table 1 about here]

Two periods of water level decline were interspersed with two periods of short-term water level increase exceeding 1 meter, 1985-1987 (1.5 m) and 2002-2005 (1 m). Although missing data for 1977-1981, water level during 1977-1985 dropped two meters from a maximum of 75 m amsl in 1977 to 73 m amsl in 1985, while levels in 1987-2002 dropped 4.6 m overall. Water levels displayed a mean annual loss of 0.25 and 0.30 m/yr and seasonal variation of 0.4 and 0.47 m during the two periods, respectively.

In addition to two periods of water level increase > 1 m (1985-1987 and 2002-2005), 1.5 and 1 m, respectively, the 1987-2002 period of water level decline was punctuated by two brief water level reversals of < 1 m fluctuation. Although the overall decline in lake level during the study period has been attributed to over extraction of ground water for agriculture, periods of increased level were during years when rainfall exceeded pumping (Mitraki *et al.,* 2004).

The relationship between area of lake bottom exposed and water level was characterized by three distinct periods during 1977-2005 (Figure 3). Lake area change for each 0.5 m increment of water level change was relatively constant at 200-250 ha between 76.0 and 70.5 m amsl, increased sharply (360 to 1360 ha) between 70.5 and 69.5 m water depth, and declined rapidly (1360 to 528 ha) between 69.5 and 69 m. The two inflection points in the relationship (70.5 and 69.5 m water level) correspond to maximum lake depths of 1.5 and 0.5 m, respectively. Such large areas of lake bottom exposed per 0.5 m water change reflect the essentially flat nature of the Lake Koronia basin, with slopes of 0.18, 0.029 and 0.052%, respectively, for the three depth intervals.

[Figure 3 about here].

**Historical distribution of *Phragmites***

*Phragmites* extent increased steadily in the Lake Koronia basin from 97 ha in 1977 to 785 ha in 2005 associated with a progressive decline in water level (Table 1). Annual aerial expansion rates during periods of decreasing water level (11-32 ha/yr) were smaller than those when water level increased >1.5 m in 1985-1987 and 2002-2005 (38-116 ha/yr). These rates far exceed those reported by Havens *et al.* (2003) for constructed wetlands in Virginia (0.1-5.6 ha/yr) with little bottom slope. Similarly, the 28.9% per annum increase in *Phragmites*' area between 1977 and 2005 exceeded rates for Quebec (18%) and France (25%) reported by Hudon *et al.* (2005) and Alvarez *et al.* (2005), respectively.

During 1977-1989, *Phragmites* colonization was able to keep pace with shoreline exposure during progressive water level decline but not with increasing rates of bottom exposure recorded thereafter (Figure 4). Non-colonized bare sediment areas ranged from 17 to 221 ha annually during 1994-1999, increased markedly (678-1497 ha) during 2000-2002, then declined to 20-94 ha for 2003-2005.

[Figure 4 about here]

*Phragmites* distribution along the shore of Lake Koronia was extremely dynamic, with some areas showing aerial decline and others expansion for the same temporal period (Figure 5). Note that annual values for both expansion and retreat represent the balance between dynamics at both landward and lakeward plant distribution margins. Prior to 2002, areas of interannual expansion and retreat of *Phragmites* were similar, with retreat exceeding expansion only during the period of water level increase during the mid 1980s and the minimal water level decline of the late 1990s. Thereafter, as water level fluctuated wildly from its maximum increase (2.02 m) in 2003 to nearly complete basin desiccation in 2005, the area of *Phragmites* showed its greatest expansion of the entire study period, while areas of interannual retreat were only slightly elevated from previously recorded values.

[Figure 5 about here]

The distribution of *Phragmites* along the 4,364 m transect in Lake Koronia for the period 1977-2005 displayed two temporally distinct periods (Figure 6). The first period, 1977-1999, is characterized by a narrow horizontal extent of *Phragmites* (242-501 m) with progressive lateral movement of both landward and lakeward vegetation margins in response to long term temporal reduction in lake level. The second period, 2002-2005, is characterized by wide horizontal vegetation extent (1,299-1394 m) and relatively steady landward and lakeward terminal positions. Water level continued to decline during this period interspersed with brief intervals of increase. The overall horizontal extent of *Phragmites* continued to expand throughout the study period regardless of whether lake level was rising or falling.

