

Mapping and conservation of the reed wetlands on Lake Balaton

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2013

Budapest • Tihany • Wien

This thesis is dedicated to my secondary school teachers Rudolf Urbanek O. Sch.P and János Urbán, who have fuelled my interest in biology, geosciences and mathematics.

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Acknowledgements

Many times, when I had difficulties during my research, I would try and boost my own morale by starting to formulate the acknowledgements of my prospective thesis. The sheer number of people who have taken the effort to help me throughout my work and the examples of their research and life have always helped and will help me to stay on track.

Interdisciplinary science is only possible through the cooperation of many scientists with different backgrounds, and I was fortunate enough to grow up with and learn from many colleagues who helped and inspired me.

I am grateful to Prof Péter Bíró, the director of the Balaton Limnological Institute for the opportunity to work at the Limnological Institute. I would also like to thank my supervisor, Dr. Sándor Herodek, for guiding my research and my studies, for teaching me to think about Lake Balaton as a system, for his patience, his wisdom and humour. I also gratefully acknowledge the support of Prof. Norbert Pfeifer who hosted part of the research and offered me the opportunity to finish this thesis during my employment at the IPF TU Wien.

The research leading to this thesis has received financial support from the NKFP 3B-022-04 (BALÖKO) programme, the Stiftung Aktion Österreich-Ungarn, and EUFAR under the contract No. 2271 in the 7th framework programme of the European Community.

My first steps as a wetland biologist were led by Viktor Tóth, my start as a geoinformation scientist can be credited to István Elek, my introduction to remote sensing to Gábor Molnár and Gábor Timár, my interest in geosciences to Balázs Székely. I am grateful for their readiness to discuss life and science and their helpfulness in research and management.

I can only list a few of those from whom I learned a lot: I picked up conservation biology from Scott and Selina Heppell, LIDAR remote sensing from Christian Briese and Werner Mücke, photogrammetry from Norbert Pfeifer, Camillo Ressler and the late János Ringhoffer, mathematics from Ottó Deák and my secondary school teacher János Urbán, chemistry from Prof. András Perczel and my teacher Lajos Dragon Faragó O. Sch. P., ecology from Beáta Oborny and Júlia Török, presentation skills from Sándor Herodek and my grandfather Prof. János Zlinszky. My dedication to biology and geosciences was inspired by my secondary school class head Rudolf Urbanek O.Sch.P.

My scientific work has been helped a lot by my colleagues at the Limnological Institute, especially Rózsa Kiss, Géza Dobos, and Terézia Horváth, the staff of the EUFAR office and the crew of the NERC Airborne Research Facility, by Andrew Tyler and Peter Hunter at Stirling University, by Hans Thümingner, Markus Hollaus and Gottfried Mandlbürger at the at TU Vienna, and David H. Jewson from the University of Ulster.

I am also indebted to my friends who have provided 24-hour online tech support and helped me with software, methodology and ideas: Szabolcs Nagy, Gergely Padányi-Gulyás, Máté Stibrányi and Ágnes Vári.

I am grateful for the support of my parents during the years of research and studies, and I would especially like to thank my father dr. János Zlinszky for showing me the beauty of nature and explaining how it all works, and for helping me with career planning and project diplomacy. His dedication to science and conservation has always been an example.

Finally, I would like to thank my wife Veronika.

When I read the acknowledgements of my father's thesis some 15 years ago, I found that he was grateful to my mother for enduring the long hours and days she had to spend without him because of his work, and I made a resolution that this would not be the case for my PhD. I have broken this resolution countless times, and I am grateful to Veronika for her patience and her persistent support, for caring for me and Erzsébet and Mihály, and for sharing my love of ecology, geophysics, remote sensing and life.

1. Introduction

1.1 Importance and conservation of littoral vegetation habitats

Conservation of biodiversity and natural habitats is one of the main challenges facing humanity in the 21st century. Freshwater systems are especially in focus, because healthy fresh water habitats are a dwindling resource. Water quality protection is mostly addressed through pollution mitigation, but the protection of the microfauna and microflora that are the basis of the self-purification of natural waters is also essential. Many of the small or even microscopic organisms are not known about in any detail, some are not even identified at the species level yet. Therefore, one of the ways to ensure their protection is to protect their habitat.

It is well known that the littoral zone of lakes and rivers typically hosts more diversity than the open water (Wetzel, 2001). This is caused by the wider variety of environmental conditions encountered in the shore zone that create an array of microhabitats. It is enhanced by the fact that some terrestrial or pelagic species require conditions specific to the coast during particular stages of their life cycle, such as reproduction or larval development.

The littoral zone and especially the emergent shore vegetation within this is also a very productive system in terms of carbon fixation and increase in biomass: this is because water is an unlimited resource in these areas and, therefore, macroscopic plant growth is only limited by competition for light or nutrients. The intensive production of biomass has an effect throughout the food web and means that the shore zone is widely used by pelagic and terrestrial animals alike for feeding.

In many cases, the objectives that conservation should focus on are obvious: sadly, direct habitat destruction or direct pollution is abundant throughout European landscapes. While efforts to remedy their effects are essentially worthwhile, it is also important to identify the patterns and indirect causes of habitat degradation on a wider scale. Major anthropogenic change to a landscape might not catch the eye immediately but can nevertheless have a strong effect on natural habitats. Identifying these processes is a prerequisite for informed management decisions.

It is often necessary to reconsider the scale of observation for these cases: ecology traditionally works on time scales and site sizes that can be spanned by fieldwork and identifies processes and patterns based on this. Broadening the view requires the development of new observational methods, which can then be calibrated using a classical

approach. Remote sensing works on spatial scales that can be out of reach for fieldwork and, therefore, has a potential to identify and explain change over large areas (Kerr and Ostrovsky, 2003; Wang et al., 2010). While many aspects of remote sensing have become part of our everyday lives, it is a discipline of science in its own right. It is also under rapid development and needs to be adapted to the needs of ecological research.

This thesis investigates a widespread problem facing habitat conservation today, i.e. the loss of littoral reed vegetation in Europe. Focusing on Lake Balaton in Hungary, data sources are identified and investigation methods are developed that allow for surveying the extent, change and type of reed wetlands in and around the lake. Based on data collected with these new methods, the effect of human presence on reed wetlands is quantified through several centuries and the main cause of the present-day reed die-back on the lake is identified. Finally, a cost-effective method for future monitoring of these habitats is proposed and a suggestion for sustainable management is presented.

1.1.2 Littoral vegetation

Littoral vegetation plays an important role in the functioning of lakes, providing a wide range of microhabitats that host a high diversity of species (Ostendorp, 1993; Tschardtke, 1999; Winfield, 2004) and provide a constant input of energy to the food web through intensive biomass production (Ostendorp, 1989; Wetzel, 2001). Some functions of littoral vegetation, such as protection from erosion and floods and pollution demobilization are also important from an economic point of view (Vymazal, 2011; Sierszen et al., 2012). However, the last few decades have seen a considerable loss of wetlands and, according to the Millennium Ecosystem Assessment (World Resources Institute, 2005), wetlands are the ecosystem with the highest rate of loss globally. Although the loss of freshwater shore wetlands is only a minor contribution to this, the threatened status of European and North American shore wetlands is also well documented (Bildstein et al., 1991; Dienst et al., 2004). Lake shores are intensively used by humans for habitation, transport, industry and recreation. Lakes are also highly susceptible to climate change (Adrian et al., 2009) because they are strongly affected by climate and also they integrate changes in their catchment.

1.1.3 Reed and European reed die-back

The common reed, *Phragmites australis* is the most widespread shore macrophyte in Europe (Haslam, 1972; Rodewald-Rudescu, 1974; Engloner, 2009), forming stands of up to several hectares along the shores of lakes and rivers. Reed belongs to the PACCAD clade of the Poaceae family (Grass Phylogeny Working Group, 2001), and is closely related

among others to *Spartina*, *Molinia*, and *Panicum*. Its underground rhizomes are perennial, while its aboveground stems, leaves and inflorescences are annual, starting growth in spring, entering senescence in autumn and dying in winter. The high and closed canopy of reed allows it to regularly form monodominant stands, and it is also a suitable wildlife refuge because it is typically only rarely disturbed by human presence. The annual growth of the reed stalks results in an annual production of organic litter, which accumulates in the stands and can form sediments with high organic content together with the decaying old rhizomes.

Starting in the 1970s, the loss of reed wetland area was observed in most major Central European lakes and shores, including Lake Constance (Ostendorp et al., 2003), Ammersee (Rücker et al., 1999), the Norfolk Broads (Boar et al., 1989), Sacca di Goro lagoon (Fogli et al., 2002), Rožmberk fishpond (Cizkova et al., 2001b), Lake Fertő and Lake Balaton (Kovács et al., 1989). Ostendorp (1989) lists 35 different lakes reported by different studies to have reed stands affected by die-back. In this thesis, the definition of reed die-back according to van der Putten (1997) is used: “a visible abnormal and non-reversible spontaneous retreat, disintegration or disappearance of a mature stand of common reed (*P. australis*) within a period not longer than a decade ($\pm 25\%$).

The loss of reedswamps showed similar stages and symptoms in many sites around Europe (van der Putten, 1997). The affected stands were characterized by lower stalk density and height, delayed flowering, bud death and stunted root growth in some cases but the main symptom was that the usually equidistant and homogeneous distribution of stalk growth changed. In the first stage, a mosaic of dense and less dense patches formed, then open water aisles and lagoons opened up in the reed stand, these expanded, reducing the area of reed to clumps and, finally, these clumps were toppled by wave action (Kovács et al., 1989; van der Putten, 1997) (Fig 1.).



Fig. 1: Aerial photograph of reed stand on Lake Balaton near Tihany affected by die-back, showing typical clumped growth. Photo © Civertan Bt 2000.

The similarity of the die-back process across many sites suggested a common process related to common causal factors. However, widespread investigations by a cooperation of European wetland scientists, EUREED, concluded that die-back could be related to several causal factors, and it is often not possible to separate cause and effect at the ecophysiological level (van der Putten, 1993; Kovács et al., 1994). The review of Ostendorp (1989) lists 26 different main causes in different studies of reed die-back, which can be grouped under the following categories: direct destruction on purpose, mechanical damage by waves, drifting debris or ice, grazing by waterfowl, rodents, herbivorous fish or livestock, water or sediment chemistry including eutrophication and rhizome fouling, and finally lake water level changes. Other assumed causes are incorrect harvesting practices (Kárpáti et al., 1987a), changes in salinity (Hanganu et al., 1999), changes of genetic diversity (Neuhaus et al., 1993), insects (Tscharntke, 1999) and fungi (Fischl et al., 1999).

Comparative studies during the second stage of the EUREED cooperation have refined this list, separating direct anthropogenic influence, such as filling in, intensive pollution and mechanical harvesting from the two main assumed factors which act together on the level of whole lakes: Van der Putten (1997) identified these as “water table management enforcing the effects of eutrophication”.

Eutrophication was a widespread problem of European lakes and coastal areas during the second half of the 20th century, and, in many lakes, eutrophication and reed die-back

happened simultaneously (Boar et al., 1989; Ostendorp, 1989). Laboratory experiments have shown that the accumulation of organic sediment has a negative effect on the growth of reed at the level of single stalks (Weisner, 1996), and some studies describe eutrophication as the main cause of organic sediment accumulation in reed stands (Schröder, 1979b; Dinka, 1986; Schröder, 1987; Boar et al., 1989).

On the other hand, water regime is well known to be the major controlling factor of wetland vegetation patterns (Mitsch and Gosselink, 2003). Wetland vegetation has an optimal range of water depth and flooding frequency (Wetzel, 2001), which controls the location of wetlands in relation to topography. Therefore, if the flooding regime changes, the location of the wetlands will also have to change. While this is a regular phenomenon on shores that still have their full natural zonation, artificial stabilization of coastlines and fixed land use patterns generally result in loss of littoral vegetation as a consequence of any form of water level rise.

The damaging effect of floods for reed wetlands has been the focus of several studies on Lake Constance (Krumscheid et al., 1989; Ostendorp et al., 2003) and other lakes (Rücker et al., 1999; Bodensteiner and Gabriel, 2003), while laboratory studies have proved that extremely high water levels during the spring growth period can result in loss of reed (Crawford, 1992). It is also known that the establishment or regeneration of reed stands can be facilitated by lowering water levels and sustaining natural water level fluctuation (Coops et al., 2004). During the period of reed decline on major Central European lakes, many Northern European and some Mediterranean lakes experienced an increase of reed area parallel to increases in water level fluctuation (Weisner, 1991; Maemets and Freiberg, 2004; Hellsten et al., 2006; Papastergiadou et al., 2006; Liira et al., 2010).

Since oxygen availability for the underground organs of plants is one of the most important limiting factors of vegetation in wetlands (Crawford, 1992), and water level fluctuations and currents have an important role in the aeration of the sediment (Schröder, 1987; Urbanc-Berčič and Gaberščik, 2004), there is a strong possibility of a connection between water level fluctuations and reed die-back and expansion.

Sediment redox potential can affect reeds through different processes. Reed and other wetland plants have a convective aeration system that supplies oxygen to the underground organs through a network of aerenchyma (Armstrong et al., 1999). The ability of this system to sustain growth in the rhizome tips, which are far from the source of oxygen depends on the resistance of the aerenchyma to convective flow and the oxygen demand of the surrounding sediment (Crawford, 1992). If the oxygen demand of the sediment is high,

then the activity of the apical meristem of the rhizomes is discontinued and the growth of the rhizome stops (Armstrong et al., 1996a). The short-chain volatile organic acids that are produced by the decomposition of organic matter in an anaerobic environment (Cizkova et al., 1999; Armstrong and Armstrong, 2001) can also have a toxic effect on the reed plants, often leading to the formation of callus in the aerenchyma and thus inhibiting convective air flow (Armstrong et al., 1996b). Some studies also argue that the overload of nitrogen in the sediment and water column leads to a decrease in the reserve carbohydrate stock of the rhizome (Cizkova et al., 2001a). According to Fogli et al (2002), the low redox potential in the sediment can also lead to the formation of sulfide compounds which have a negative effect on reed growth. Continued high water levels probably also interfere with the regeneration process of reed from seedlings, since germinating reeds do not survive even a few centimetres of flooding (Rea, 1996)

In addition to these hypotheses and results, the review of Ostendorp (1989) stresses the importance of a historic approach in the research of reed die-back: “Understanding the complex environmental changes in the littoral zone of lakes needs a historic perspective”. The establishment of the reed zone and changes in reed area typically happen at a rate of 1-10 m/year, which is roughly the rate of extension of the rhizome (Haslam, 1969; Rodewald-Rudescu, 1974). This means that changes of several hundred meters can take up to several hundred years and that the current state of the littoral reed belt of lakes can reflect events that happened decades ago.

In historic times, Lake Balaton was closely connected to a system of tributary wetlands both in the hydrological and ecological sense. Therefore, the ecological history of the lake is discussed together with these wetlands.

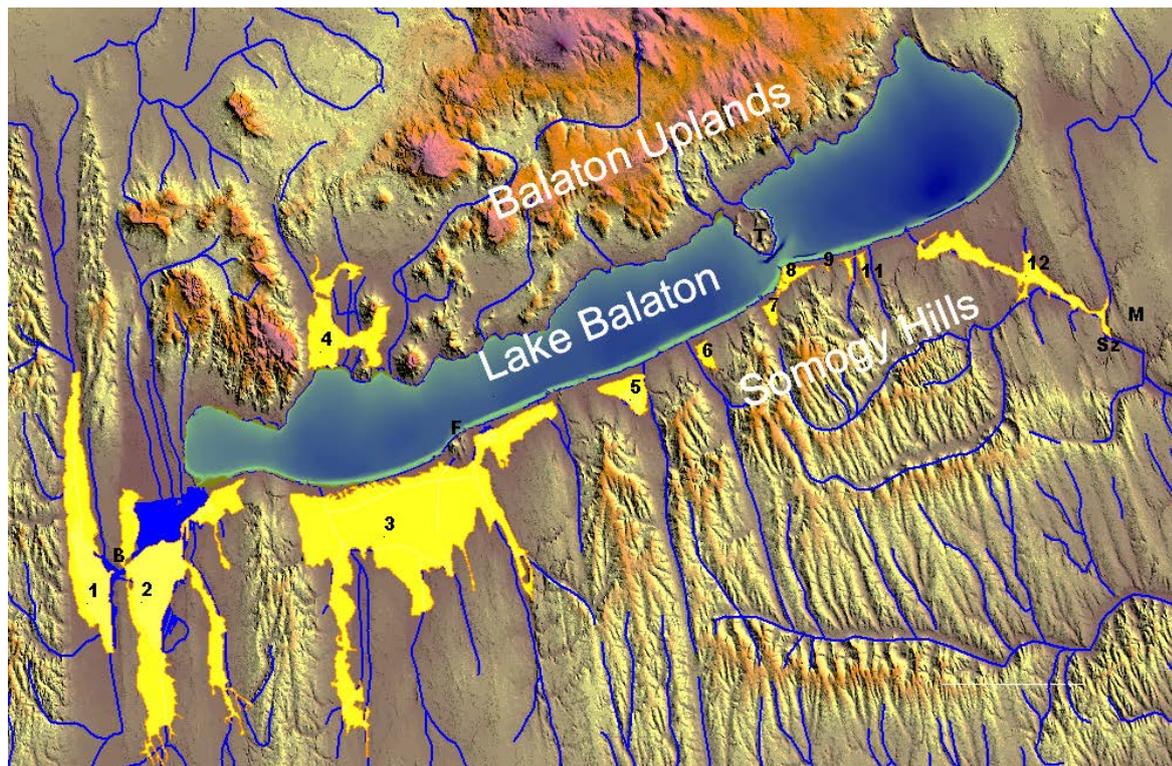


Fig. 2: Lake Balaton and its original surrounding wetlands. T: Tihany, F: Fonyód, M: Mezőkomárom, Sz: Szabadhídvég, B: Balatonmagyaród. 1: Kis-Balaton Western Basin, 2: Kis-Balaton Eastern basin, 3: Nagy-Berek, 4: Tapolca basin, 5: Szemes valley, 6: Ószöd valley, 7: Köröshegy valley, 8: Szántód wetland, 9: Zamárdi valley, 11: Balatonendréd valley, 12: Sió valley

1.2 Study area: Lake Balaton

The present-day area of Lake Balaton at the average water level (+100 cm, 105.09 m above the Adriatic sea level benchmark which is used throughout this thesis) is 597 km², and its average water depth is 3.3 m (Virág, 1998; Zlinszky et al., 2008) (Fig. 2). The lake has an elongated shape in SW-NE direction (Fig. 2), with an approximate length of 77 km that is usually divided into four main basins: the Keszthely, Szigliget, Szemes and Siófok basin (from SW to NE). The Zala river enters the Keszthely basin from SW, supplying about half of the total inflow, most other rivers flow into the second basin, and the Sió canal drains the fourth to the Danube River. The long-term average water balance of the lake (rounded to 1 decimal place) is 0.6 m precipitation on the surface of the lake, 0.9 m inflow, 0.9 m evaporation from the surface, and 0.6 m drainage through the Sió (Virág, 1998). The Northern shore of the lake is sheltered by the hills of the Balaton Uplands, while the southern shore is less protected. The prevailing wind is also from the NW, perpendicular to the main axis of the lake. Large grained, sandy sediments are maintained by wave action and currents on the southern shore, creating a sandbar about 200-300 m

wide, while fine-grained organic sediment mainly accumulates in the bays of the Northern shore (Entz and Sebestyén, 1942).

On a geological timescale, Lake Balaton is a very young formation, existing since 15000 YBP as separate sub-basins with a maximum water level of 112 m ASL (Cserny and Nagy-Bodor, 2000) but permanently joined since 5000 YBP. Several hypotheses exist for the formation of the lake, detailed especially in Horváth and Dombrádi (2010), but the general view is that the lake was formed by neotectonic processes changing the previously established drainage network and creating a series of depressions (Síkhegyi, 2002; Fodor et al., 2005). The strong seiche- and wave-induced abrasion, which occurred during the short flood periods when these were joined, eroded the ridges between the sub-basins and finalized their connection. The area still shows considerable tectonic activity (Gráczer et al., 2012) and differential uplift (Bendefy, 1964; Joó, 1992).

Human activity on the region clearly started earlier than the formation of the lake: The establishment of a single permanent lake basin instead of the periodically connected sub-basins is dated to the late Neolithic. During this period, many of the present-day settlements around the Lake were inhabited and some of the land was used for agriculture. Without discussing the complete history of human presence on Lake Balaton, (Bendefy and V. Nagy, 1969; Virág, 1998, 2005), it is necessary to draw attention to a key point: The landscape around Lake Balaton has always been actively modified by humans and thus the “original”, “natural”, “healthy” state of the lake can only be discussed when this is taken into account.

Water levels of historic times can be estimated from archaeology (Bendefy and V. Nagy, 1969), abrasion forms (Cholnoky, 1918), dendrochronology (Kern et al., 2009) and historic maps (Zlinszky, 2010). The water level was similar to the present-day situation or slightly lower during the Roman age (Virág, 1998) and remained at the same level during the early Medieval period, probably not exceeding the level of 105-106 m ASL until the 13th century. Colder climate and increased precipitation during the Little Ice Age (ca. 1500-1700 A. D.) occasionally raised water levels up to 107-107.5 m ASL during the 17th century (Sági, 1968).

The first map of Lake Balaton surveyed by geodetic methods (Krieger, 1776b) is also the first map that clearly depicts reed wetlands around the lake and in the neighbouring valleys. The First Habsburg Military Survey (Jankó, 2007) was also conducted during the late 18th century and covers the whole watershed of the lake. The first major interactions with the hydrology of the Lake Balaton watershed must have happened in the centuries prior to this

map: the First Military Survey already shows a large number of water mills and their corresponding mill dams and ponds. Most of these cannot be accurately dated: some are of medieval origin and persisted through the Ottoman occupation of the area, others were probably destroyed during the period when Lake Balaton was a zone of border conflict between the Austrian and Ottoman Empire and then rebuilt afterwards.