Rates of interannual expansion of *Phragmites* along the lake transect exceeded retreat throughout the study period (Figure 7), with mean rates of horizontal movement for landward and lakeward edges of *Phragmites* into the lake basin of 55 and 129 m/year, respectively. The rapid increase of water level in 2003 (2.05 m) resulted in only a 17 meter and 11 meter retreat of the landward and lakeward plant distribution limits, respectively, along the transect. The annual rates of horizontal movement of *Phragmites* along the Lake Koronia rates exceed those of both Alvarez *et al.* (2005) from water level manipulations experiments in France (40 m) and Clevering & van der Toorn (2000) for colonization of a new polder in the Netherlands (0.4 m). Direct comparison, however, is hindered without detailed discussion of factors controlling plant distributions among the three sites.

Hampe & Petit (2005) noted that fewer than 4% of published studies dealing with geographic distributions have examined the edge dynamics of freshwater biotic populations and focused on front edge dynamics while ignoring rear edge dynamics. Population aerial expansion can result from vegetative growth of the plant front or through outlier “founder” establishment via long distance dispersal, while rear edge population retreat can result in either extirpation or creation of isolated relict populations.

Lakeward expansion of the *Phragmites* distributional front during progressive water level decline in Lake Koronia was extremely rapid, and likely attributed more by vegetative growth than seed dispersal. Movement of the landward trailing edge of the plant population was approximately half that of the lakeward edge and was also mostly as a front with little establishment of outlier subpopulations. Once established, both distributional fronts were extremely resistant to lake level increase.

Prior to 1995, mean water depth within the *Phragmites* bed was mostly 0.5 meters or less.  Overall, extremes in *Phragmites* distribution along the Koronia transect were from 2.3 m above water level in 2002 to a water depth of 1.5m in 2003 (Figure 6).

[Figure 7 about here]

## SUMMARY AND CONCLUSIONS

Suggested controlling factors for the intrabasin distribution of the emergent macrophyte, *Phragmites australis*, include sediment organic content, basin slope, trophic state and hydrology. Although it has been suggested that *Phragmites* prefers inorganic sediments with slow accumulation rates (Pelechaty, 2004; Pyke & Havens, 1999), Lake Koronia, with flocculent organic sediments when flooded has displayed some of the most rapid colonization rates reported.

While slope has been considered a major (Andersson, 2001) or insignificant (Fensham *et al.,* 2004) determinant of *Phragmites*' distributions, a minor shift from 0.18 to 0.029% slope in Koronia resulted in a 84 ha/y increase in the rate of lake bottom colonization. Clearly, however, expansion of *Phragmites* at Lake Koronia relative to slope was ultimately controlled by the rate of water level change and associated area of bottom exposed. Lake area can vary by 250 ha during the annual hydroperiod, when water level is higher than 70.5 m, but with further water level decrease and a minor change in slope, the exposed area can increase seasonally by >1250 ha, favoring rapid expansion of *Phragmites*.

While recognizing the importance of the above environmental variables, especially minor changes in slope, the current study focused on distributional patterns of *Phragmites* relative to long term lake level decline. Although Lathrop *et al.* (2003) identified three patterns for *Phragmites* expansion in brackish tidal marshes of the eastern United States (colonization (new patches), linear clonal growth (along a preferred axis) and circular clonal patches (non-directional, random spread)), the overall temporal trend for *Phragmites* in Lake Koronia was lakeward advance of vegetation often balanced by a landward loss. Mean annual advance of the lakeward margin (129m/yr), however, normally far exceeded the retreat of the landward margin (55m/yr), rates that exceed some of the highest reported literature values (40m/yr) (Alvarez *et al.,* 2005). Once established, *Phragmites* stands in Koronia were extremely resistant to change in water level as evidenced by the observed range of water level depths of vegetated areas of 2.3 m above water level to 1.5 m water depth.

Although the period of extended drawdown during summer observed in Lake Koronia and wide temperature fluctuations should have facilitated seed germination and survival of young plants (Coops & van der Velde, 1995; Coops *et al.,* 2004, Ekstam & Forseby, 1999; Weisner & Ekstam, 1993; Mauchamp *et al.,* 2001), the current study was not able to assess the importance of seeds vs vegetative growth in the spread of *Phragmites* in Lake Koronia. Indirect evidence for the importance of vegetative growth over seeds, however, is the observed inability of *Phragmites* to colonize recently exposed large areas of bare lake bottom at Koronia rapidly.

The most problematic relationship of *Phragmites* distributions is with lake trophic state. Cultural eutrophication in several Swedish lakes has been accompanied by expansion of *Phragmites* in shallow littoral zones (Andersson, 2001), while many German and Swiss lakes undergoing eutrophication have lost *Phragmites* zones (Ostendorp *et al.,* 1995; Kubin & Melzer, 1997). In addition, Pelechaty (2004) found that *Phragmites*-dominated macrophyte communities were more representative of low rather than high trophic state lakes in Poland. In part, this confusion is a function of both how trophic state is defined and basin configuration and the importance of littoral to pelagic areas.

Trophic state can be defined narrowly by chemical and biological indicators of phytoplankton production in open water or more broadly as the total system autotrophic production from both open water and the littoral zone. Shallow lakes such as Koronia, where trophic state is defined by the balance between phytoplankton and macrophytes, often display nearly complete dominance by one or the other (alternative stable states) that is stable long term (Scheffer *et al.,* 1993; Scheffer, 1998). In most cases, submersed macrophyte communities are of prime interest.

For extremely shallow lakes like Koronia, submersed macrophytes are of no importance; instead the alternative stable states are algae (phytoplankton and benthic algae) and emergent macrophytes such as *Phragmites*. Thus, Koronia is structured more like a wetland than a lake and is displaying progressive replacement of open water by dense stands of emergent macrophytes. Such conditions require a reassessment of how to view changes in structural alternative stable states relative to system function.

For lakes with extensive near shore macrophyte zones, Crisman *et al.* (2005) proposed that the landward extent of the littoral zone be defined functionally to include only those vegetated areas that interact with open water, roughly delineated by the landward limit of wave influence. More interior vegetated areas would be considered as a fringing wetland.

Although not part of the current study, there is a critical need to develop criteria for assessing the functions of *Phragmites* at Koronia. During the current wetland phase, these include the importance of the zone of interaction between *Phragmites* and both upland and open water habitats. What is the required balance between edge vs. interior areas of *Phragmites* zones required to maximize ecological potential of Koronia ecosystem. It is suggested that Koronia has changed from being a lake to being a wetland as a result of anthropogenic hydrological alteration and that this ecosystem shift has the potential to be reversed provided sufficient water can be allocated to Koronia to displace *Phragmites*. In the meantime, it is essential that criteria be established to evaluate functional aspects of importance to ecosystem management that recognize that the lake has shifted to a wetland.

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**Tables**

Table 1. Historical trends in water level and *Phragmites* distribution during 1977-2005.

| **Time Period** | **Water Level Change amsl** | **Change in *Phragmites* Area** |
|---|---|---|
| 1977-1985: Gradual Water Decrease | | |
| Total Fluctuation | 75 to 73 m | 97 to 354 ha |
| Mean Annual Change | -0.25 m/y | 32.21 ha/y |
| Mean Seasonal Fluctuation | 0.40 m | N/A |
| 1985-1987: Short-Term Water Increase | | |
| Total Fluctuation | 73 to 74.5 m | 354 to 277 ha |
| Mean Annual Change | 0.75 m/y | -38.5 ha/y |
| Mean Seasonal Fluctuation | 0.67 m | N/A |
| 1987-2002: Gradual Water Decrease | | |
| Total Fluctuation | 74.5 to 69.9 m | 277 to 437 ha |
| Mean Annual Change | -0.30 m/y | 11 ha/y |
| Mean Seasonal Fluctuation | 0.47 m | N/A |
| 2002-2005: Short-Term Water Increase | | |
| Total Fluctuation | 69.9 to 70.9 m | 437 to 785 ha |
| Mean Annual Change | 0.33 m/y | 116 ha/y |
| Mean Seasonal Fluctuation | no data | N/A |

Crisman, T.L., Alexandridis, T.K., Zalidis, G.C., and Takavakoglou, V., 2014. Phragmites distribution relative to progressive water level decline in Lake Koronia, Greece. Ecohydrology, 7: 1403-1411.