1.2.2 Wetlands surrounding the lake

The Krieger map and the First Habsburg Military Survey show the vast expanses of reed wetlands connected to the lake, adding up to a lake and wetland system with a total area of nearly 900 km². Today, these basins hold small rivers and streams that flow through wetlands and fishponds before entering the lake. The length and area of these river valleys decreases from the southwest to northeast (Fig. 2). The Kis-Balaton wetland was slightly upstream of the Lake along the Zala river and had two basins of 18 and 50 km² with average ground elevations below 106.5 m ASL, the downstream one closely connected to the lake. The ecological history of Kis-Balaton is summarized in detail by Dömötörfy et al. (2003). This wetland area served as a pilot site for wetland vegetation studies for more than a century, since it was (and is again) one of the largest continuous reed wetlands in Hungary. Botanical studies of this area were initiated in the late 19th century by the Hungarian Geographical Society: Lóczy (1913) and Cholnoky (1918) conducted the first geophysical studies dealing with the formation of the Kis-Balaton basin while Borbás (1900) wrote the first botanical monography of the area. Soó (1930) extended the species list published by Borbás, conducted phytosociological surveys and already pointed out that the diversity of species and communities found in Kis-Balaton exceeds those of Lake Balaton. Kéz (1931) mainly dealt with the tectonic history of the region but also described the loss of open water to reed and to wet meadows as a consequence of the canalization of the Zala river. This publication maps the process of drainage in time, and includes the earliest known aerial photograph of Kis-Balaton. The role of Kis-Balaton in reducing the pollution and sediment load of Lake Balaton is also first described by this publication, and sedimentation of the Keszthely basin and later eutrophication of the whole lake (Herodek et al., 1988) led to an initiative to restore the wetland to its original state. Using mainly historic maps and levellings, Lotz (1978) reconstructed the original extent and water level of the lake and, after funding was secured, the upstream basin of the former wetland was flooded again by a system of dykes in 1985, and the downstream basin partially in 1992, while final restoration is still under way to date. Thanks to the accumulated knowledge

about this area and the interest of national stakeholders and hydrobiologists, the process of vegetation transition was very closely followed and documented. The aerial photo-based study of Szeglet et al. (1999) summarized the changes of the reed-water boundary from the drained state in 1950 to the reconstructed phase. Before the flooding, a vegetation survey by terrestrial geodetic methods was also undertaken in an effort to measure and estimate the primary production and the nutrient retention capacity of Kis-Balaton (Kárpáti et al., 1983). The long-term efforts of P. Pomogyi et al (1997; 1998), which involved a combination of fieldwork, stereoscopic evaluation of orthophotographs that were collected annually or even twice a year and later other airborne methods (Zlinszky et al., 2011), have resulted in a good understanding of the succession sequence from meadows or open water to reed wetlands. The factors governing the re-establishment of floating island vegetation have been investigated by Somodi and Botta-Dukát (2004). The review of Fisher and Acreman (2004) states that the nitrogen and phosphorus retention effect of wetlands only lasts a few decades until the absorption capacity of the sediment is saturated. This has also been identified on Kis-Balaton and its role in water quality management of Lake Balaton is a subject of dispute (Somlyódy and Herodek, 1997; Tátrai et al., 2000). The importance of the recreated Kis-Balaton as a wetland habitat is beyond question and was also recognized by the Ramsar Convention. Thus, monitoring the ecological status of the vegetation received more attention, leading to the first ecophysiological surveys identifying reed die-back (Engloner and Gubcsó, 2001). The rest of the tributary basins of the lake are not surveyed in such detail, partly because of their smaller size, more difficult accessibility and less prominent hydrological position. The largest wetlands are supported by several smaller streams draining the waters of the hills on the North (Tapolca Basin) and the South shore (Nagy-Berek) (Fig. 2). The Nagy-Berek was connected to the second basin of the lake, with an average area of 90 km² below the historic water level. The Tapolca Basin, which is surrounded by volcanic mesa hills, has about 28 km² of area lying lower than the historic water level of the lake and holds a wetland system that is still loosely connected to the reed belt of Lake Balaton. Most of the other reed stands are located in relatively short and narrow tributary valleys of the southern shore of the lake. The Szántód wetland is on the south shore, not in a valley but inside the basin of the lake itself, enclosed by sand spits deposited by currents opposite the Tihany peninsula. The Sió wetland is the upstream part of the Sió valley draining the waters of the lake into the Danube. Each of the southern shore tributaries is separated from the lake by a sandbar, which was sustained by waves. Compared to the present-day situation, the large connected area of open water and

reedswamp increased evaporation rates, which is believed to have created an equilibrium between incoming water and evaporation to such an extent that outflow along the river Sió was limited to rare flood events. During periods of high precipitation, the expanding water surface would have increased evaporation, thus introducing a feedback loop stabilizing water levels.

Local drainage and canalization reduced the water level and areal extent of these areas, mostly during the late 19th and early 20th century (Józsa, 1899; Lotz, 1973). The Zala river was canalized between 1920 and 1928 for its final 10 kilometres through Kis-Balaton before entering the lake. As the water levels dropped, wet meadows were formed in the area previously occupied by reeds, and reed colonized the former open water areas, reducing the open water area from 13.9 km² in 1990 to 0.68 km² in 2010. The Nagy-Berek wetland system was drained between 1908-1911. Before this period, Nagy-Berek was a swamp of 87 km², including 23 km of regularly harvested reed stands. During the drainage process, a system of canals was built, and since the terrain level of the Nagy-Berek wetland is well below the water level of Lake Balaton, the water has to be pumped up into the lake to the present day. Large areas of the remaining wetlands were subsequently converted to fishponds, where conditions favourable for fish production are sometimes maintained through artificial fertilization and often alien species are introduced. The adverse effect of these fishponds on the local fauna is well studied and exists up to the present day (Takács et al., 2007; Erős et al., 2012).

The tributary basins of the southern shore were originally separated from the lake by the sandbar which had a width of 10 km, but since the inflows connecting these wetlands to the lake were not regulated, fish could enter from the lake and spawn in the wetlands. These spawning areas were lost through drainage and, in the cases where they remained, the connections were often lost through separation by sluices and pumping stations. The construction of a motorway along the southern shore of the Lake and through the remaining wetland valleys involved filling in of some still existing wetlands and fishponds, and generally disrupted the already heavily stressed ecological contact between the southern part of these wetlands and Lake Balaton.

This system of connected habitats has a stabilizing effect (Standovár and Primack, 2001) on the biodiversity of the Balaton catchment as a whole, and supports a range of wildlife that would not be possible in the lake or the wetlands alone. Therefore, the reed areas within the lake have to be conserved and the connectivity of wetland habitats in the landscape should be ensured.

1.2.3 Water levels of the lake in literature

The highest water level of Lake Balaton was probably reached around 10000 YBP, according to Timár et al. (2010). The highest water level of the lake clearly documented by measurements was 107.14 m for the year 1824 (Fig. 28). Bendefy and V. Nagy (1969) describe water levels of 110-112 meters on Lake Balaton on the basis of historic documents and some maps, but these are subject to language and cartography interpretation errors and are by no means certain. Typical decadal water level fluctuation could reach four meters, and water levels even dropped to 103 m ASL (two meters below the present water level) during an extremely dry period in the early 1830s.

The first known effort to control the water level of the lake was the demolition of the dam of the Balatonkiliti mill downstream of the outflow of the lake in 1847 in order to protect agricultural land from flooding (Virág, 1998). The full drainage and canalization of the Lake was already planned in the late 18th century, but this was not realized because of lack of funding, until nearly a century later.

Construction of a railway line along the southern shore started during an extremely dry period in the mid-19th century. It was sited along a sandbar between the lake and the agricultural areas of the shore. The highest previously recorded water level was 106.73 m ASL, therefore the elevation of the railway tracks was fixed at 107.61 m and considered as a sufficient safety margin. However, during the winter of 1860-1861 and 1861-62, blocks of ice were deposited on the tracks by storms.

Regulating the water level was estimated to be cheaper than relocating the track, so the expansion of the Sió canal was funded by the railway company on the condition that the water of the lake had to be lowered by at least a meter. The sluice and lock system at the outflow of the Sió river from the lake was opened in 1863, starting artificial regulation of the water level of the lake. This date also marks the start of regular water level recordings: A water gauge was built and levelled as part of the shore protection walls near the outflow.

The lowest regulation water level was fixed at 104.09 m ASL, (marked as a water level of 0 cm), and the maximum regulation level was planned at 105.09 m (+100 cm). Despite the regulations, the water level of the lake dropped below the 0 level during the dry summer of 1863, although the sluice remained closed.

The 0 water level was reached in 1865, but stayed low during the next years and reached a recorded minimum of -45 cm in 1866. Water levels increased during the next decade and by 1879, the recorded maximum of +193 cm was reached, adding up to a decadal water level fluctuation above 2 meters despite regulation. Many of the water level fluctuations

corresponded closely to the water level changes of Lake Fertő, (Dobesch and Neuwirth, 1979) which means they were mainly a result of variations in climate. The capacity of the Sió canal was limited to 10 m³/s, which is less than the average inflow of the tributaries and very low compared to the maximum. During the 1880-s, minima were regularly below the 0 mark and maximum water levels exceeded 140 cm.

1.2.4 Changes in the water level of Lake Balaton during the 20th century

The establishment of the railway line was also beneficial for tourism. However, the lake often flooded the newly established resorts when it reached the level of 120 cm but was too shallow for bathing on the southern shore during low periods. The capacity of the Sió canal was expanded from the original 10 m³/s to 20 m³/s in 1904, and further increased during the refurbishment of the sluice in the 1940-s to 40 m³/s and the 1970-s to 80 m³/s.

Since the initiation of the recordings, the lowest water level only dropped below the 0 benchmark on two occasions: in 1921 and during the drought of 1949, which was also the long-term minimum of -23 cm. During the first half of the 20th century, maximum water levels sometimes reached +150 cm but remained below +120 cm since 1950 (Fig. 36). After 1972, the water level variations were further constrained by raising the lowest permitted water level to +70 cm. Bauxite mining on the Balaton Uplands required lowering of the karst water table of the north shore, drying many springs feeding tributaries of the lake. This and another drought led to a minimum water level of +57 cm during 1957. The inflow of water was sufficient to keep the level within the regulation margins until 2000, the start of an extraordinary drought period of four years. The sluice of Sió was closed during May 2000 at the water level of +104 cm but water levels dropped and reached a minimum of +23 cm during the November of 2003.

1.2.5 Reed wetlands of Lake Balaton

The establishment of reed on Lake Balaton was probably governed by climate, and preceded the formation of the lake itself. The earliest proven palinological record of the presence of large stands of reed in the immediate neighbourhood of a precursor of the lake can be dated to 10000 years before present (Nagyné Bodor et al., 2000), which coincides with the time of the probable maximum extent of the lake (Timár et al., 2010). Reed is typically known to inhabit sheltered bays on gently sloping shores or closed wetland basins, but is also to be found as a weed on relatively dry disturbed surfaces as long as its roots have a sufficient water supply. This dissertation follows the general practice in Hungarian literature (Pomogyi et al., 1998; Virág, 1998) that reed wetlands are not necessarily

completely covered by *Phragmites australis*: the typical emergent littoral vegetation of Lake Balaton is dominated by reed but also include patches of *Salix*, *Populus* or *Alnus* trees and areas where reed mixes with or is dominated by *Typha*, *Carex*, *Glyceria* or *Schænoplectus*. Since the mosaic of these species forms a single distinctive habitat type on Lake Balaton, unless otherwise stated, the terms “reed belt”, “reed vegetation” or “reed wetland” include these sub-habitats as well (corresponding to the Hungarian term “nádas”). At present, reed wetlands are more abundant in the sheltered bays of the Northern shore and continuous reed belt can be found only in the westernmost part of the southern shore. The cause of this pattern could be wind shear, ice scouring or the lack of organic sediment on the southern shore (Virág, 1998).

The Krieger map of 1776 shows 8.75 km² of reed on the north shore and 2.95 km² on the southern shore, which is remarkably similar to results of the survey of 1993 (8.99 and 2.29 km² respectively), although the water was nearly 2 m above present-day levels. Reed areas of settlements around the lake during the late 19th century were documented by Jankó (1902): 6.32 km² on the Northern shore, which is somewhat smaller than the previous records. This is probably explained by the extinction of major reed stands on the higher areas of the shore during the periods of water level around 103 m ASL. Large areas of the lake bed near the shore were uncovered by water during these periods.

While the extent of the reed belt along the Northern shore is clearly known and only changed significantly in the last centuries at places where harbours and beaches were built, the history of the reed zone on the southern shore of the lake is a subject of dispute. Borbás (1900) described the absence of reed from all the southern south-western and south-eastern shores of Lake Balaton, except for a few instances of low and loose stands. Major reed wetlands were only documented further from the immediate shore, landward from the sandbanks, such as in the enclosed tombolo triangle of Szántód (a tombolo is a sand spit system formed by an island deflecting water currents). The comprehensive book on Lake Balaton by Entz and Sebestyén (1942) confirms this and describes reed on the Southern shore only growing in sheltered patches created by human modification of the shoreline. After this was published, detailed maps of the shore areas of the Festetics estate (surveyed in the 1930-s at a scale of 1:4000) were discovered that show many kilometres of reed along the Southern shore of the second basin, on the northern side of the sandbar separating Nagy-Berek from the lake. Thus, the time of reed establishment on the Southern shore of the lake remains debated to date.

Botanical and especially phytosociological investigations of the reed stands of Lake Balaton were initiated by Vince Borbás (1900) and continued by Rezső Soó and later László Tóth (Soó, 1938; Tóth, 1972). According to their results, homogeneous and dense reed stands occupied the boundary of wetlands to open water (*Phragmitetosum*), where waves regularly mix the water column, with submerged macrophytes present in the internal, flooded area of the stand (*Hydrocharosum*, *Fontinalosum*), and *Typha* and *Carex* species mixing with reed towards the shore (*Typhetum/Magnocaricosum*).

Starting with the late 1950-s, the nutrient cycle of the lake was extensively studied, and in order to evaluate the role of the shore zone in this, the element composition and accumulation of reed was investigated. Podani, Kovács and Dinka conducted surveys of the stoichiometry of reed around the lake (Dinka et al., 1979; Podani et al., 1979; Dinka, 1983), also focusing on the bioaccumulation of pollutants (Dinka, 1986) and the decomposition of litter (Dinka et al., 2004). The function of periphyton on reed in relation to nutrient load was assessed by Lakatos et al. (1981).

1.2.6 Reed die-back on Lake Balaton

The decrease of reed area is not a new phenomenon on Lake Balaton: Cholnoky (1918) writes “*approaching the shore, permanent reed stands appear in 1 meter deep water. Reeds can also be found in deeper water, but those are dying back. After having colonized the area during longer periods of low water, it retreats when the water level rises*”.

Tóth et al. (1961) were probably the first to report the clumping typical for die-back reed on Lake Balaton, in a patch in Szigliget during investigations of biomass production. Subsequent aerial imaging of the Szigliget Bay between 1971 and 1975 provided an exact record of the onset of reed die-back there: the area of the reed belt is reported to have expanded between 1971 and 1973, with the loss of area starting in 1974 at this site (Kárpáti and Varga, 1976). The vegetation map of Kárpáti et al. (1987b) also showed signs of reed die-back in the Bozsai Bay. According to Kovács et al. (1989); Kovács et al. (1994), during the second half of the 1970-s and the early 1980-s, reed die-back became a widespread phenomenon on Lake Balaton. Descriptions of the symptoms match reports of reed die-back on other European lakes: stalk density inhomogeneities first appeared in the internal part of the reed stand, these opened up into gaps and channels between patches of reed, and then the patches broke up into single clumps of 0.5-3 m diameter, which were finally toppled by waves. At the final stage, a new water-reed border formed where the gaps and lagoons initially appeared. To the author’s best knowledge, no systematic anatomical or

histological investigations have been undertaken on Lake Balaton with the aim of identifying the extent of reed die-back at the single stalk level. Engloner and Gubcsó (2001) studied the histological consequences of reed die-back on Kis-Balaton. Images of histological sections from reed collected on Lake Balaton by Fischl et al. (1999) for mycological studies (kindly shared in original by Prof. Fischl) show similarity to those of laboratory-induced reed die-back published by Armstrong (1996a), which also suggest that “European reed die-back” affected the reed belt of the lake.

Since the eutrophication of Lake Balaton also peaked during this period, this was first suspected as a cause (Dinka et al., 1979; Podani et al., 1979; Kovács et al., 1989). A review of die-back lists several influencing factors: increasing wave energy, changes in the water chemistry, eutrophication, parasite insects, grazing by rodents, waterfowl or fish (Kovács et al., 1994). Wave energy was assumed to have increased due to the building of concrete shorewalls, and the soft sediment deposited in their foreground was regarded to be too unstable to support reed. Artificial gaps in the vegetation cut by anglers in order to aid access to the open water became more widespread during this period. Mechanized reed harvest was also identified as a cause of reed area loss, since the weight of the machine could crush the rhizomes (Kárpáti et al., 1987a). Eutrophication was described as affecting reed health through excessive nitrogen loads that are known to cause loss of sclerenchyma in the stalks and by excessive accumulation of fine-grained particulated organic matter. Kovács et al. (1989) identified the presence of toxic short organic acids in the sediment of decaying reed areas on Lake Balaton. In summarizing the results of reed research on Lake Balaton, Virág (1998) described the raised water level as the potential cause of reed die-back on Lake Balaton, since the seiche action of the lake (Muszkalay, 1973) can probably not remove the accumulated organic sediment from the wetlands if the water level is not low enough.

Based on these studies, the redox potential was regularly measured in both the sediments of a healthy and a stressed reed stand on Lake Balaton from 2000 to 2010 (Herodek and Tóth in prep). The distribution of anoxic sediments showed that there was a close correlation with the pattern of reed die-back, since there was a lower redox potential in the stressed stands than in the healthy ones; and the most negative redox potentials were measured at a distance of 8-10 meters from the reed-water boundary. This is the zone where the formation of gaps and lagoons was typically observed. Increasing redox potentials were measured during the low water level period starting with 2000 in both stressed and healthy

stands, and reached the values characteristic for healthy reed in the previously stressed areas in 2003.

The changes of the reed-water boundary were difficult to measure in the field, but observations showed that the area of some reed stands increased during the drought.

1.3 Remote sensing for wetland research

Correct habitat management requires up to date knowledge of the status of the habitat and also information on how it reacts to changes in the environment. In case of reed, regular on-site vegetation mapping is limited by the difficulties of fieldwork in a wetland setting, and experimental studies that predictions could be based on are rare. This latter is because size and life cycle of the reed plant limits laboratory growth to cases where large tanks are available. Therefore, regular monitoring not only plays a role in simply following changes in the habitat (Erwin, 2009; Hunter et al., 2010) but often serves as a substitute of the classical ecophysiological experimental approach. Based on a time series, the reaction of the vegetation to a range of conditions can be measured but this has to take place over a large area to exclude local effects, and several decades might be necessary for a suitable variety of conditions. Therefore, aerial imagery time series can be used for reed monitoring and research (Csaplovics, 1982; Rucker et al., 1999; Whyte et al., 2008).

The main problem with classical aerial imagery is that it cannot be evaluated automatically for wetland vegetation but requires processing by a skilled operator in order to deliver quantitative measurements of vegetation extent and health. Single image methods usually do not separate different types of emergent littoral vegetation but stereoscopic viewing can bridge this gap (Csaplovics, 1982; Dömötörfy and Pomogyi, 1997).

The need for quickly available and accurate data over large areas fuels methodological development of a number of sensors for wetland vegetation classification and monitoring.

The potential of multispectral and hyperspectral methods has proved successful in many surveys (Schmidt and Skidmore, 2003; Belluco et al., 2006; Pengra et al., 2007; Wang et al., 2007; Siciliano et al., 2008; Artigas and Pechmann, 2010; Burai et al., 2010; Hunter et al., 2010). Nevertheless, passive optical imaging of vegetation has its limitations: the pixels of high spectral resolution images are typically larger (0.5-2 m) than aerial photograph pixels (0.1-1 m), and this causes aggregation of the spectral information encountered horizontally, which is difficult to resolve during classification (Belluco et al., 2006). The potential of spectrally based classification to identify different types of vegetation is always

controlled by the *de facto* differences in their reflectance spectra, which can be limited in some cases (Schmidt and Skidmore, 2003).

1.3.2 Airborne Laser Scanning as a tool for wetland vegetation mapping

Airborne Laser Scanning (ALS, also known as LIDAR) has a strong potential for use in wetland vegetation surveys. This method was considered because it is routinely used over very large areas. Also, sensor and application development is driven (and often funded) by the commercial sector for construction preparation and terrain modelling. Flight campaigns are less sensitive to illumination than passive sensors and are already operationally used for vegetation parameter mapping in forests (Hollaus et al., 2006).

Airborne Laser Scanning samples the Earth's surface by measuring the signal travel time of laser pulses between airborne platform and the terrain and back. The pulsating laser is mounted on an aircraft, the beam is directed towards the terrain by a mirror scanning perpendicularly to the flight direction, and the time is measured for each light pulse to return to the sensor as an echo after reflection from the surface. The travel time is directly proportional to the distance, which can therefore be computed (Wehr and Lohr, 1999). A dense set of points in a three-dimensional coordinate system is created from these distances combined with the position and orientation of the sensor platform (the aircraft). This latter is typically constantly tracked by a synchronized global navigational satellite system (GNSS, also known as GPS) and an inertial measurement unit (IMU) recording the rotations and accelerations of the platform with respect to a fixed (inertial) reference. Multiple points can be recorded from a single pulse, if different parts of the illuminated footprint have different distances from the sensor. This is the typical case in tall vegetation, which allows ALS to sample the vegetation canopy and the terrain surface below it at the same time (Fig. 16). ALS is traditionally used for mapping terrain topography (Wehr and Lohr, 1999), exploiting its ability to penetrate vegetation but removing the echoes from canopy as they are not informative for terrain modelling (Kraus and Pfeifer, 1998; Kobler et al., 2007; Fricker et al., 2012). Since the ALS points of the canopy provide a strong representation of the vertical and horizontal structure of the vegetation due to the high sampling density and accuracy, ALS holds potential for vegetation mapping. ALS mapping of vegetation structure is operational in forests (Hollaus et al., 2006; Jochem et al., 2011; Eysn et al., 2012; Lindberg and Hollaus, 2012), rapidly developing in shrublands (Streutker and Glenn, 2006; Riano et al., 2007; Garcia et al., 2011; Mitchell et al., 2011; Sankey and

Bond, 2011) but applications to riparian vegetation types remain rare (Nayegandhi et al., 2006; Mücke et al., 2010).

ALS has sometimes been used as a standalone tool to assess the hydrological roughness of floodplain vegetation for hydrological modelling but this has not been usually extended to a level of detail suitable for sub-habitat identification or wetland condition monitoring (Cobby et al., 2003; Straatsma and Baptist, 2008). Object-based analysis of derivatives of the point cloud has been successful in outlining riparian vegetation and streambed extent (Johansen et al., 2011). Multiple wavelength or multi-temporal surveys have proved to contain sufficient information for vegetation classification beyond the level of growth forms. For example, *Spartina* stands and the sediment accumulation they facilitate in a saltmarsh environment were successfully outlined using two consecutive ALS surveys (Rosso et al., 2006). Dual wavelength ALS has been applied by Collin et al. (2010) for mapping saltmarsh vegetation (17 categories) and very high accuracy (92%) was reached by multivariate classification of rasterized spectral and spatial ALS products, applying image processing methodology to a pseudo-image created by fusing different raster ALS products as if they were spectral bands.

1.3.3 Wetland vegetation mapping based on the fusion of ALS-derived data with other data

Due to its potential to sample ground elevation even below a canopy, the first applications of ALS in wetland ecology were for creating a very detailed digital terrain model (DTM), which was then applied as a background variable map to explain the patterns of different vegetation types classified from airborne true colour or infrared orthophotos. Knight (2009) used an ALS-derived DTM to calculate tidal inundation patterns in mangrove wetlands and locate potential mosquito habitats. Jenkins and Frazier (2010) also used ALS data for outlining upland swamps and identified vegetation categories within these boundaries on the basis of multispectral satellite data. Morris et al. (2005) combined ALS data with multispectral images to map intertidal habitats and evaluate the link between different vegetation categories and elevations above tide level. Gilvear et al. (2004) used an ALS derived digital surface model (DSM) as a background dataset for visual interpretation of hyperspectral data and found that the introduction of vertical structural information in addition to spectral properties increased the accuracy of visual interpretation.

While in the previously listed studies, ALS was used as a background or as an introductory step of vegetation classification to delineate areas in focus, rasterized ALS data can also be fused with imaging spectrometer images on a pixel basis. In this case, some actual spectral bands from the imaging sensor are combined with ALS data products in a single image file. This creates a data structure similar to a colour image with several channels (pseudo-bands) (Mather, 2006). Several such studies demonstrate a significant increase in wetland classification accuracy compared to using only spectral or ALS data (Geerling et al., 2007; Onojeghuo and Blackburn, 2011). In riparian areas of Australian savannahs, the fusion of QuickBird satellite images with several ALS-derived data layers allowed the identification of riparian vegetation by object-based classification (Arroyo et al., 2010). Hence, according to the cited literature, the combination of ALS and optical imagery produced the best results in vegetation mapping.

1.3.4 Enhancing the information contained in ALS point datasets

Single-band laser scanning data (e.g., 1064 nm) alone are considered to hold insufficient information to be reliably used for classifying wetland vegetation to health categories and genera. This is because the traditional approach to vegetation mapping from remotely sensed data involves classification on the basis of spectral differences (Mather, 2006). However, several methodological studies have shown that the information content of ALS data can be enhanced after collection by various processes including intensity correction (Höfle and Pfeifer, 2007), radiometric calibration (Lehner and Briese, 2010; Habib et al., 2011), and dropout modelling (Höfle et al., 2009).

Most commercially available ALS systems record information on the amount of backscattered energy, *i.e.*, the amplitude (often referred to as intensity) and, in the case of full-waveform recording instruments, also the echo width. This parameter seems to hold significant information for species identification (Moffiet et al., 2005; Brandtberg, 2007). The amplitude of the returning laser pulse depends on the reflectance of the sampled surface but is modulated by many other factors, including (but not limited to) the energy of the laser pulses, the atmospheric transmittance, the angle between the beam and the local surface normal (*i.e.*, the angle of incidence) and the distance between the ALS system and the target. Maps of echo amplitude can be used for visual interpretation of terrain features (Brandtberg, 2007) but the quantitative application of echo amplitude is only possible if most of these effects are removed and it can be calibrated to actually represent the optical properties of the surface (Lehner and Briese, 2010). Several solutions to this problem have

been proposed, ranging from applying a smoothing filter (Chust et al., 2008) to modelling signal path and local surface normals (Habib et al., 2011) and combining this with surface reflectivity measured with an active instrument (Lehner and Briese, 2010). If the radiometric calibration of the data points is reliable enough, reflectance can be used as one of the input variables for classification.

The presence of open water is important for wetland vegetation mapping but it is difficult to map through single-band ALS. A calm water surface is an almost perfect specular reflector and thus only reflects a high amount of radiation back into the sensor when observed at approximately nadir (*i.e.*, straight down, when the laser beam and the ray of the reflected echo coincide) (Höfle et al., 2009). At other observation geometries the amount of radiation reflected towards the sensor is often too low to be detected by the receiving unit and this is enhanced by the fact that the reflectance of water in the near infrared wavelengths, which are often used for ALS, is generally low. Therefore, echoes from a water surface are often not recorded at all. Brzank et al. (2008) proposed a point-based fuzzy classification procedure for water surface mapping that calculates the membership weights of the class “water” for each ALS point on the basis of the recorded amplitude, elevation and point density. Höfle et al. (2009) demonstrated a method based on the combination of radiometrically corrected intensities and relative positions of ALS points that allows high accuracy identification and outlining of open water areas. This latter solution involves the reconstruction of the missing ALS points (dropouts) that were not recorded due to specular reflection. The GPS time tag of the points, the scanning rate and the scan pattern, and segmentation of the points on the basis of the local surface roughness, the density of points with intensity values below a threshold, and intensity variation are combined to model this process.

2. Objectives

Lake Balaton is a protected natural area and there is considerable interest at national and international levels in sustaining the emergent macrophyte stands inside and near the lake. In order to implement adequate conservation measures, the natural state of the wetlands has to be assessed as a benchmark and the main causes for change have to be identified. Then a methodology for monitoring the results of these initiatives has to be developed.

- On the scale of the Lake Balaton watershed, the objectives were (1) to calculate the original unregulated water level of the lake, (2) to quantify the historic extent

and changes of wetland vegetation, and (3) to assess the effect of water level control measures on the reed wetlands of the watershed.

- On the scale of Lake Balaton itself, similar objectives were defined: (1) to quantify historic extents of littoral reed vegetation and changes in its area at a scale of a few meters, (2) to compare these with biotic and abiotic environmental factors and determine a possible target for conservation measures that can facilitate regeneration of the reed belt, and (3) to compare the observed key factor of reed die-back on Lake Balaton with results of reed die-back and regeneration studies on other lakes in order to find the common cause of reed area loss on many major European lakes.
- In order to monitor the habitat quality and health of wetland vegetation, the goal was to create a new surveying and mapping methodology that is relatively cheap, involves automatic data processing and can be applied over large areas in different settings.

3. Data and methods

3.1 GIS methodology in general

The high spatial variability of wetland vegetation calls for a spatially explicit investigation method, which is not typical for classical hydrobiology. Maps have always been used in conservation ecology, but Geographic Information Systems (GIS) allow quicker and more accurate analysis of spatial data through the calculation and visualization capabilities of database science, coordinate geometry and computer graphics. Since maps use a coordinate system to represent positions on the surface of the earth, the data they represent can easily be integrated in such systems, extended with information collected locally, processed, queried and finally visualized. The availability of satellite-based global datasets such as SRTM (Shuttle Radar Topography Mission) or GoogleEarth has facilitated the use of GIS in ecology, and the spread of Global Navigation Satellite System (GNSS, commonly referred to as GPS) technology means that spatially explicit data collection is within the reach of scientists without the need for an understanding of geodesy.

Data sources for spatially accurate investigation can be field surveys, remote sensing results or pre-existing maps. Processing remotely sensed data for ecological studies involves (i) finding a mathematical representation of the mapping process, (ii) fitting points of the data source to corresponding points in the spatial reference frame, and (iii)

simplifying the information content to extract the relevant information. Once these steps are complete and a map of the studied habitat is prepared, the extent and health state of wetlands can be compared in a time series to allow identification of die-back and regeneration. In the next step, comparing the quantified changes in extent or health with the local values of environmental variables supports the identification of controlling or influencing factors, which can be the targets of conservation efforts.

3.2 Historic maps of Lake Balaton: contents and properties

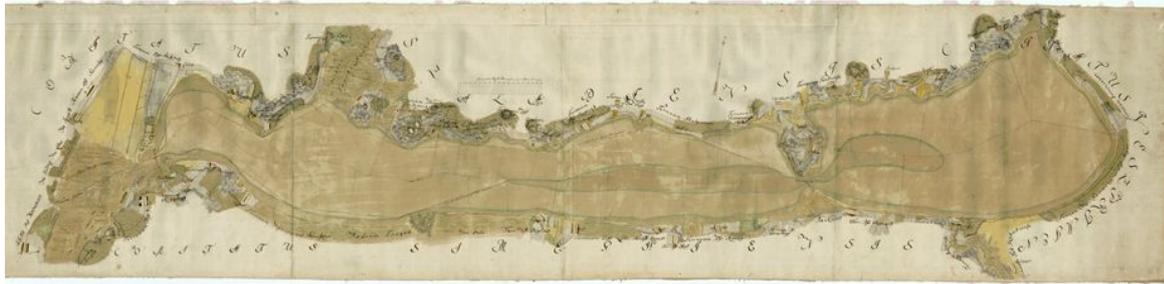


Fig. 3: Krieger's map of Lake Balaton (1776)

3.2.1 Surveying and content of the Krieger map

The canalization and eventual full draining of Lake Balaton was first planned under Queen Maria Theresia in the 18th century (Bendefy, 1973). The main reason for this was probably that the army of the Habsburg Empire had switched to central provisioning under Queen Maria Theresia, and this meant an expanding demand for agricultural products and also a strong need for water transport, which was the main means of moving large loads at the time. A royal commission was established in order to investigate the possibilities and costs of draining Lake Balaton. Sámuel Krieger, a young surveyor who graduated at the Military Academy of Gumpendorf in 1768 and worked as an official engineer for Zala County and the town of Sopron was selected by the commission to map the lake (Bendefy, 1972). We have no written record of Krieger's measurement methods, but the methods he probably studied at Gumpendorf are known from preserved textbooks. The high quality and accuracy of the map suggests that he used 'state of the art' methods of his time to complete it: i.e. triangulation, levelling and astronomical geodesy. This probably involved sighting of the most prominent landmarks with a telescope rule and marking the sighting direction on the draft of the map, then filling in the details by free hand ("*à la vue*"). This is supported by the fact that many high visibility landscape features are marked on the map even if they are not directly relevant to the content, such as churches, roadhouses or even large trees. Vantage points that offer a wide panorama over the lake are mapped with very high

accuracy (~10 meters). The scale of the map is 1:34560; 1 viennese inch to 500 viennese fathoms (Bendefy, 1973). The Viennese fathom was the standard length unit of the Austrian Empire at the time, it corresponds to 1.89 metres.

The surveyor summarized his measurements and recommendations to the royal committee in a detailed description in Latin (*Descriptio*) in five written pages and several adjoined tables. This was republished by Cholnoky in 1918 in original language to save it from possible destruction (Krieger, 1776a). The map shows the administrative territories of settlements around the lake, including the areas to be gained by the planned lowering of the water level. It also depicts the canal system Krieger planned: a canal from the mouth of the Zala River along the Northern shore to the deepest point of the lake, the outlet canal eventually planned to run from the straits of Tihany to the town of Fok (the present-day city of Siófok) and along the Sió River, and a canal along the Southern shore of the Szigliget Basin to collect the waters of the swamp. The area of the lake that would remain according to the maximum water level decrease of three and a half fathoms is also marked on the map (labelled *Residuum ex Lacu Balathon post demissionem ad pedes 20 juxta projectum 3ium*: remaining area of Lake Balaton after descent of 20 feet according to plan 3) (Fig. 4). Krieger proposed three separate plans based on the same canal system: decreasing of the water level by 1 fathom, 2 fathoms or three and one-third fathoms. He calculated the areas the settlements would gain and also the profits to be earned, if the resulting areas were used as meadows, according to plans 1, 2, and 3, summarizing these numbers in the tables of *Descriptio* (Fig.4).

fathoms is quite different and much less detailed. The bottom of the lake has a slight dip towards the south, with the deepest areas of the lake very near the Southern shore, not in the central part as mapped by Krieger. As the lake floor has hardly any relief, Krieger failed to notice this slight slope. He probably measured some points along the depicted line of the 3.33 fathom contour and assumed the deepest part to lie between them, which would be the bathymetry he illustrated on the map.

3.2.2 Surveying and content of the Habsburg Military Surveys

While mapping of single landscape features, such as a lake was often initiated by the necessity of data for construction, regional-scale maps were typically surveyed for military purposes. Before the use of geometry and projection systems as a basis for maps, the size of an area to be mapped was limited by the scale and the size of a sheet of paper. This was because the problems raised by the curvature of the Earth when joining several map sheets could not be solved.

The second half of the 18th century marked a revolution in geodetic surveying methods: the application of triangulation, precise levelling and astronomic geodesy, which finally permitted the creation of large series of maps covering whole countries and empires. Maps like the Cassini map of France, Müller's map of Bohemia, the first military survey of Norway, or the first military survey of the Habsburg Empire have been composed of several map sheets surveyed one-by-one, but fitted together as a system (Dumont and Debarbat, 1999; Krejci et al., 2009; Pettersen, 2009). The oldest known detailed map system depicting the whole catchment area of Lake Balaton is the First Military Survey (mapped at 1:28800), so it is a benchmark of a relatively natural state of the lake and its surroundings (Fig. 5).



Fig. 5: Cutout of the First Habsburg Military Survey, showing the similar map legends of the different sheets, and the level of mapping detail.

This map system is unique in its coverage of six present-day countries with a mapping scale finer than many national topographic maps today, and is thus an invaluable source for environmental history and conservation. With a level of detail including the size and shape of every single building, it demonstrates the state of the Austrian Empire before industrialization, intensive agriculture or long-distance transport.

The presence and extent of wetlands, rivers and fords was of high military importance, as these represented obstacles for transport that could only be traversed after considerable engineering efforts, if at all (Jankó, 2007). Although the First Military Survey has no defined map legend, the symbols used on the sheets only have minor differences. Ambiguities were solved based on the written description of the mapped areas which was noted during the mapping and a Hungarian translation published by Dobai (1983). According to the order of the Royal Military Council (Hofkriegsrat), these descriptions were required to contain “whether the swamps and wetlands can be traversed on horseback or foot, whether this is only possible in some seasons, if they dry out regularly” (Jankó,

2007). Areas described as under shallow water the whole year round with vegetation covering the surface were considered wetlands.

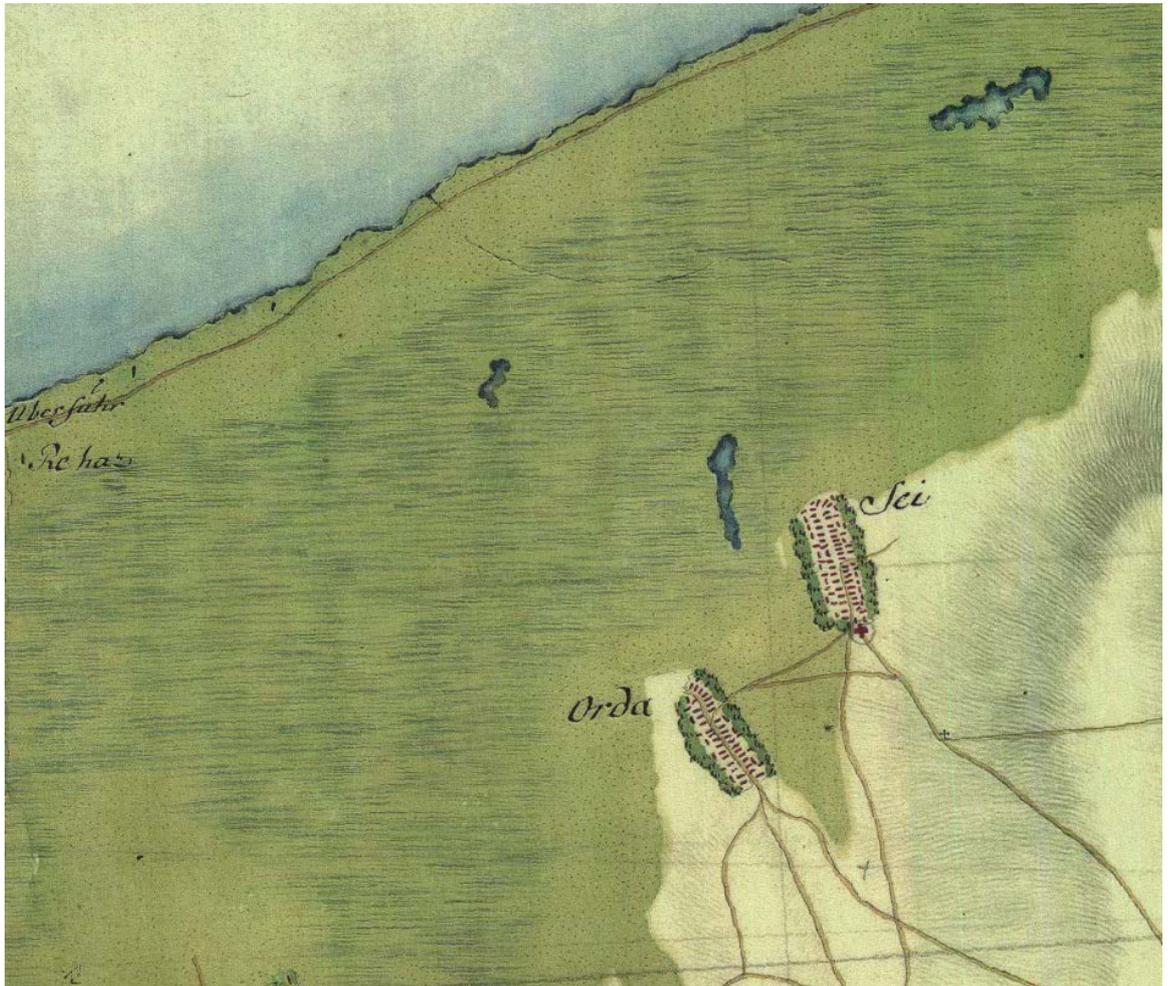


Fig. 6: Detail of the First Military Survey, showing dry areas, periodically wet meadows, wetlands and open water.

The symbols for these areas consequently involve fine grey or blue parallel hachures on the original maps, while meadows that are only wet during part of the year are marked differently (Fig. 6). During the several decades that it took to complete the First Habsburg Military survey, mapping methods, especially cartographic projections evolved considerably. Therefore, as soon as it was completed, a new mapping was ordered (the Second Military Survey), which had a unified map legend and a well-defined mathematical projection. The scale of the map was again 1:28800 but a uniform symbology was used and more points were surveyed to increase accuracy. This was completed in the Balaton region not long before the sluice on the Sió river was first opened, and so serves as a benchmark for studying the resulting changes (Fig 7).



Fig. 7: Cutout of the Second Military Survey, showing systematic map legend and accurately surveyed boundaries

The Third Military Survey was completed in the 1870s around Lake Balaton, now based on a metric system and a mathematical grid, and a scale of 1:25000 (Fig. 8). While the originals of the two previous map systems are well preserved in the Austrian Military Archives (Kriegsarchiv), the colour originals of the Third survey were handed over to Hungary after the separation of the Austro-Hungarian Monarchy, and some were lost in the Second World War. These sheets only exist in black and white copies with letters symbolizing the land cover categories.



Fig. 8: Cutout of the Third Military Survey, showing level of detail and elevation contours

Since the First Military Survey had no geodetic projection but consisted of a system of sheets surveyed separately according to a common ruleset and in a pattern that was aimed at enabling ideal fit of sheet edges (Jankó, 2007; Podobnikar, 2009), it cannot be georeferenced by reprojection. The First, Second and Third Military Survey map sheets are already scanned and distributed on DVD by Arcanum Kft. (Jankó et al., 2005; Timár and Molnár, 2006; Biszak et al., 2007) in georeferenced format. The Second and Third Surveys could be integrated in GIS by reprojecting, but the global accuracy of the First Military Survey was not sufficient for this, it had to be georeferenced.

The Krieger map did not exist at all in digitized form but had to be scanned from the original. This was kindly provided by the Archives of Zala County (Krieger, 1776c). The large size of the map presented some problems (180×40 cm) because high scanning resolution and reasonable file size had to be balanced. The original map was brought to Budapest from Zalaegerszeg and scanned on a wide format scanner (VIDAR Atlas 40) at the Dept. of Cartography and Geoinformation of Eötvös Loránd University. A resolution of 400 dpi and a colour depth of 24 bpp was selected but as the resulting file was over 2 GB it

could not be opened with most laptop or desktop PC-s at that time (2006). The Eastern and Western parts of the map were also scanned separately but even these separate files were too large to handle. The images were LZW (Lempel-Ziv-Welch) compressed and resampled to 250 and 100 dpi (SCP EasyScan 7.1).