## Figures

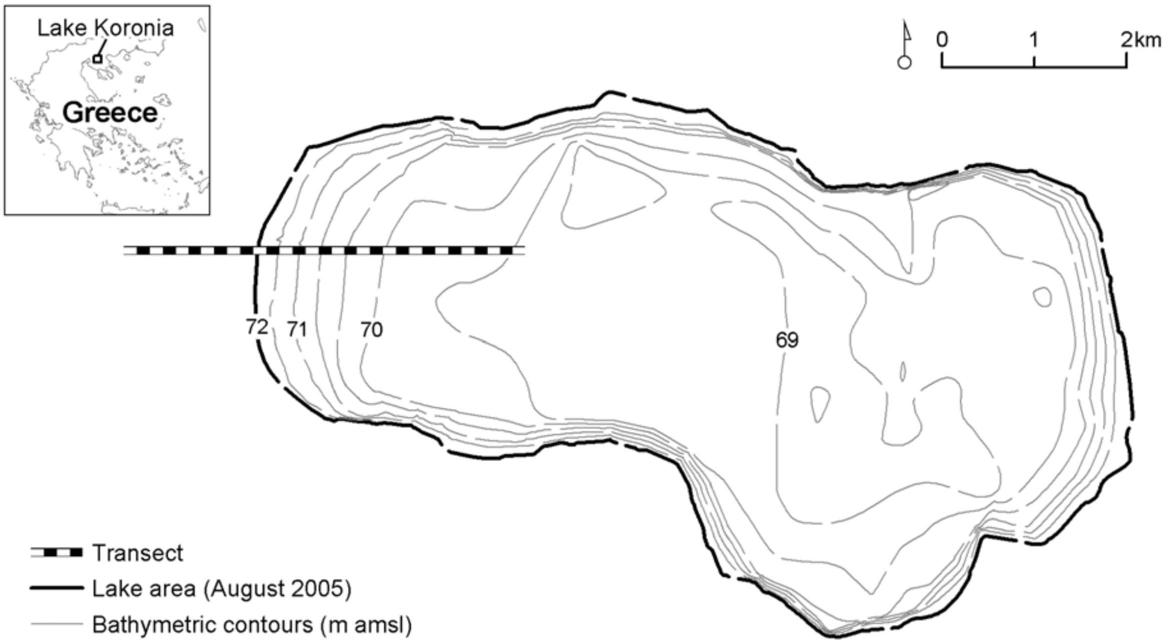


Figure 1. Location of Lake Koronia and in-lake transect. Elevations are in meters above mean sea level (amsl).

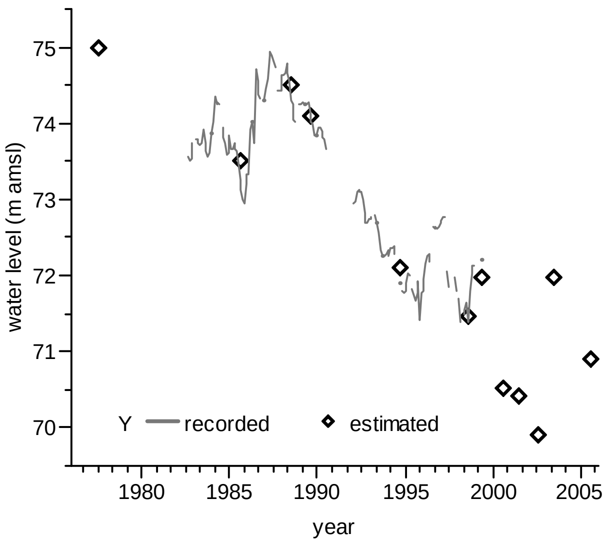


Figure 2. Recorded and estimated water levels for 1977-2005 expressed as meters above mean sea level.

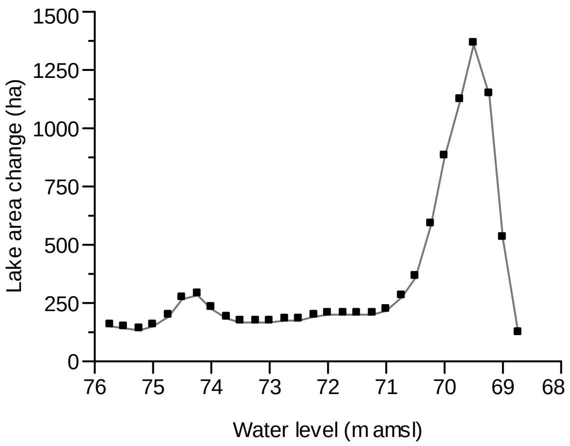


Figure 3. Change in lake area relative to water level.