3.2 Georeferencing historic maps of Lake Balaton

The next step was to transform the maps to fit a reference coordinate system, in this case, the Hungarian National Projection EOVS (Egységes Országos Vetület) and the HD 72 Geodetic Datum. This process is called georeferencing and involves the identification of points on the map with known coordinates in the reference projection system, calculation of a transformation (warping) function in the two dimensions of the image and finally transfer from the coordinate system of the scanned map sheet (defined by scan lines and pixels) to the GIS projection (defined by Easting and Northing, or Longitude and Latitude).

3.2.2 Georeferencing the Krieger map

Georeferencing of the Krieger map was carried out on the 250 dpi copy to save computing power. The crossings of the main streets of the villages on the map, the location of bridges over some watercourses and some mills and a church tower were used as ground control points. ER Mapper 7.01 software (Earth Resource Mapping Ltd., West Perth, WA, Australia) was used for georeferencing, and 36 control points were located on the Krieger map and the 1:1000 national topographic map of the region (surveyed between 1957-1980) which we used as a reference. Linear transformation was applied, and the RMS (Root Mean Square) error of the points remained under 70 pixels, or 350 meters. This corresponded to a maximum error of 1 cm at the scale of the map sheet. Mapping errors that may have been caused by the methods Krieger used are estimated to be of the same order of magnitude.

As a final step, Global Mapper 9 (Global Mapper Software LLC, Parker, CO, USA) and a powerful desktop computer were used to georeference the scanned and LZW compressed original file of 400 dpi, using the previously georeferenced and tiled image of 250 dpi as a reference. The georeferenced 400 dpi file was also cut into a mosaic of 6*3 separate GeoTiff files to enable handling of the tiles with conventional software. As a result of this procedure, the Krieger map can now be evaluated and distributed in full detail for further studies.

3.2.3 Georeferencing the First Military Survey

The Lake Balaton catchment area (5900 km²) is covered by 51 map sheets of the First Military survey. In order to have a sufficient spatial accuracy even in the case that some control points were incorrectly located, at least 10 reference points were created for each map sheet, adding up to a control point for every 17 km², on average. The amateur Hungarian art memorial protection portal www.muemlekem.hu (Kunszt and Kovács, 2012) offered a welcome opportunity for this: any building originating from the 18th century is almost certainly under at least local protection as an art memorial and thus listed on the site. The database of this network was queried for each village and suitable objects were located based on the address and present-day maps. Since each single building is shown on the Military Survey, the correctness of the database could be verified. After localizing a total set of more than 500 control points in this way, the constrained polynomial warping method developed by G. Molnár (2010) was used in order to ensure perfectly fitting sheet boundaries while using low-order transformation functions that keep the general assumption that the maps are free from large local errors (Fig. 9). This method involves separate cubic transformations for each map sheet based on the control points it includes, under the general constraint that the edges of the sheets have to fit exactly together. This is achieved by calculating the transformation equations based on the control points for each sheet, modifying this based on the transformations of the neighbouring sheets and then generating an evenly spaced grid of “virtual control points” to force the accurate warping. The result was a seamless mosaic of the 51 map sheets, covering the whole catchment of Lake Balaton.

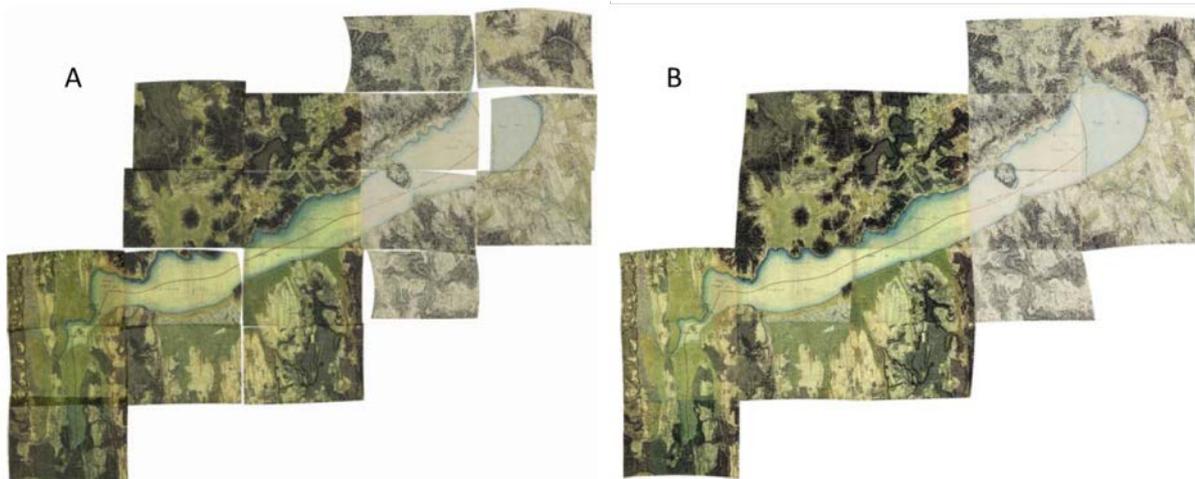


Fig. 9A: separately georeferenced map sheets of the First Military Survey around Lake Balaton, using individual third-order transformations. Sheets do not fit at boundary. B: separately georeferenced map sheets of the First Military Survey around Lake Balaton, joined with the constrained polynomial georeferencing method (third-order transformation). Sheets are near-seamlessly joined. Reproduced from Molnár (2010) with kind permission of G. Molnár.

3.3 GIS processing of historic maps to wetland data

In order to gain numeric datasets that can be used for wetland history assessment, the graphic information on the map had to be simplified and converted into a GIS feature. The most widespread and robust method for this is on-screen digitizing in a GIS by a skilled operator. This involves the creation of points, lines or polygons along the boundary of a selected object, usually by drawing over them with a mouse or stylus, zoomed in onscreen to enhance accuracy.

3.3.2 Historic water level of Lake Balaton from the Krieger map

The Krieger map was used to calculate the elevation of the water level at the time of surveying (1776). The present-day elevations of the bed of Lake Balaton are well surveyed, and the magnitude of the change can also be estimated by comparing digital bathymetric maps (Zlinszky and Molnár, 2008, 2009). Since the difference in elevation between the bathymetric maps surveyed in 1895 and 1975 were found to be negligible, the more detailed digital bathymetric model calculated from the most recent complete survey of Lake Balaton was used as a basis. The 3.33 and the 2-fathom depth contour lines were digitized from the georeferenced digital Krieger map at an on-screen scale of 1:20000



Fig. 10: The digitized 3.33 fathom bathymetric contour of the georeferenced Krieger map in Global Mapper Software used for processing. Cutout shows digital bathymetric model of Lake Balaton which was used for elevation calculations.

The XY points of the elevation contour lines were overlaid on the digital bathymetric model to add a Z (elevation) coordinate to each of them (Fig. 10). In this way, the coordinates of the points corresponded to the 3D position Krieger surveyed on the lake floor. The Z coordinate of the points was then increased by the depth of the corresponding bathymetric contour, so these new points would represent the position of the water surface (Fig. 11).

Although some errors were induced by a difference in detail between the bathymetric survey and the map of Krieger, the XYZ point cloud created marked a well-defined elevation range (Fig. 11). Since the procedure was completed for two separate contour lines (2 fathoms and 3.33 fathoms) of the Krieger map, these were regarded as two independent measurements of the same elevation of the water level, and their difference was checked.

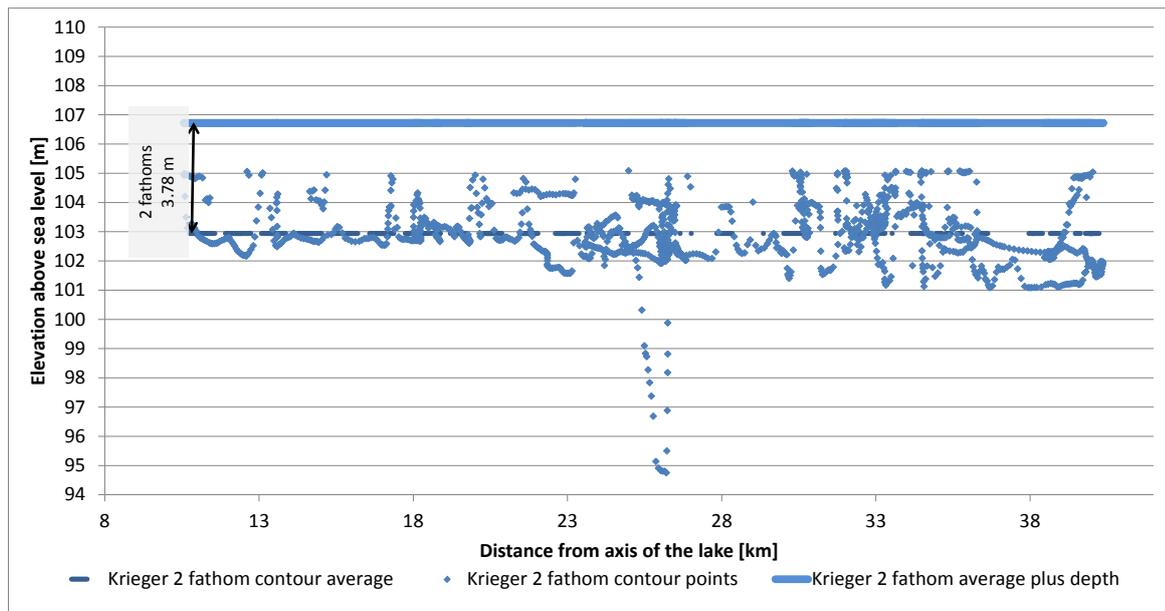


Fig. 11: Method of water level calculation from bathymetric contours of the Krieger Map. A profile was created from elevation points with XY positions digitized from the Krieger map and elevations read from the digital bathymetric model of the lake. The average elevation of these points was increased a constant elevation corresponding to the water depth these points represent in order to estimate the historic water level of the lake.

3.3.3 Wetland boundary mapping on the Military Surveys

On the georeferenced First, Second and Third Military Survey map sheets, the boundaries of all open water surfaces, forests and wetlands were digitized for the whole catchment of Lake Balaton, again at an on-screen scale of 1:20000. Minor errors of the boundary position and fit of coincident edges were corrected using the topology module of the open source GIS software GRASS.

In order to assess the elevation profile of the wetlands before major drainage works, the outlines of the 18th century reed wetlands (from the First Survey) were overlaid on the scanned and georeferenced 1:10000 present-day topographic maps of the region (Fig. 12). The base contour interval of the modern maps is 2.5 meters in areas with high relief, and 2 meters or even 1 meter in areas of low relief. Every intersection of the digitized historic wetland boundary and a present-day elevation contour was marked as a point and the corresponding elevation attached in the attribute table (elevations were standardized to the Adriatic sea level benchmark).

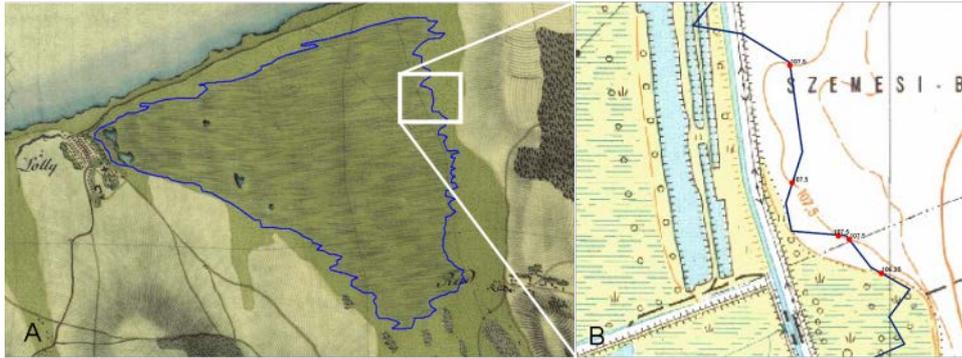


Fig. 12 A: digitizing the boundary of a wetland on the First Military Survey. B: creation of elevation points at the intersections of the wetland boundary with elevation contours.

The result was a set of points with XYZ coordinates marking the location and elevation of the boundaries of the wetlands in the natural state of the area. The visualization of both sets of points (lake water level from the Krieger map and wetland boundary elevations from the First Military Survey) was simplified in two dimensions, along an elevation axis, and a horizontal axis which indicated distance of the points from the mean direction of the lake (shifted by 10 km to the NW in order to get positive values for every point). Since the valleys are relatively parallel to each other and are perpendicular to the lake, these graphs show the slope profile of the valleys and the main elevation tendencies (Figs. 24, 25, 26, 27).

3.4 Historic aerial photographs

In the case of aerial photographs, the mathematical representation of the mapping process means the reconstruction of the straight path of light from each terrain feature through the optics of the camera to the film surface. To make this possible, special metric cameras are used in photogrammetry, which have well-calibrated optical properties. The level of detail, the spatial coverage and the radiometric accuracy (colour depth/contrast) of the image are in trade-off. The intensity of light reaching the sensor depends on the distance to the target, and the amount of energy reaching a given point on the sensor field (film or Charge Coupled Device, CCD) and, therefore, the signal-to-noise ratio also depends on the size of the sensing units (grain size of the film or resolution of the CCD), which in turn controls the spatial resolution.

3.4.2 Aerial photography surveys used

Adequate colour differentiation and covered area together with high spatial resolution was ensured by using medium-altitude (1500-5000 m), metric camera aerial image sets on large or medium-format films (30×30 cm; 23×23 cm; 6×6 cm). This was necessary since

the full width of the reed belt had to be covered together with some artificial reference points, and because the colour of water and vegetation could be very similar (green on green). Military imaging surveys from the summers of 1951 and 1963, and hydrographic surveys during the February of 1975 and summer 1987, 2000 and 2003, were obtained from military and hydrographic archives. Panchromatic films were used before 1980, true colour surveys were carried out in 1987 and 2000, and infrared false colour images were collected during 2003. Pixel resolutions were between 1 meter (1951) and 25 cm (1975)

3.4.3 Scanning and georeferencing of archive aerial images

The selected images from the years 1951, 1963 and 1987 were scanned from contact copies (1951, 1963) or enlargements from medium-format diapositives (1987) to 244 bpp (bits/pixel), 400 dpi (dots/inch) .jpg or .tiff files (UMAX PowerLook II, UMAX Technologies Inc., Dallas, TX, USA) and orthorectified using ER Mapper. The black and white images from 1975 were scanned by the data provider, directly from the large-format negatives. The images from 2000 and 2003 were scanned, orthorectified, georeferenced, and delivered as orthophotos by the manufacturer (Eurosense Hungary Ltd, Budapest, Hungary).

For the final step of the reconstruction of the survey process, the distortions caused by the central projection through a camera lens had to be corrected (orthorectification). ER Mapper 7 was used for this step, which was carried out in the same process as the georeferencing. The 1:10000 scale national topographic maps were used as a reference, and camera models were created on the basis of the image area and the camera parameters as supplied by the archiving company. A minimum of 6 ground control points were used, which were selected depending on the resolution of the image at building corners, road crossings, electric pylons or other ground objects. The 10-m resolution Digital Elevation Model was used as a basis for correcting distortions resulting from elevation differences within the images. Accuracy of the georeferencing was tested by creating a transparent overlay of the orthorectified image on the base map. If visible errors were present, the georeferencing process was repeated using different control points. The maximum accepted RMS error of a control point was 5 m.

3.4.4 Sampling strategy, wetland area measurements

To assess fine-scale changes of the reed boundary, 73 test sites of 200 meters length were selected along typical reed-dominated shores of Lake Balaton (Fig. 13). On the basis

of field experience, these were located to represent the full range of reed habitats on the lake and to be relatively far from beaches and harbours if possible, therefore, excluding the direct effects of human presence. Since reed die-back happens at the lakeward side of the stands, our study focused on the reed-water boundary and not the actual extent which is influenced by terrestrial processes as well. During this study, the reed areas between the boundary of the emergent vegetation to the open water and the official boundary of the lake (corresponding to the elevation isoline defined by the +100 cm water level and thus permanent) were calculated, and any changes in the position of the landward boundary were ignored.

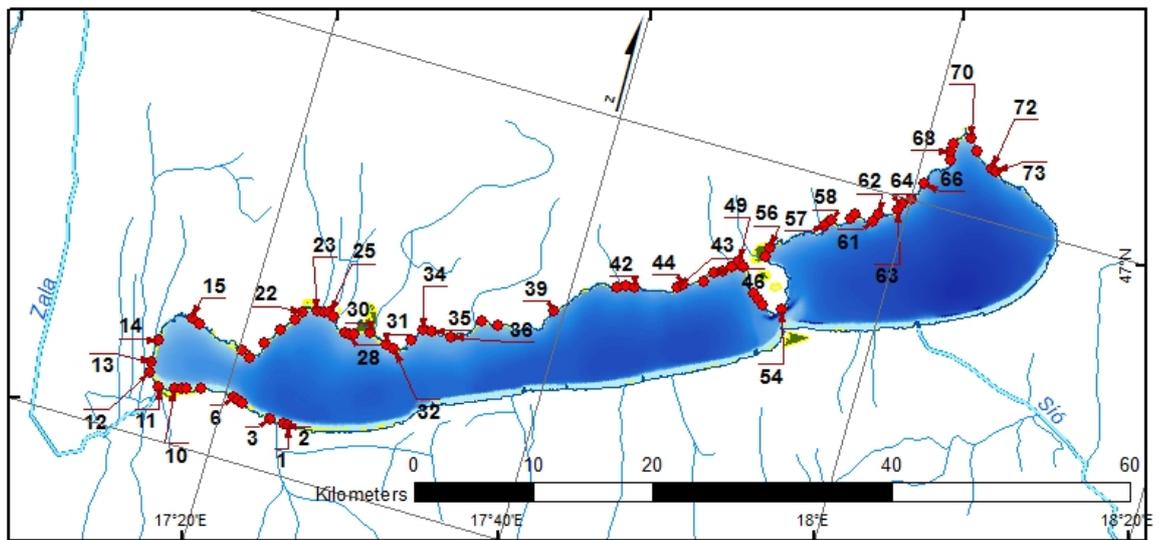


Fig. 13. Location of study sites around Lake Balaton.

The reed front was digitized at an onscreen scale of 1:100, resulting in pixel sizes of several millimetres, therefore, the boundary between reed and water could be followed with the accuracy of the image. The outlines of the lake and the test site were followed topologically by snapping the cursor to the nodes of the outline. The boundary of any reed islands or clumps in the sample areas was also digitized at the same scale and all resulting sub-polygons were merged to one feature for the calculation of the full area occupied by reed along the selected extent of shore. The resulting accuracy of each digitized vertex with respect to the base map corresponds to the local RMS accuracy of georeferencing added to the pixel size, therefore, adding up to 5+1 meter in the theoretical worst case. Water depths were obtained by overlaying the digitized reed polygons on a raster-based digital bathymetric model of the lake, which was calculated from the data of the latest lake bed survey (Sass, 1979; Zlinszky et al., 2008). For each studied period and site, the difference of the total reed area on the corresponding orthophotos was calculated (Fig. 14).

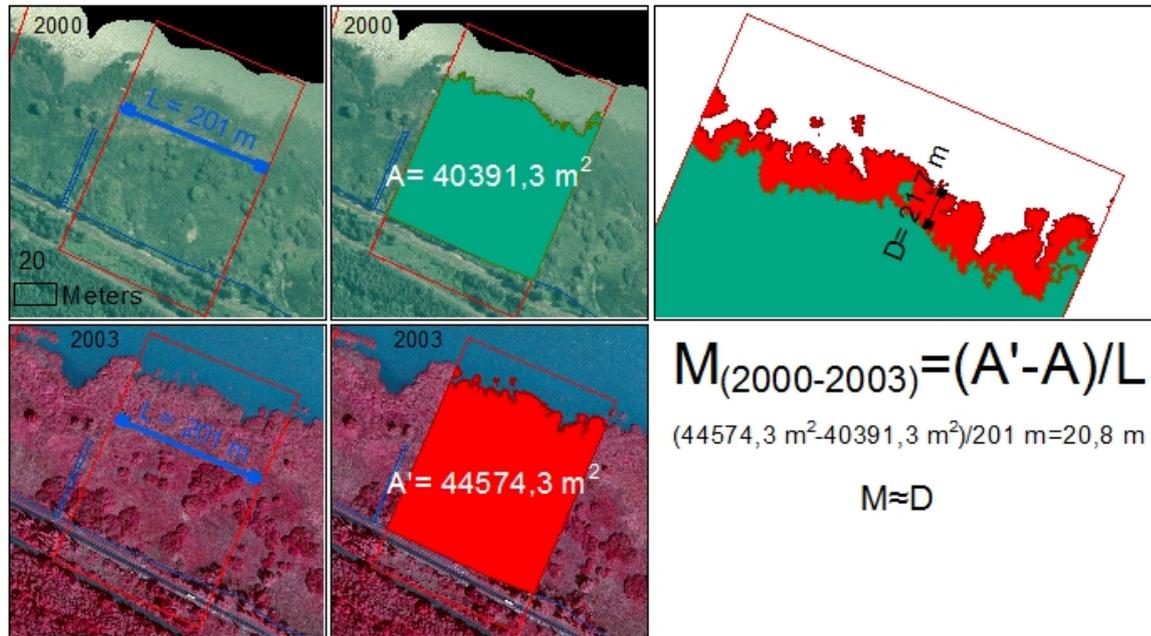


Fig. 14: Calculation of the front movement index. Aerial images show the extent of the same reed site in 2000 (above) and 2003 (below). The digitized and calculated area of the reed shows slight increase between the two studied years. The calculated overall front movement value for the study site closely represents the local front growth.

The actual change was then quantified by the reed front movement index, which is the difference between two surveyed years in total reed area for a sample site divided by the length of the sample site along the shore. Therefore, this index represents the change of reed area (in square meters) encountered along one meter of shoreline (in meters) and the dimension of the index is meters. If the area of a reed stand increased between two surveys, the reed front (as of this definition) moved towards the open water, or retreated towards the shore, if the area decreased. As this is a simplification of the actual changes, it means that the effective reed front of a studied site changed even if the actual main boundary of the standing vegetation and the open water remained constant while smaller open water gaps in the stand expanded or decreased. Standard deviations and standard errors were calculated, and significance was tested for the front movement indices in each study area with t-tests performed against an artificial dataset simulating zero change, with a simulated front movement index of zero for each study site.

To estimate the water depth the reed stands reached, the digitized polygons from 1951 were overlain on the digital bathymetric model of the lake (Zlinszky et al., 2008). ArcGis Spatial Analyst was used to extract the maximum water depth (based on the minimum elevation) of the bathymetric model raster within each reed polygon.

3.5 ALS survey and classification

In order to test the applicability of Airborne Laser Scanning for wetland vegetation health mapping, a dedicated airborne survey was organized.

The ALS data were collected during the EUFAR AIMWETLAB survey in August 2010, by the NERC (Natural Environment Research Council) Airborne Research and Survey Facility. The detailed rationale and full technical background of the survey is explained in Zlinszky et al. (2011). The shore zone of Lake Balaton and the Kis-Balaton wetland were surveyed, adding up to 1000 km² of total measured area. Kis-Balaton and the larger shore wetlands on the lake were measured with a pattern of overlapping parallel strips, but to save flight time, most of the lake was covered by an irregular pattern of strips following the shoreline (Fig. 15).

Fig. 15: Surveyed ALS flight strips around Lake Balaton and Kis-Balaton.

A Leica ALS50 sensor operating at 1,064 nm wavelength with a sinusoidal scan pattern was employed. With this instrument a maximum of four echoes can be distinguished for each pulse. The instrument settings and mission parameters were chosen to provide a 1 pt/m² point density, 22 cm footprint diameter and ca. 1 km swath width from an elevation

of 1,200 m above ground level. Horizontal and vertical point position accuracies were 0.15 and 0.1 meters respectively, according to sensor specifications. Echo amplitudes were modulated by an automatic gain control (AGC) and the AGC and amplitude values were included in the attributes of each point. The dataset was pre-processed by the NERC Data Analysis Node to the level of ASPRS (American Society of Photogrammetry and Remote Sensing) .las files, and erroneous points resulting from atmospheric or multi-path echoes were identified.

3.5.2 Categories used for vegetation classification

The categories of the classification were vegetation types selected before the flight. They were based on field experience and knowledge from archive aerial photo interpretation (Dömötörfy et al., 2003; Zlinszky, 2007). The aim was to produce a map relevant for the assessment of the health and habitat role of reed wetland vegetation, with categories that could be recognized in the field, as well as potentially including all possible land cover types that were present in the littoral zone:

- Wetland: For the purpose of this ALS methodology development study, wetlands are defined in a vegetation ecology sense contrary to other definitions that might be used for geomorphology, hydrology, pedology etc. Wetlands are areas where the water or groundwater surface is regularly near or above the sediment surface or the soil is regularly fully saturated with water and where the vegetation is mainly composed of emergent macrophytes (Wetzel, 2001).
- Trees/shrubs (referred to as trees in the following): Although trees and shrubs can be present in wetlands, separating them into different classes is beyond the scope of this thesis, so this category is simply defined as areas where the dominant plants have a branching woody stem. Typically, these are *Populus*, *Salix* or *Alnus* trees, but other genera are also present. These plants are expected to be higher than wetland vegetation, and are usually found on slightly elevated patches of dry land on the shore, within or near wetlands.

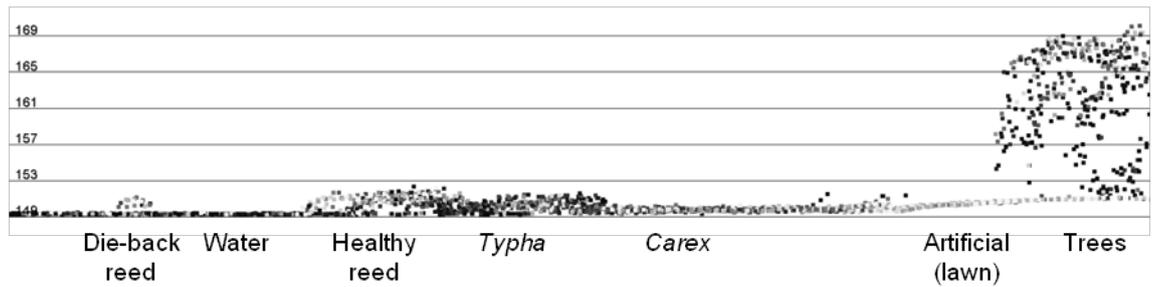


Fig. 16: Typical ALS profiles of main classification categories. Vertical labels show ellipsoidal height in meters. Points included in the profile are within a strip of 15 m width and about 120 m length. Point brightness corresponds to ALS echo amplitude: brighter points have higher echo intensities, darker points have lower intensities

Trees typically produce multiple echoes of the ALS pulse, so both the top of the canopy and the terrain surface can be identified on a vertical profile of the point cloud (Fig. 16).

- *Scirpus/Schaenoplectus* (abbreviated in the following as Scirpus): Although these are also emergent shore macrophytes, their stand structure differs from wetland macrophytes, because they grow at a much lower stem density and although the tips of the leaves emerge from the water, most of their length is submerged. Such areas are typically found on the most exposed edges of wetlands because of their ability to tolerate waves.
- Water/artificial: This class includes water surfaces and man-made structures. For the purpose of mapping wetland vegetation, water surfaces do not have to be separated from artificially cultivated or covered areas (grazed or mown grasslands, agricultural areas, asphalt and concrete surfaces), bare soil or otherwise unvegetated structures. Water typically has a very low reflectance in the near infrared spectral band where the instrument operates (Höfle et al., 2009; Lang and McCarty, 2009) similar to tarmac surfaces and railway embankments, while very high reflectance is produced by the dense closed canopies of cultivated fields, the flat surface of mowed grasslands, and gravel or concrete surfaces (Fig. 16). Depending on the roughness of the water surface, the observed reflectances are very low (points can be completely missing), or extremely high wherever the local water surface is perpendicular to the incoming pulse (on wave slopes and/or at sensor nadir).

The wetland class as defined above is further divided into vegetation classes containing reed stress categories and genera of other species. Classification to species level was not attempted because identification of species of the *Typha* and *Carex* genus is usually based on properties of flower attributes (*Carex*) and leaf veins (*Typha*), and is thus difficult and often uncertain even when done in the field. Different genera mostly represent different

forms of growth and are thus relevant categories for habitat identification, and also correspond to the typical zonation of shore wetlands without subdivision to species level.

- *Typha*: *Typha* plants are characterized by their narrow and long leaves, which can reach up to 250 cm of height. Leaves all grow from the base of the stem and not along the stalk, and are relatively thick and rigid, so they are usually near-vertical for most of their length. This means that the penetration of the ALS pulse is high in these areas, often reaching the ground or water surface, where most of the pulse energy is lost to low reflectance of water and bare soil or specular reflection from water. Together with the dark green colour of the leaves, this means that *Typha* areas are usually characterized by low ALS reflectance (Fig. 16). *Typha* is very tolerant to anoxic sediment but is sensitive to wave action; therefore it is mostly found in the central areas of wetlands, in water depths between 50 and 100 cm, surrounded on all sides by *Carex* or reed. It can also form mixed stands with other species or monodominant stands on the open water boundary in sheltered areas.
- *Carex*: *Carex* plants also have leaves that all sprout from the base but these are less rigid and usually have a curved shape as they bend towards the ground. The canopy height can also reach 200 cm, but this is rare: 50–130 cm is typical. These leaves interlock to form a dense closed canopy, which restricts ALS signal penetration and reflects most of the pulse energy (Fig. 16). *Carex* stands are characteristic on the shore side of wetlands, in periodically dry areas with water shallower than 50 cm year round.

Reed: The canopy of *Phragmites* consists of leaves growing in regular intervals along the stem, which can reach a height of up to 4 meters above the water level (Engloner and Papp, 2006; Engloner, 2009). This means that signal penetration is initially high but the signal rarely reaches the water surface as it gets reflected from the subsequent layers of leaves (Fig. 16). The echo amplitude is usually high as the canopy is dense but in some cases (especially on the SW shore of the lake) canopy density can be low enough to allow some penetration and thus loss of energy to specular reflection from water.

- **Healthy reed:** A reed stand was regarded during ground truthing and validation as healthy if the stalks were high (above the approximate height of 1.5 m), had an even density with no open water between them, and if the majority of the stalks were vertical.

- Die-back reed: Reed areas were categorized as being in a state of die-back if the density or height was very low or if clumps were present, separated by open water areas (van der Putten, 1997).
- Stressed reed: Stressed reed was defined by alternating areas of low and high stalk density (Ostendorp, 1989), with the canopies closing over any open water patches.
- Ruderal reed: Ruderal reed areas are those where abundant nutrients and light allow the encroachment of terrestrial species, mainly nitrophilous weeds (e.g., *Urtica dioica*) or climbing plants (*Humulus lupulus*, *Solanum dulcamara*). These are typically found on the shore side of wetlands, around paths and artificial openings and in areas where waves deposit organic debris.

3.5.3 Ground truth data

During the months before the flight, ground truth polygons were outlined in the field using a differential GNSS receiver (Leica GS 20, Leica Geosystems, Heerbrugg, Switzerland). These polygons were approximately 10 × 10 m plots where the abundance of the main macrophyte species was found to be homogeneous. Water depth, vegetation height, reed health and the coverage of the 17 most frequent species (including emergent macrophytes, submerged and floating-leaved plants and trees) in the study area were recorded on the basis of the Braun-Blanquet scale (with 0 for absence and 5 for full monodominant cover) as attributes of these polygons. In order to have a number of reference areas clearly dominated by a single species, some nearly monodominant plots were cleaned of sub-dominant plants by hand clipping. Out of 82 plots altogether surveyed, 46 were monodominant and 36 were mixed, adding up to about 8,000 m² of reference data for about 100 km² of wetland vegetation within a full surveyed area of ca. 1,000 km². A set of 60 control points was also collected, where the dominant genus and its health were registered for quality control using the categories defined above (3.5.2). In order to facilitate radiometric calibration, the reflectance of a bright surface adjacent to one of the reed stands (white dolomite gravel parking space, reflectance at 1,064 nm: 53.5 ± 3.8%) and a nearby dark surface (freshly deposited bare topsoil, reflectance at 1,064 nm: 13.8 ± 2.0%) were measured with a spectroradiometer (ASD Fieldspec 3, Analytical Spectral Devices, Boulder, CO, USA) simultaneously with the flight on one of the survey days. Since the flight also involved hyperspectral imaging (Zlinszky et al., 2011), care was taken to collect data only under ideal atmospheric and illumination conditions. Because of this, it was

assumed that the slight variability of atmospheric conditions during the flight period of ten days is negligible and the calibration constants calculated on the basis of the reflectance measurements these two areas are valid for the whole survey.

3.5.4 Visualization and quality control

ALS point clouds were visually inspected in FugroViewer (Fugro Inc, Leidschendam, The Netherlands) in planar and profile views (Fig. 16). After calculation of elevation rasters using moving planes interpolation in OPALS software (Mandlbürger et al., 2009) the remaining elevation differences in the overlapping areas created by the flight pattern were mapped. The errors in the calibration of the sensor system (misalignment) resulted in different elevations (in the range of up to 10–50 cm) of the same areas. These could not be resolved due to the relatively small overlapping area of strips, therefore it was decided to continue on the basis of individual strips and exclude absolute elevation of points from the classification scheme. Small variations in ground sampling density (<10%) were also present between strips.

However, it was also shown that different vegetation types have different point cloud profiles and reflectance characteristics. It was assumed that the echoes themselves did not contain enough information for point-based classification without full waveform recording such as Wagner et al. (2008). Therefore, a raster approach was selected: a number of parameters were calculated in grid cells from the neighbourhood of each point and these rasters were used as the input values for the classification algorithm.

3.5.5 Input parameters and calculations

The ALS data were processed using modules of the scientific laser scanning software OPALS (Mandlbürger et al., 2009). Depending on the nature of each variable, raster sizes were selected to average across several ALS points within large cells or to map their parameters to a high resolution raster. Parameters used for classification were the following:

- Surface reflectance: (Fig. 17(a–c)) As described in Section 2.5, the echo amplitude is influenced by the atmospheric attenuation, the range, the incidence angle and the area and reflectance of the footprint. In the case of the laser scanning system applied here, the recorded signal was additionally dependent on an automatic gain control which amplified the received signal strength in order to allow 8 bit recording but keep the range. These effects were corrected by the OpalsRadioCal module (Lehner and Briese, 2010). This tool corrected each echo

amplitude value for the above mentioned influencing factors by applying a mission specific calibration constant representing the sensor and atmosphere properties. The calibration constant was derived from ground truth calibration targets with *in situ* measured reflectance (*cf.* Section 3.3.2). This was then applied by the OpalsRadioCal module while reconstructing the signal path length through the atmosphere and the reflection of the signal from the terrain based on the angle between the laser pulse and the local surface.

Applying the calibration constant to the ALS amplitude data yielded calibrated reflectance values for each echo as a dimensionless number between 0 and 1 (Lehner et al., 2011). These reflectance values were rasterized to a 1 m grid to conserve each reflectance observation from the 1 pt/m² data as accurately as possible.

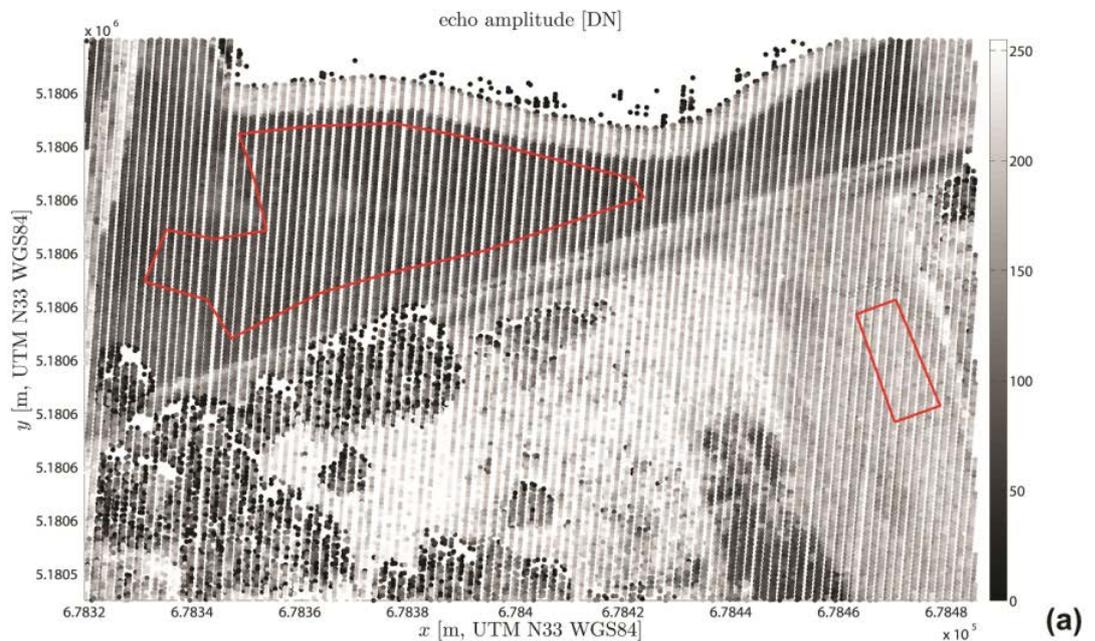


Fig 17 (a): Uncalibrated ALS echo amplitude of the area used for radiometric calibration. Range 0 (black)–255 (white). Polygons outlined in red are areas where reference spectra were collected.

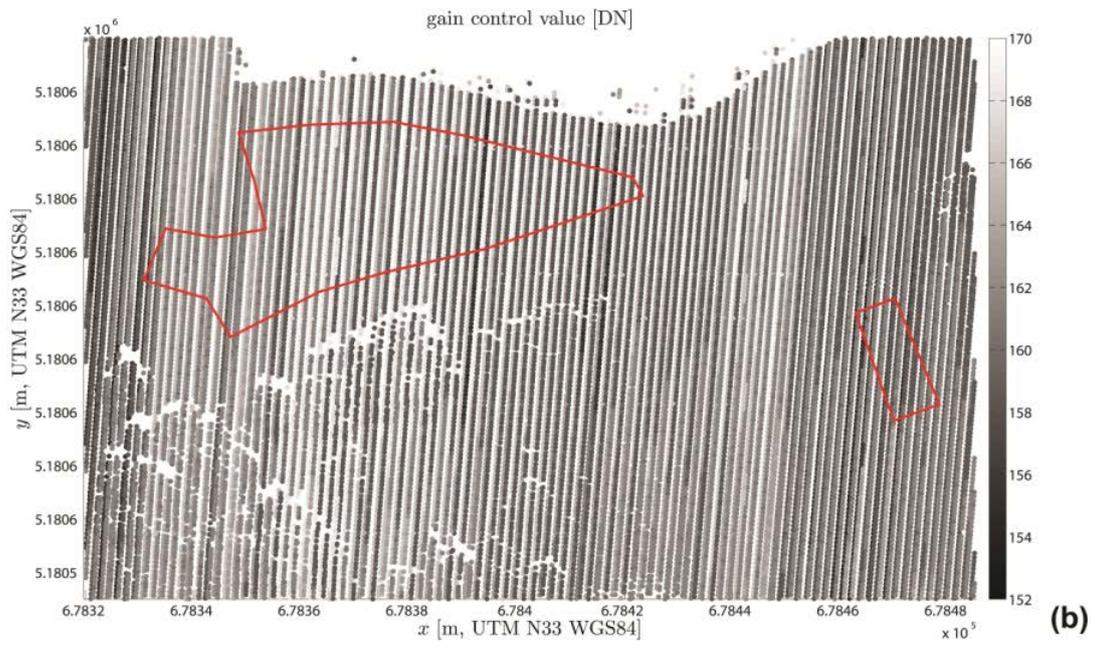


Fig. 17.(b): Gain control values. Range 152 (black)–170 (white). Note abrupt change in gain control due to the low reflectance of water in the top (void) area of the image, and alternating high and low levels of gain control values of alternating scan lines caused by the presence of a low reflectance surface (water).

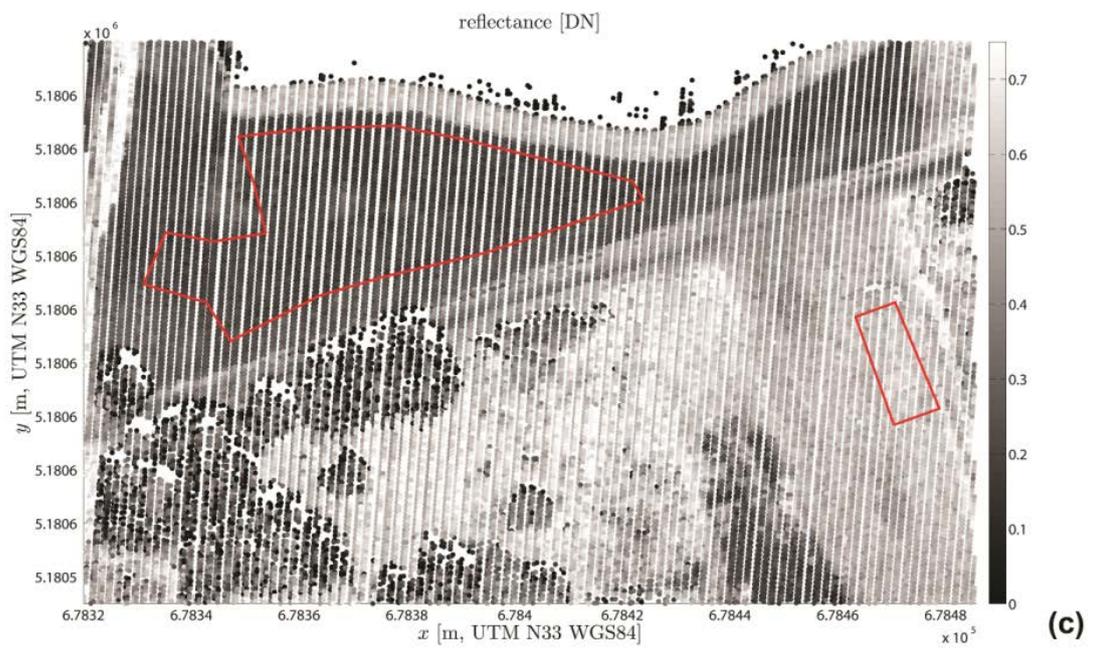


Fig 17.(c): Calibrated surface reflectance. Range 0 (black)–1 (white). Note that the linear feature visible on Figure 17(a) caused by a major change in gain control level has been corrected as well as the alternating bright and dark scan lines.

- Dropout point count: (Fig. 18 (a,b)) The best described symptom of reed die-back is the formation of patches and clumps instead of a single continuous reed stand. In order to find a simple method to map these areas, the shape of the reed edge and the position of open water leads and lagoons had to be assessed. From specularly reflecting surfaces, hardly any light reaches the sensor system, so open water is indicated by missing points called dropouts (Höfle et al., 2009). This is especially true in reed stands or near the shore where the vegetation creates a wind shadow and thus the water surface is very flat. Since the sensor has a continuous sinusoidal scan pattern, any dropout points caused by the presence of water are expected to be somewhere along the line joining the preceding and following points. For the purpose of this study, only the presence of missing points (and not their exact number or location) was used to outline water, creating one point marking the gap of any size in each scan line.