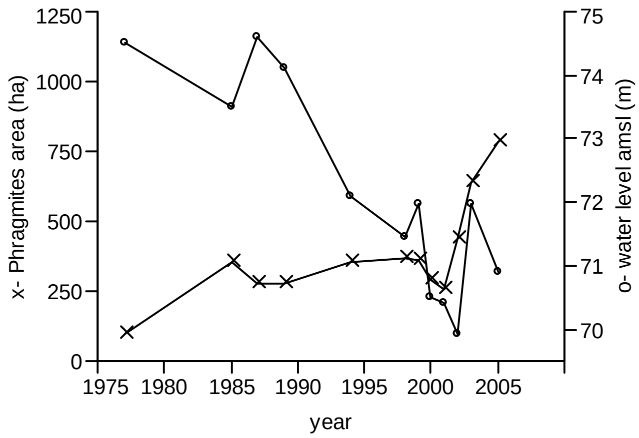


Figure 4. Relation of *Phragmites* area to water level for the period 1975-2005.

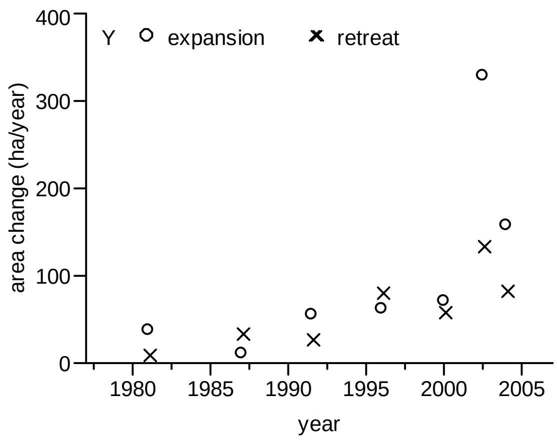

Figure 5. Expansion and retreat of *Phragmites* during 1980-2005.

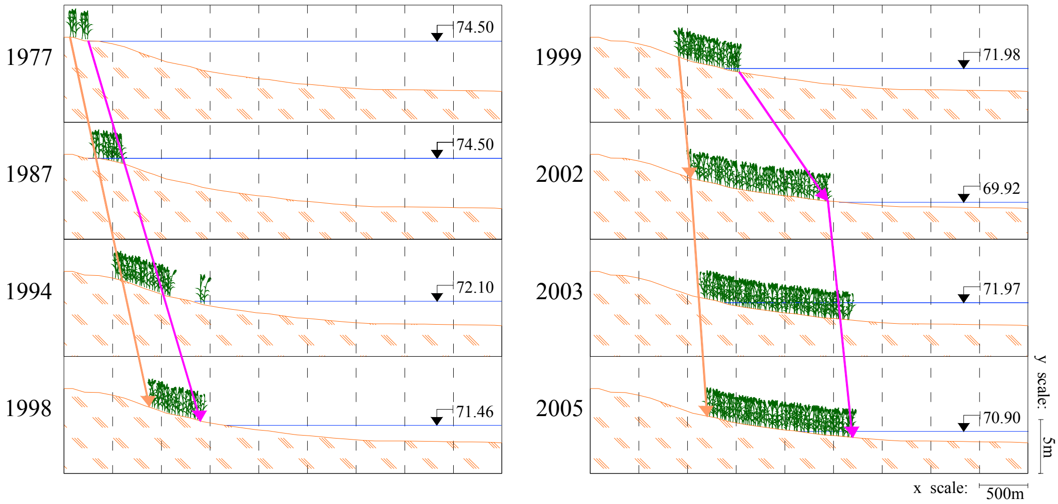


Figure 6. Distribution of *Phragmites* along a 4,364 m transect relative to water level fluctuation for 1977-2005.

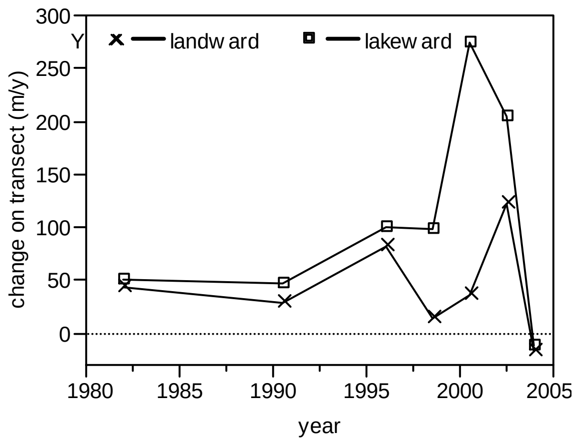


Figure 7: Annual rates of horizontal movement of *Phragmites* along the transect during 1980-2005.