Since each point has a recorded GPS time, missing points could be detected by a Matlab (Mathworks, Natick, MA, USA) script wherever the GPS time difference between two echoes was above a threshold derived from the pulse repetition rate. To create a set of points representing the missing echoes of the water surface, the coordinates of the points preceding and following each dropout were averaged, so that the new point was created in the midpoint between them. If one edge of the scanned strip was above water, this created a row of estimated dropout points along the water boundary instead of on the area of the open water.

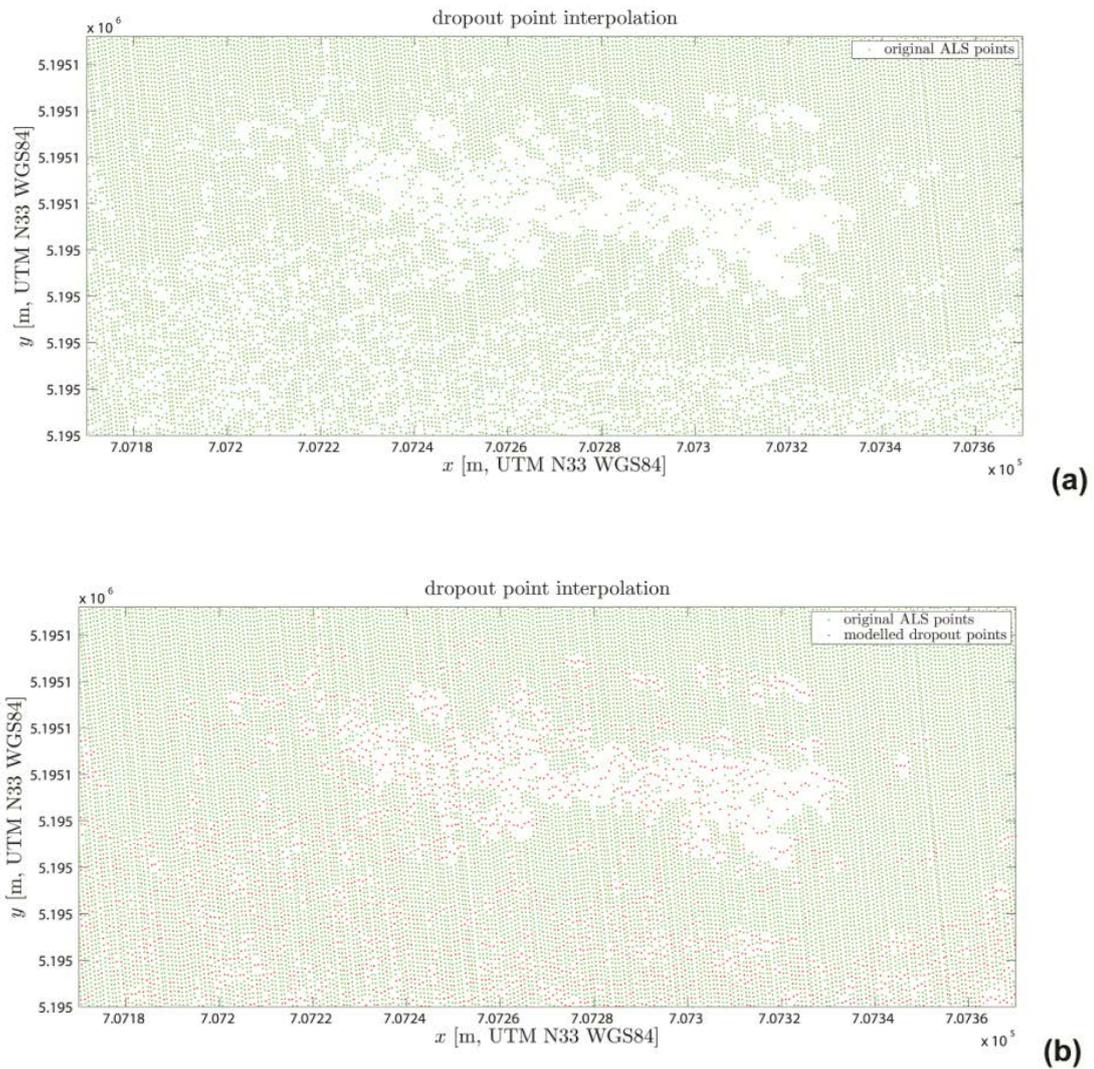


Fig. 18 (a): Planar view of the ALS point set in a die-back reed area. Open water patches within reed create dropout points. Image extent about 5 m \times 25 m. (b): Dropout interpolation generates a set of points within the void areas created by specular reflection from water. Points shown in red are created by the dropout modelling algorithm in the mid-point between the preceding and following echo on the scan line.

For the size of gaps typical for die-back reed (1–5 m according to field experience), this simple algorithm created a row of interpolated dropout points along the centre of the gap and parallel to the flight direction. These points were not written into the original point cloud, but a separate raster with 5 m \times 5 m cell size was calculated containing the number of such dropout points in each cell. The threshold of 3 was applied based on signature analysis (see Section 3.3.5) that proved to recognize areas where the reed boundary was not straight or where gaps and islands were present.

- NDSM (Normalized Digital Surface Model) height: the canopy height of some mapped vegetation categories is characteristic. A surface model representing the top of the canopy was created selecting the highest ALS points in the cells of a $2.5\text{ m} \times 2.5\text{ m}$ grid (Fig. 19.) and rasterizing. The raster cell size selected was a trade-off between averaging over several scanned points and retaining high resolution for mapping. A basic terrain model was calculated by rasterizing the elevation of the lowest point in each cell of a $10\text{ m} \times 10\text{ m}$ grid. Visual investigation has shown that in most cases, such a large cell size is sufficient to have at least one ground/water echo inside. The elevation difference of these two rasters was calculated to a $2.5 \times 2.5\text{ m}$ raster to create a normalized digital surface model of the canopy height in m, bearing in mind that moderate-density ALS-derived NDSM height typically underestimates the canopy height.

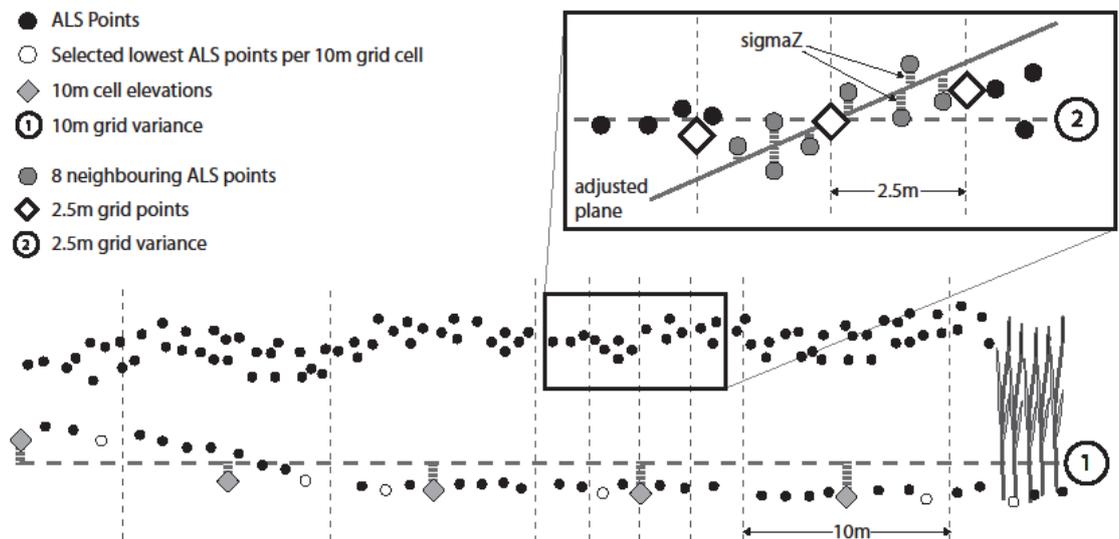


Fig. 19: 3D vegetation structure parameters used for ALS vegetation mapping. Cross section view of ALS point cloud and grids interpolated for vegetation classification. Note different scales of surface roughness that correspond to input parameters for classification.

Therefore, absolute vegetation heights were not calculated but this layer was found to sufficiently represent the existing canopy height characteristics for accurate classification. Elevation inhomogeneities between ALS points and within areas of ALS-derived elevation rasters are a straightforward way to quantify vegetation vertical structure, which, in turn, is characteristic for genera and growth forms. For the purpose of this study, roughness was assessed at three different scales, providing three parameters that were considered independent (Fig. 19).

- Slope: Standing water, which is one of the criteria of wetlands, creates very low slope angles, so the absence of a measurable slope was used as a criterion for wetland masking. To simplify calculations and to smooth out any local irregularities, the slope was represented by the variance of the 10 m × 10 m digital terrain model (DTM) grid. Variance was measured by applying a 3 × 3 pixel variance kernel to the DTM, creating a 10 m × 10 m grid of DTM variance in m.
- Grid variance: Healthy wetlands were observed to have a homogeneous stalk density and canopy height, while density inhomogeneities related to vegetation stress cause variations in the penetration of the signal and thus the vertical distribution of echoes. To represent this, a 1 m × 1 m raster model was created using moving planes interpolation (Hollaus et al., 2010) and including all points not categorized as erroneous during pre-processing (Section 3.5). The variance of this surface (in m) within a 3 × 3 cell kernel was calculated to a 1 m × 1 m grid and used as an input raster of the classification.
- Sigma Z: The small-scale surface roughness of vegetation is characteristic: the range of the vertical distribution of points in wetlands is narrower than in trees and shrubs but wider than over mown lawns or artificial areas. During moving planes interpolation, an inclined plane was fitted to the 8 nearest points within a 2.5 m distance from the central point. The standard deviation of the vertical distances of each point to the fitted plane is called Sigma Z and describes the roughness of the surface sampled by the ALS points (Fig. 19).

Sigma Z is assigned to each ALS point, and to preserve boundaries and small-scale patterns (but not overlooking the fact that this was calculated over a 2.5 m radius for each point), this parameter was also rasterized to a 1-m grid.

3.5.6 Signature analysis

The ground truth polygons were rasterized with the ArcGis 9.3 (ESRI, Redlands, CA, USA) Rasterize Tool to 1-m grid size and grouped according to the variables measured in the field. These included the monodominance and dominance of each studied macrophyte genus, different ranges of vegetation height and different categories of reed health. For five of the ALS-derived parameters used (Sigma Z, NDSM height, surface variance, reflectance and dropout point count), histograms were generated for each group. These histograms were compared visually (Fig. 20), so that similar and dissimilar groups were identified manually for each measured parameter, and threshold values for separating classes were

selected. Signature analysis was not performed for DTM variance because it was assumed that the formation of wetlands is incompatible with sloping terrain over large areas.

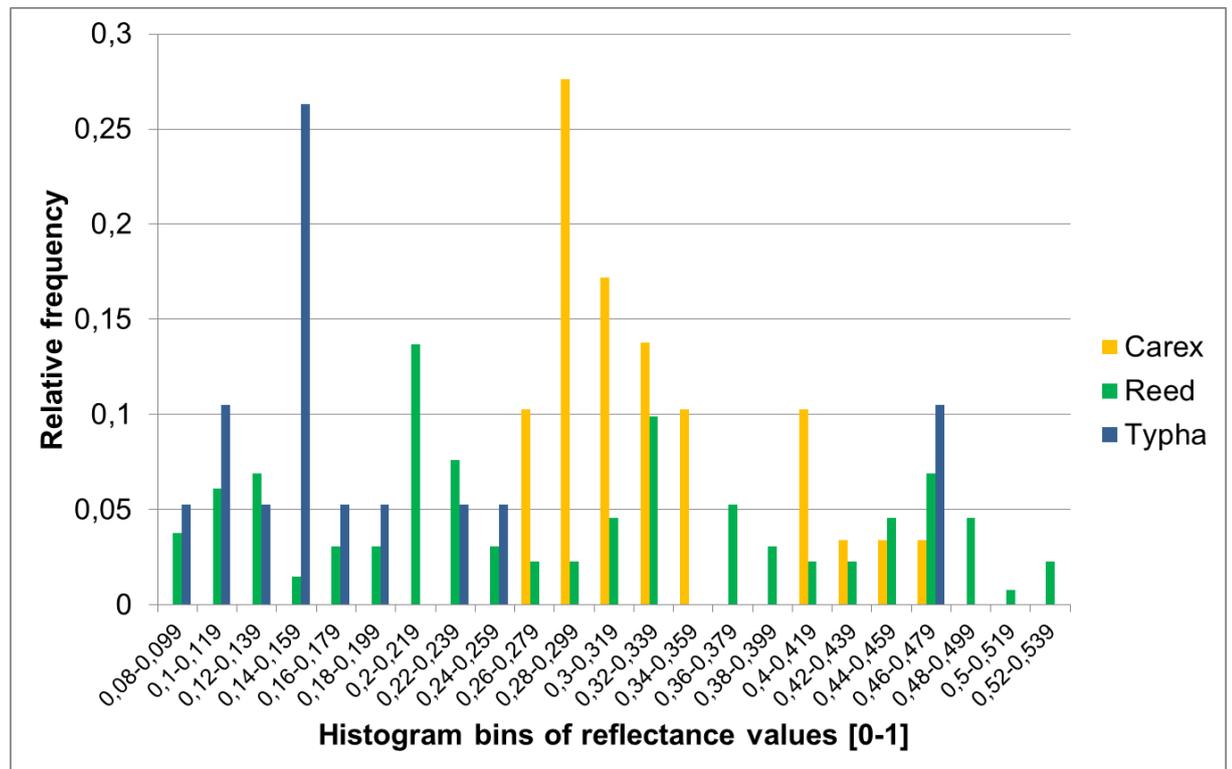


Fig. 20: Example of signature analysis, showing calibrated ALS reflectances of monodominant Carex, Typha and reed areas. Carex and Typha can be apparently well separated from each other based on reflectance, but not from reed.

3.5.7 Classification algorithms applied for wetland masking and categorization

Based on the results of the signature analysis, a manually derived rule-based decision tree algorithm was created in the batch script controlling the OPALS software. The basis of the procedure was a raster layer, and in each step of the decision algorithm, the criteria of one of the classes were tested on the given pixel. If they were fulfilled, the pixel was assigned to that particular category, and this was not changed in the subsequent steps. If not, the algorithm moved on to testing criteria of the next category (Table 1).

Table 1: Parameters used by decision tree algorithm for ALS-based vegetation categorization.

wetland vegetation classification	variables				logical operator
category	reflectance [0-1]	NDSM height [m]	dropout point count	grid variance [m]	
carex	>0.22	<0.95		<0.04	AND
die-back reed	>0.07 and <0.34		>3		AND
typha	<0.155			<0.3	AND
ruderal reed	>0.4			<0.2	AND
stressed reed				>0.2	AND
healthy reed	<0.4			<0.2	AND
input raster cell size [m]	2.5	2.5	2.5	1	
output raster cell size [m]	2.5				

wetland/non-wetland identification	variables				
category	reflectance [0-1]	NDSM height [m]	DTM variance ("slope") [m]	sigma Z [m]	logical operator
scirpus	>0.02 and <0.07	>0.28 and <0.6		>0.01 and <0.1	AND
tree		>3.5	>3	>1	OR
water/artificial	<0.045 or >0.55	<0.4	>0.9	<0.02	OR
wetland		>0.4	<0.9	>0.02 and <1	AND
input raster cell size [m]	2.5	2.5	10	1	
output raster cell size [m]	1				

The order of classification steps was selected to begin with the better-separable classes and end with those represented by less clearly constrained ranges of the input parameters. To exploit the high spatial accuracy of the data and the strong separability of non-wetland classes but to produce acceptable accuracy in the more subtle wetland sub-categories, two output files were generated. The one for discrimination between wetland vegetation and non-wetland areas had a cell size of 1 m, and the other for wetland vegetation categorization had a cell size of 2.5 m × 2.5 m. A 1 m × 1 m grid size was selected in order to map wetland/non-wetland boundaries with a resolution suitable for future change detection studies. The most strictly defined category was *Scirpus*, defined by minimum and maximum values of Sigma Z, reflectance and NDSM height. These thresholds were connected by an “AND” operator, so the pixel was only assigned to this category if all the

criteria were simultaneously fulfilled. The next category in the ruleset was trees, selected on the basis of a minimum NDSM height and a minimum Sigma Z, with an “OR” logical operator, so all pixels were classified as trees where one of the criteria was met.

Water/artificial areas were classified using a Sigma Z minimum, a NDSM maximum, a DTM variance maximum or an upper and lower reflectance threshold. If any of the selection criteria were fulfilled, the pixel was characterized as water/artificial.

Finally, pixels categorized as wetlands were those where the Sigma Z was within the thresholds selected for flat areas and trees, and the NDSM height and DTM variance were lower than the limits used for tree or artificial area selection.

After setting the output extents to the data extents and the cell size to 2.5 m × 2.5 m in the algorithm for further categorization of the wetlands, the first class selected was *Carex*, which was defined by an upper NDSM height threshold, a minimum and maximum reflectance and a maximum grid variance. The next category in the sequence was die-back reed, constrained by the reflectance range of reed and a minimum number of dropout points representing gaps in the vegetation. Next, *Typha* was classified on the basis of a maximum reflectance and a maximum grid variance, followed by ruderal reed, which was outlined by a minimum reflectance and a maximum grid variance. Stressed reed was mapped on the basis of a minimum grid variance (the same value used as a maximum for the previous categories).

Finally, the previously unclassified pixels were all categorized as healthy reed (if they were outside the grid variance and reflectance margins of stressed and ruderal reed), ensuring that no unclassified pixels were left.

The order of classification steps was refined by a manual iterative quality control process but the threshold values were strictly kept as the signature analysis recommended.

3.6 Validation of ALS classification

To check against an independent standard in addition to our own ground truth points, a set of georeferenced ground photographs collected during the summer of 2010 by the National Water Authority for a different purpose was used (kindly provided by P. Pomogyi). In the first step of quality control, 17 test strips were selected that overlapped with the original ground control areas and were relatively well distributed over the reed belt. In order to have a similar number of ground truths for each category but keeping the spatial coverage of the reference dataset, the number of images belonging to each class was assessed and a final set of 775 reference images selected. This was done by keeping every

7th image for die-back reed, every 3rd for healthy reed, every 2nd for stressed reed and water/artificial, and by keeping all of the reference images found for the remaining categories.

This resulted in approximately 100 reference images for major categories and about 50 for the less frequent classes. Ground reference photographs collected within the area of these 17 strips were assigned one or several of the dominant vegetation categories (see Section 3.2) according to visual interpretation of the images. In the rare cases where the vegetation was not clearly recognizable on a photo, that particular image was discarded.

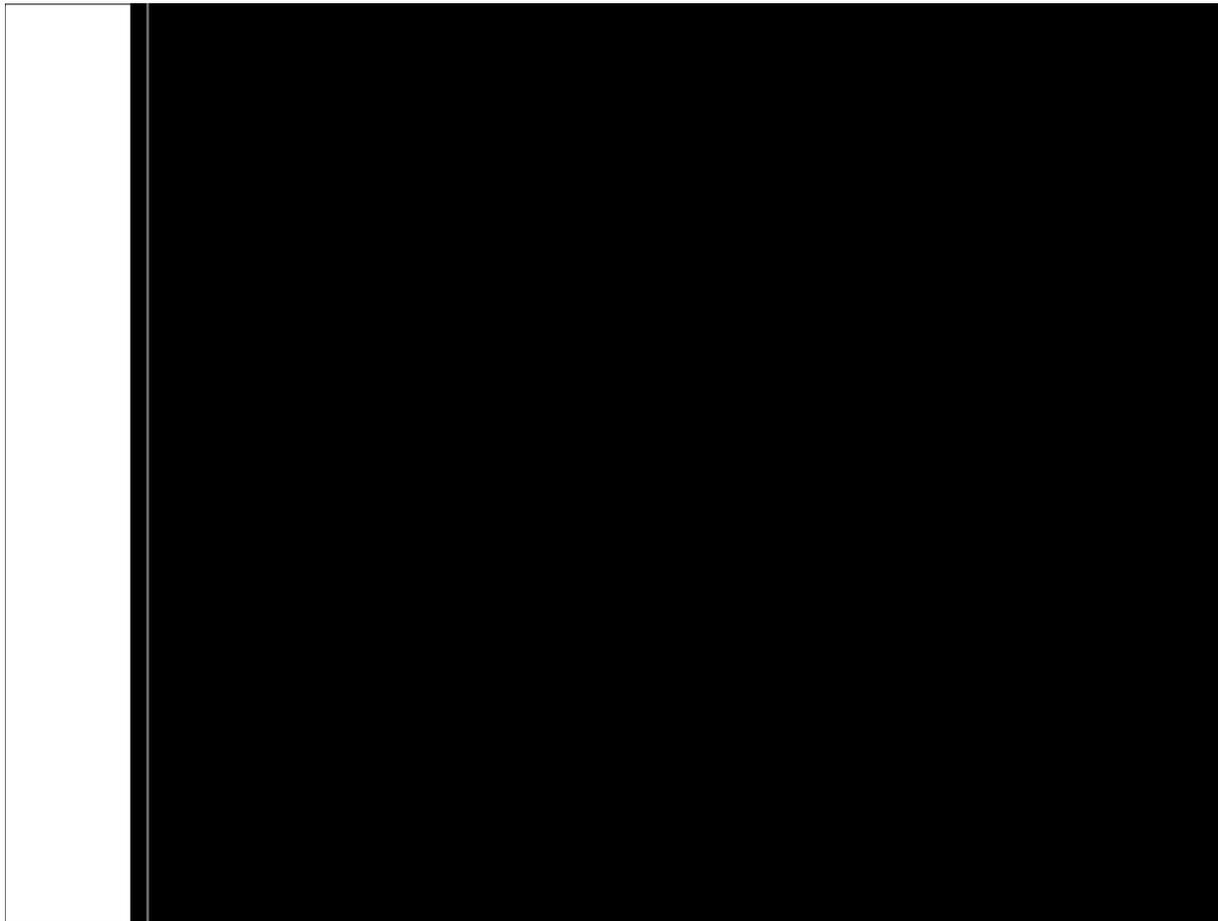


Fig. 21: Example of vegetation map, showing identified open water, tree and artificial shore areas, and the location and zonation of a wetland. Dark blue line shows the shore, the lake is on the southern side of the line. Typical vegetation zones can be observed: *Carex* nearest to the shore, *Typha* in the interior of the stand, and reed on the outside with some die-back immediately adjacent to the open water. Inset shows location of main map in the Western basin of Lake Balaton, as grey rectangle marked by the arrow. White circle shows example of waves creating false vegetation pixel artefacts.

The ground points of the photographs were overlaid on a GIS, the images visualized and their alignment and range estimated from visible shore objects. After this, the area estimated to be covered by the image was inspected on the ALS-based classified vegetation

map (Fig. 21). For close range photos, this could mean a patch of a few square meters, for longer range images, this would mean 10–20 m of shore. The vegetation categories assigned to the photographs were compared with the vegetation categories shown by the classified map for the same spot, and thus a confusion matrix (Lillesand et al., 2003) was created (Table 3).

4. Results

4.1 The water level of Lake Balaton during the studied period

Based on the elevation of the lake floor in the points where Krieger registered having measured water depths of 1, 2 and 3.33 fathoms, three different datasets were produced. The elevations derived from the 1-fathom contour points contained too much noise to be used due to the proximity of the contour to the shore and the artificial changes of shoreline, and were not used. The two-fathom contour was somewhat affected by the low density of original measurements that failed to represent the topography of the lake floor in the Tihany straits region, but in other areas, the data clearly corresponded to a narrow range in elevation around 102-103 m ASL, with a mean value of 102.94 m, a standard deviation of 1.16 m and a standard error of 0.03 m from 1512 measurements. Adding 2×1.89 m to the elevation value (2 Viennese fathoms), the measured elevation of the water level is 106.72 m. The 3.33 fathom contour also showed some errors in the Tihany straits region, but generally represented 100-101 m ASL, with a mean elevation of 100.96 m, a standard deviation of 0.56 m, and a standard error of 0.02 m from 1059 measurements. Adding 3.333 fathoms (6.3 m) to this elevation, the resulting mean water level is 107.25 m. The difference between the two water level elevations as derived from the contour lines is 0.53 m, which is well below the annual water level fluctuation of the lake, reported by Krieger to be 3-4 feet (0.9-1.2 meters). The average of the two measurements, 107.0 meters can be regarded as the earliest documented water level of Lake Balaton (Fig. 22)

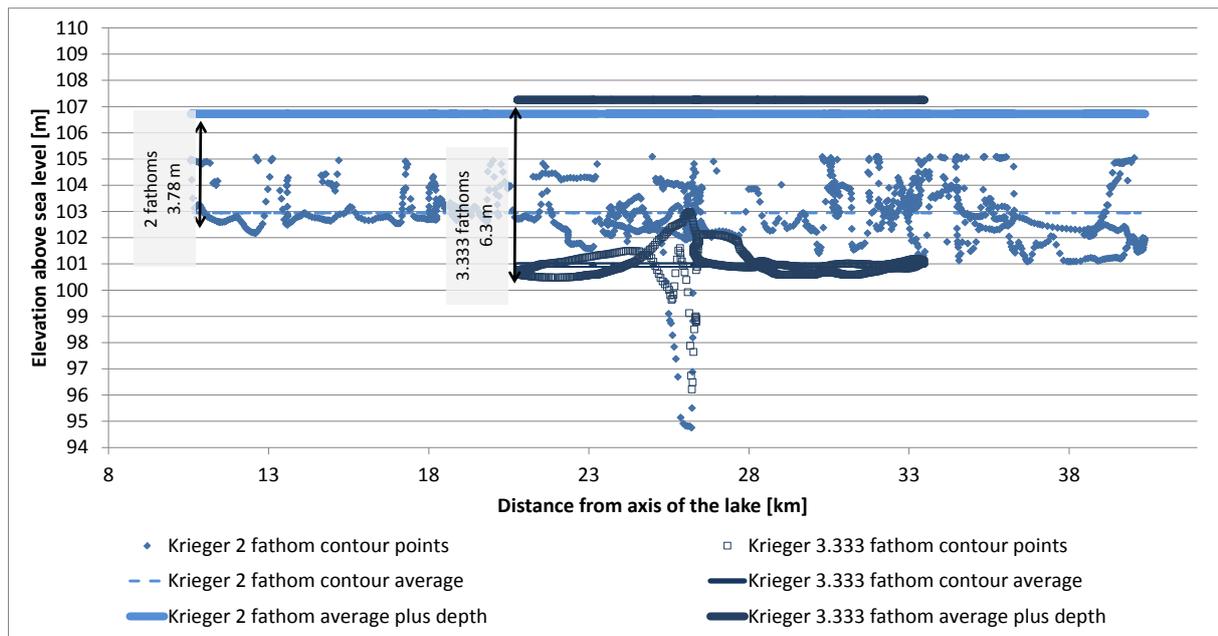


Fig. 22: Elevation range of the water level of Lake Balaton in 1776, calculated from points of the 3.33 fathom (light blue) and the 2 fathom (dark blue) bathymetric contour line.

4.2 Areal extent and elevation distribution of tributary wetlands

4.2.1 Connectivity between wetlands and the lake

The areas around Lake Balaton that were marked on the First Military Survey as permanently flooded wetlands were measured to cover 361 km² during the late 18th century. This is equivalent to more than half of the surface of Lake Balaton itself. However, the functioning of the wetland and lake network is determined not only by the area of the reed wetlands and the lake, but also their connectedness. Connectedness on the scale of macrofauna simply means spatial proximity and eventually the continuity of waterways, since most animals can move across gaps between reed wetland patches actively. However, on the scale of phyto- and zooplankton, connectedness is defined by hydrological properties: connections can be unidirectional, if the direction of flowing water is determined by a well-defined slope; or bidirectional, if the slope is low enough to allow for occasional reverse flow driven by seiche. In the former case, the wetlands are formed despite the slope due to the water retention capacity of emergent vegetation standing in water and blocking the flow of the river, while in the latter case, vegetation has no such function. The former type of wetland can be classified as fluvial, the latter as lacustrine.

The dependence of the water table in a wetland on the water table of a lake can be decided on the basis of their respective elevations: if the water level in a wetland is well above the water level of Lake Balaton, it can be regarded as largely independent on the scale of a few years. If, however, it is in the same elevation range as the water levels of the

lake, then the fluctuations of the lake will probably also flood and dry the wetland. According to the combinations of these categories, four types of wetland basins can be distinguished around Lake Balaton: fluvial valleys in close connection to the lake, fluvial valleys well separated from the lake, lacustrine type valleys in close connection to the lake and lacustrine valleys separated from the lake (Fig. 23).

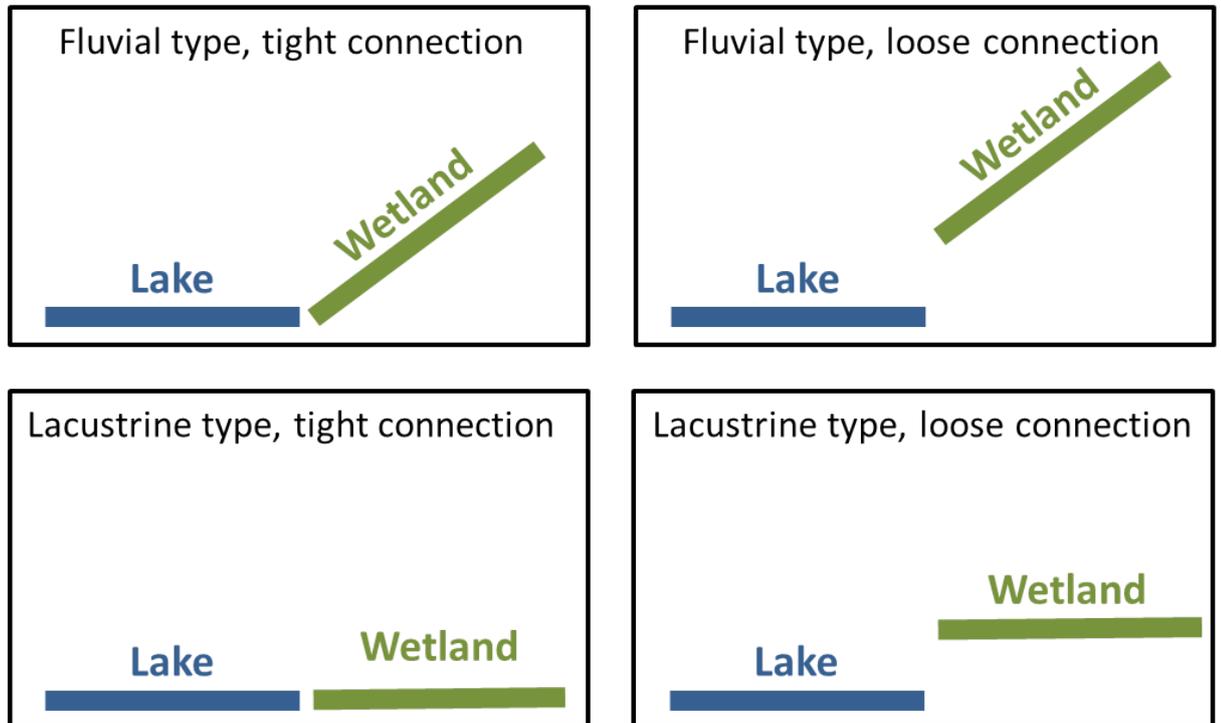


Fig. 23: Types of tributary wetlands of Lake Balaton according to slope and elevation.

On the late 18th century maps, the western basin of Kis-Balaton can be characterized as a lacustrine type wetland well separated from Lake Balaton (Fig.24). Most of the elevation points corresponding to the boundary of the wetland lie around 110 m ASL, 3 meters above the concurrent elevation of the water level of Lake Balaton.

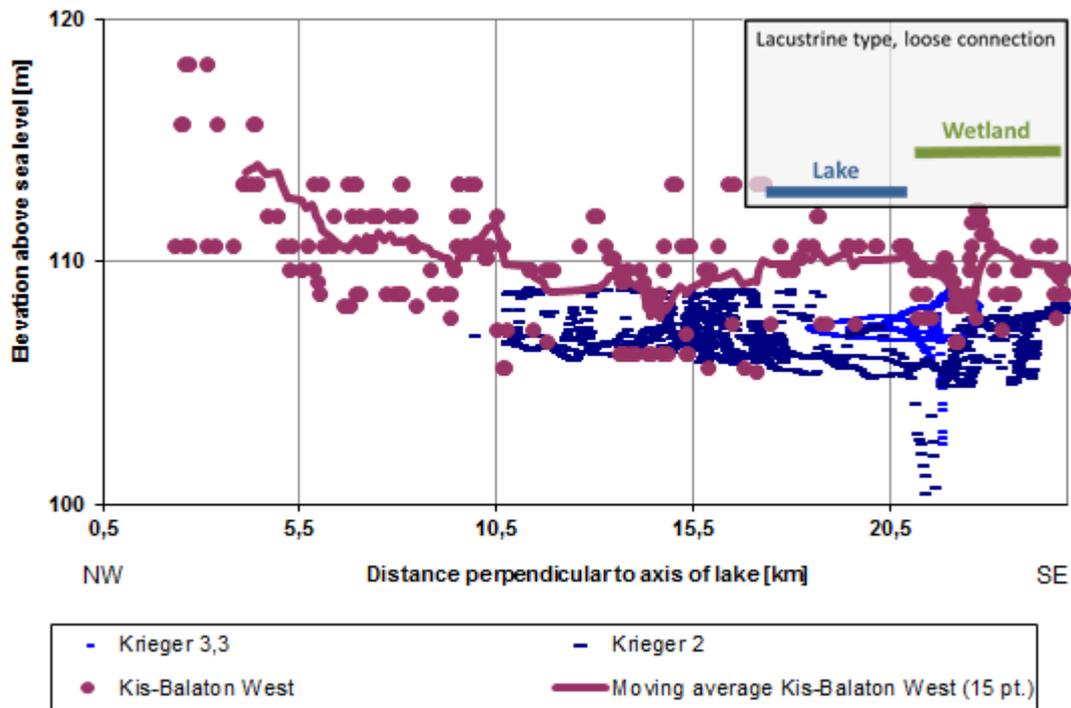


Fig. 24: Elevation profile of the Western Basin of Kis-Balaton and the water level of Lake Balaton

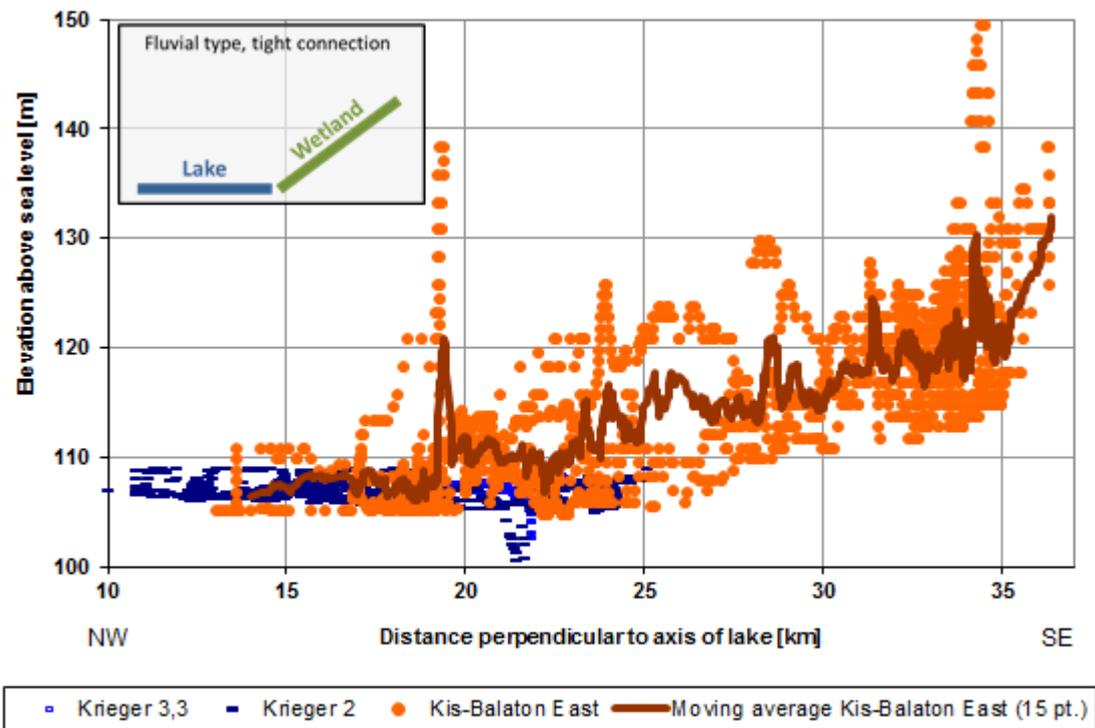


Fig. 25: Elevation profile of the Eastern Basin of Kis-Balaton and the water level of Lake Balaton

The eastern basin of Kis-Balaton was an open water bay of the lake in the 18th century, only separated from the main body of the Keszthely basin by straits which were 1 km wide at their narrowest point. Thus, the downstream part of the Eastern Kis-Balaton basin must have been very closely connected to Balaton, with water movements of the lake also affecting the wetlands in this area. The elevation profile of this wetland nevertheless shows the characteristics of a fluvial valley: The highest point of the unbroken wetland is more than 25 meters above the level of Lake Balaton, and shows a constant slope (Fig. 25)

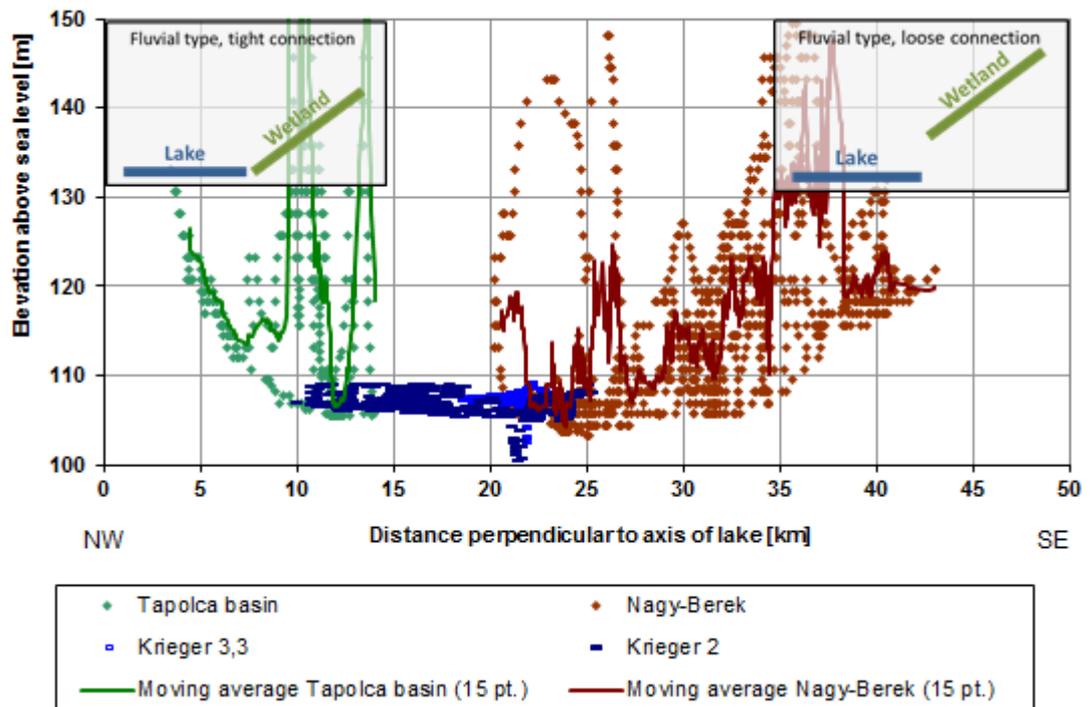


Fig. 26: Elevation profiles of Nagy-Berek and the Tapolca Basin wetlands together with the surface of Lake Balaton

Nagy-Berek, the second largest wetland adjoining the lake also has a fluvial type profile, with many side valleys that are relatively steep. Some areas relatively close to Lake Balaton are in a similar elevation range as the lake but an elevated sandbar separates the water system of the valley from the open water of the lake itself, therefore limiting the hydrological and ecological connection (Fig. 26).

The Tapolca basin joins the lake from the North, with several small streams entering through a flat wetland valley. In historic times, the southern part of this floodplain connected directly with the reed belt of Lake Balaton. Since the Northern shore is more sheltered from wind and waves, no sandbar has been deposited. This valley also shows a clear slope, which can be distinguished from the errors of the georeferencing (Fig. 27).

The smaller valleys on the Southern shore of the lake are more difficult to evaluate as the width of the wetland zone is in the same order of magnitude as the combined error of mapping and georeferencing. Most are sloping fluvial wetlands, with a few notable exceptions. The reed wetland in the tombolo triangle of Szántód is bordered by sand deposits on the North and hills on the Southwest, but is of lacustrine type with no slope at all, and lies completely in the elevation range of the lake and reaches the lake shore on the Western side. The valley of the Sió river is also shown by the elevation graph to be of lacustrine type similar to the lake in elevation.

Finally, the small wetland in the valley between Balatonszemes and Balatonlelle is also shown to lie in the elevation range of the lake and is a lacustrine valley, although it would seem to be similar to the other minor wetlands of the Southern shore (Fig. 27).

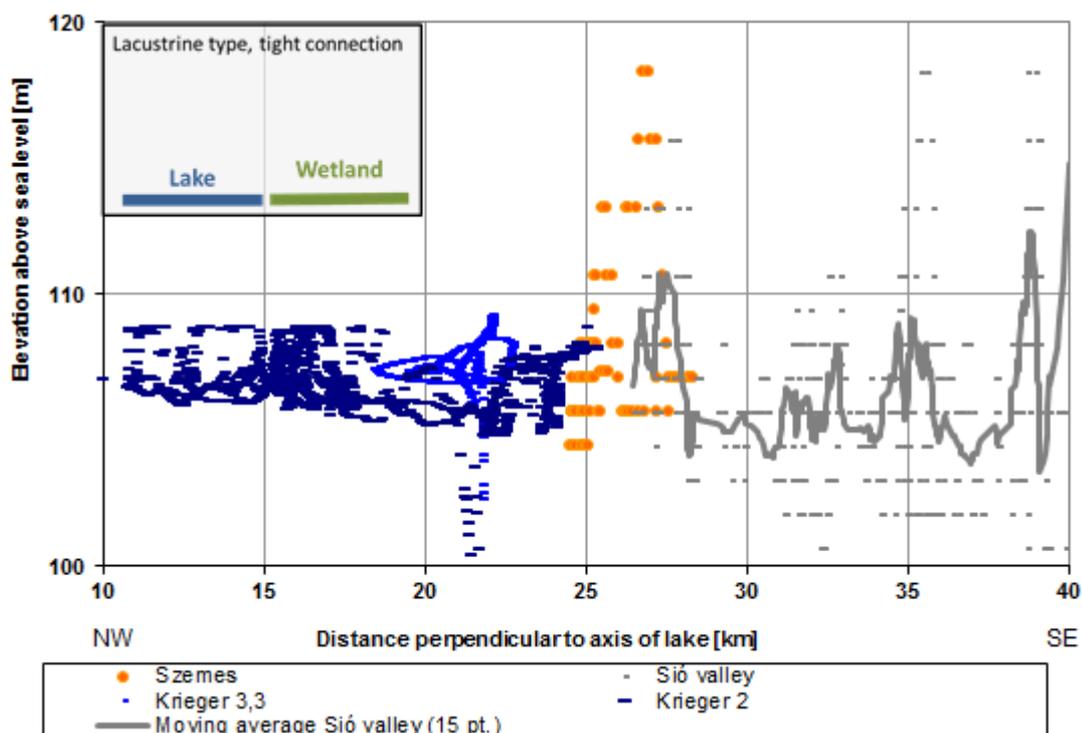


Fig. 27: Elevation profiles of the Szemes valley and the Sió valley, together with elevation points of the historic water level of Lake Balaton

4.3 Change of reed wetlands around Lake Balaton in connection with human presence

While the previously listed results describe the earliest and most natural state of the lake, including the reed vegetation that can be numerically evaluated from suitable maps, wetland areas underwent widespread changes during the studied period. During the 18th

century, wetlands on the drainage area of Lake Balaton occupied an area of 361 km², which was more than half the area of Lake Balaton at that time. By the time of the Second Military Survey, in the early 19th century, the reed vegetation had lost more than 100 km², and only occupied an area of 217 km². This change happened nearly a decade before the first documented and deliberate engineering of the water level of the lake. During the 19th century, further wetland areas were lost, leaving 186 km² of wetlands on the whole watershed directly following the drainage of Lake Balaton. Most of the change happened on the major wetlands between the First and the Second Survey, which then hardly changed between the Second and the Third (Fig. 28). The present-day area of these wetlands according to a satellite imaging-based dataset (Corine Land Cover 2000) is also included for comparison.

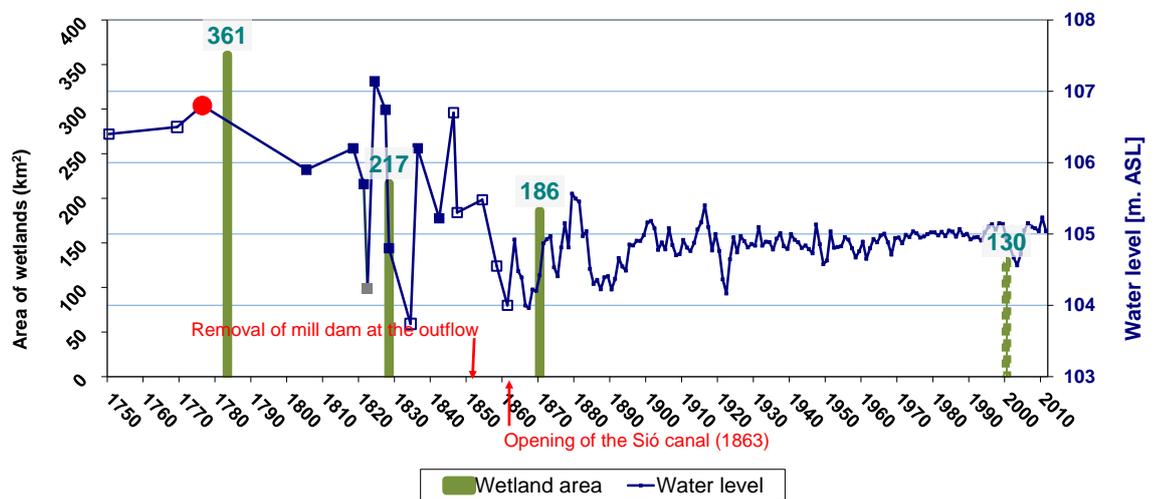


Fig. 28: Reconstructed changes in the water level of Lake Balaton, together with wetland areas from the Military Surveys and dates of major water level regulation efforts on Lake Balaton. Present-day wetland area from the Corine Land Cover 2000 database is added for comparison. Empty points represent water levels reconstructed from paper maps, grey point from historic documents, blue points represent water levels from levellings. Red dot marks water level measured from Krieger map, unmarked points show direct measurements.

The investigated maps show that many mills were abandoned or demolished on the watershed, which broke the continuity of wetlands along the steeper upstream parts of the adjoining valleys. The development of drainage canal systems and fishponds can also be followed from these maps. The final separation of the wetland valleys from Lake Balaton was a consequence of the construction of roads, railways, shorewalls and residential areas.

4.4 Reed die-back and regeneration

4.4.1 The distribution of reed around Lake Balaton

The weakening of the connection between the wetlands on the watershed and Lake Balaton raised the importance of the shore wetlands of the lake. The historic maps that were investigated are neither detailed nor accurate enough to follow the changes of the lake wetlands closely enough, and the first aerial photo survey covering the whole study area was carried out in 1951. The width of the reed belt in our study sites and the water depth on their lakeward edge in 1951 are shown by Fig. 29 and 30 respectively.

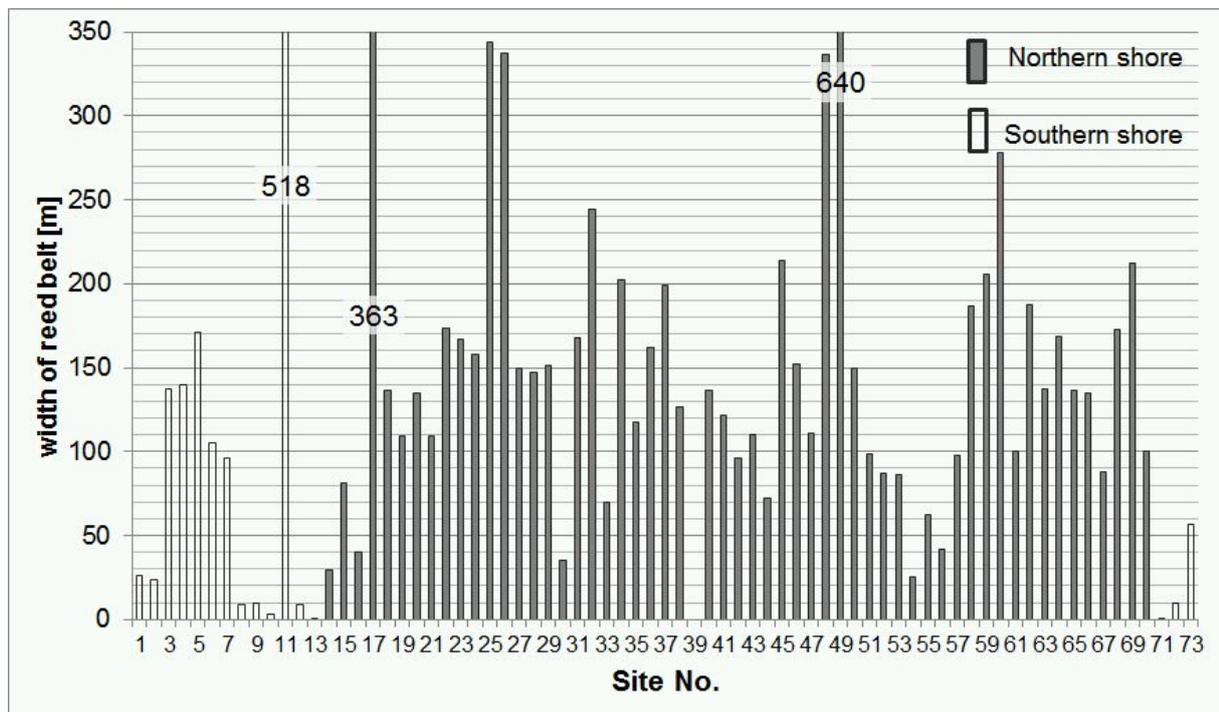


Fig. 29: Width of reed belt in 1951 at study sites on Lake Balaton.

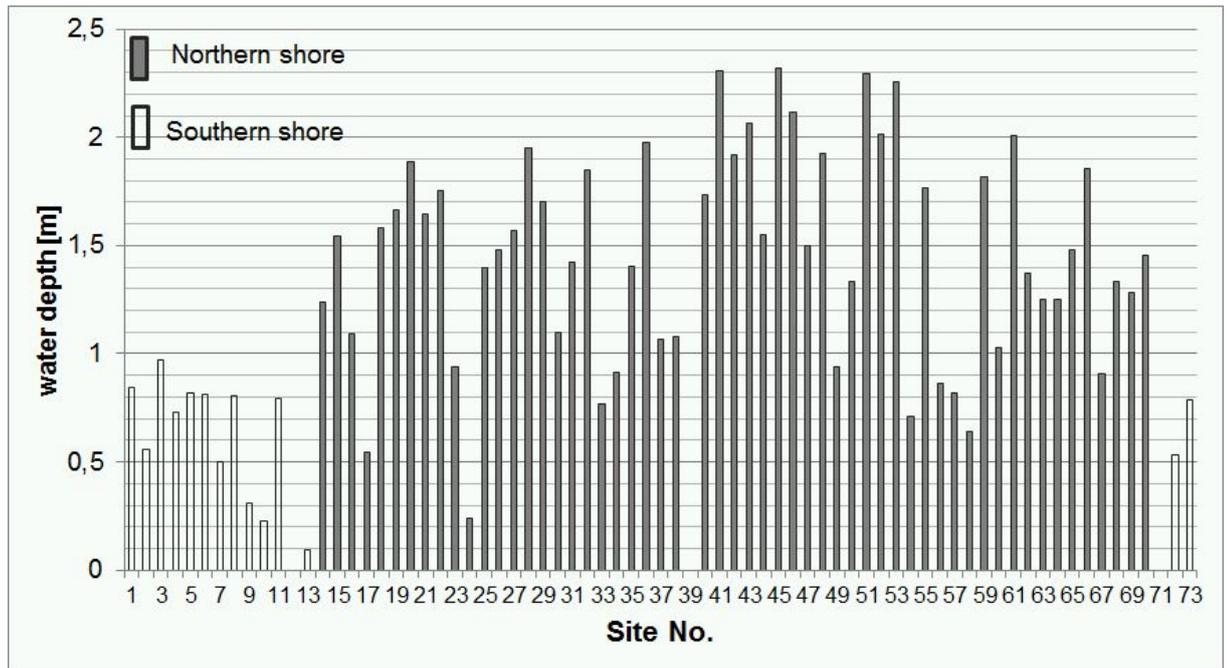


Fig. 30: Maximum water depth of reed study sites in 1951 derived from a digital bathymetric model of the Lake (Zlinszky 2008).

The largest reed areas on Lake Balaton are located in the sheltered bays of the Northern shore. The first basin of the lake from SW (the Keszthely basin) only holds 5% of the total surface of the lake and is 1 meter shallower than the average depth, so it can be regarded as the largest bay. At the mouth of the Zala river to this basin (site 11), the width of the reed wetland zone was 521 m perpendicular to the shore, with a maximum water depth of 0.80 m (at a water level of 100 cm) on the water side. At the border between the Keszthely and the Szigliget basin, on the northern side near Vonyarcvashegy, the reed zone had a width of 349 m, with a maximum depth of 0.54 m (site 17). The reed belt in the second (Szigliget) basin is sheltered by the hills from the North and West. In 1951, it had a width of 350 m, with a maximum water depth of 1.48 m. The Szemes and the Siófok basins are separated by the Tihany Peninsula, which creates a narrow strait (1.5 km) between the Northern and Southern shores. The Bozsai Bay on the NE corner of the Szemes basin holds a large reed area where at the studied site the reed belt was 645 meters wide, and the water depth of its front was only 0.94 m (site 49).

On the open stretches of the north shore, the reed stands are narrower and reach deeper waters. In areas where hillslopes meet the shore (sites 41, 43, 45, 46, 51, 52, 53, 61), reed stands extended into up to 2.5 meters of water.

On the Southern shore, only the Keszthely and Szigliget basin held a larger reed belt. These could reach widths of 200 meters perpendicular to the shore, but were always in

water shallower than a meter, and have sandy sediment with low organic content up to the present day. Some of the reed stands on the NE shore between Balatonkenese and Balatonfűzfő are in a similar situation: although sites 72 and 73 face south, they are on shallow sandy sediments probably deposited by slumping of the cliffs, and show characteristics typical for Southern shore reed stands in general. The southern side of the Szemes and Siófok basin did not have a reed belt, only small patches.

4.4.2 The changes of the reed fronts between 1951 and 2003

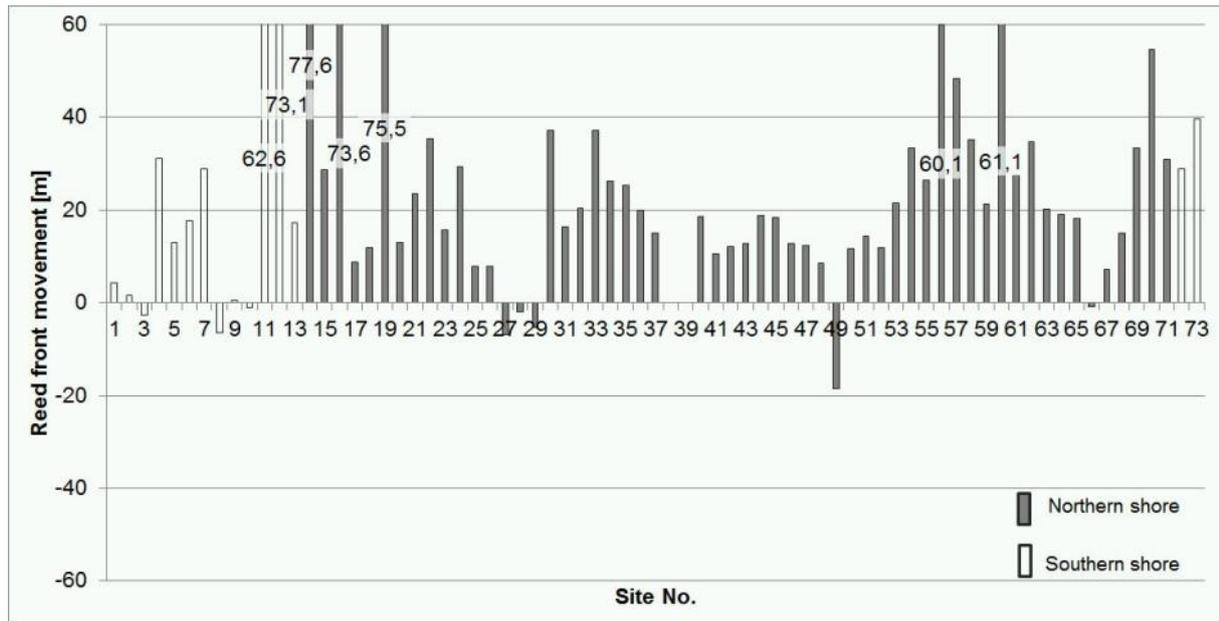


Fig. 31: Reed front movement index of study sites between 1951 and 1963

Between 1951 and 1963, the reed stands showed significant lakeward progress (Fig. 31). Out of the 58 studied sites on the Northern shore, the area of 51 increased, and the median of the reed front movement index was +19 meters. The reed front advanced more than +70 meters at three sites in the first basin, and more than +60 meters in two sample areas in the fourth basin. The reed area expanded at 12 of the 15 sites on the Southern shore, with a median of +17 meters. The reed front progressed more than 60 meters near the mouth of the Zala river (site 11,12), and +31 meters on the sandy south shore of the Szigliget basin (site 4). At sites 72 and 73, which are on the NE shore of the Siófok basin but have shore characteristics typical for the southern side, +29 and +39 meters of reed front movement were recorded.

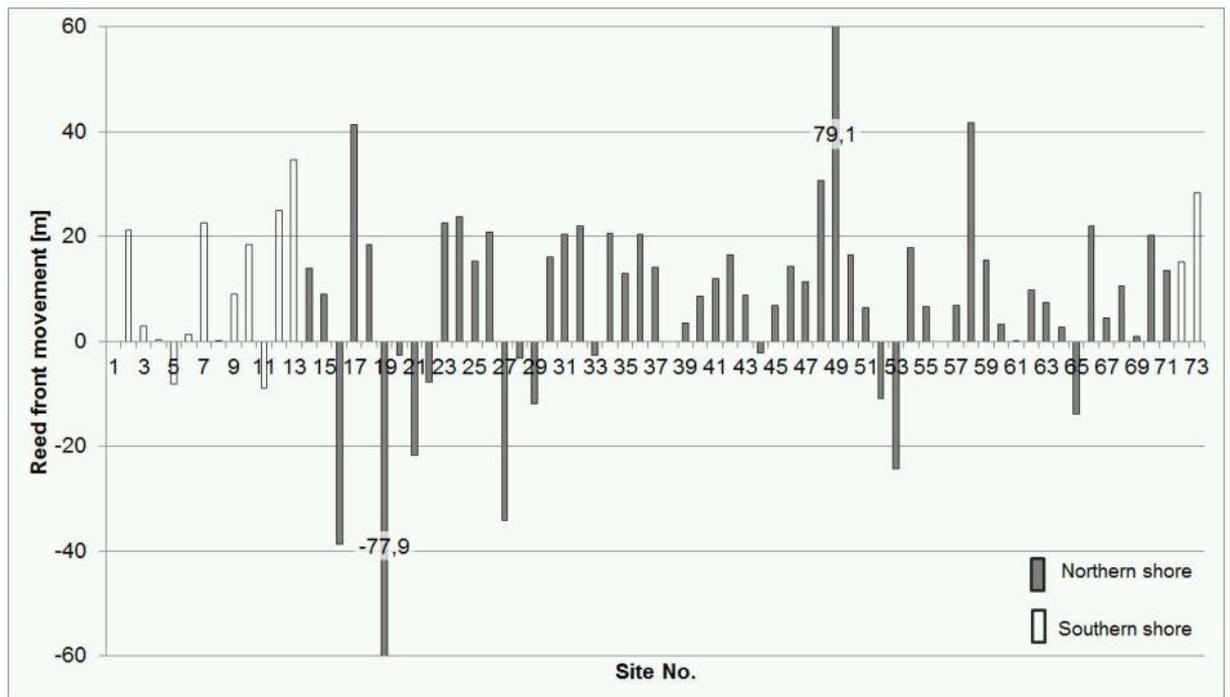


Fig. 32: Reed front movement index of study sites between 1963 and 1975.

The expansion of reed continued between 1963 and 1975 (Fig. 32), albeit at a slower rate than during the previous 12 years but still significantly on both shores. Reed loss was measured at 13 of the 58 Northern shore sites, but the overall front movement was still positive, with a median of +11 meters. The most intensive growth (+79 m) was recorded in the Szemes basin during this period in the sheltered corner of Bozsai bay (site 49). The regression was largest, -79 meters, at Vonyarcvashegy on the border between the Keszthely and Szigliget basin (site 19). The loss that already started during the previous period continued in part of the Szigliget basin (sites 27, 28, 29), mostly in water depths around 2 meters. On the Southern shore the progress of reed continued on all except 2 sites (5, 11), and the median of the front movement was +12 m.

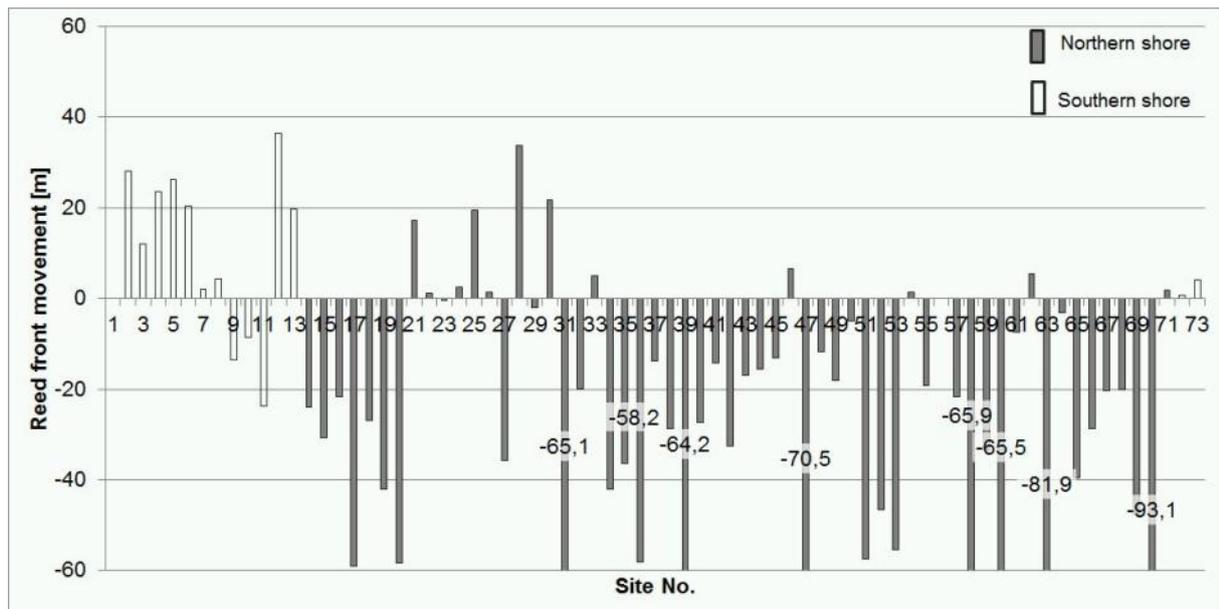


Fig. 33: Reed front movement index of study sites between 1975 and 1987.

The front movement changed dramatically for the period between 1975 and 1987 (Fig. 33). The median of the front movement index for the Northern shore sites was -21 meters, with a significant trend of reed die-back at 45 of the 58 sites. The largest regression was -59 meters in the Keszthely basin (site 17), -58 meters in Szigliget (site 20), -70 meters in the Szemes (site 47) and -93 meters in the Siófok basin (site 70). Growth continued at 9 Northern shore sites (4 showed changes smaller than 2 meters), mainly on the eastern side of the second basin but also at sites where currents or rivers deposit large-grained sediment (sites 30, 54). The difference between the two shores was most explicit in this period. The progress of the reeds on the Southern shore continued in all except three sites, the median front movement being +8 m.

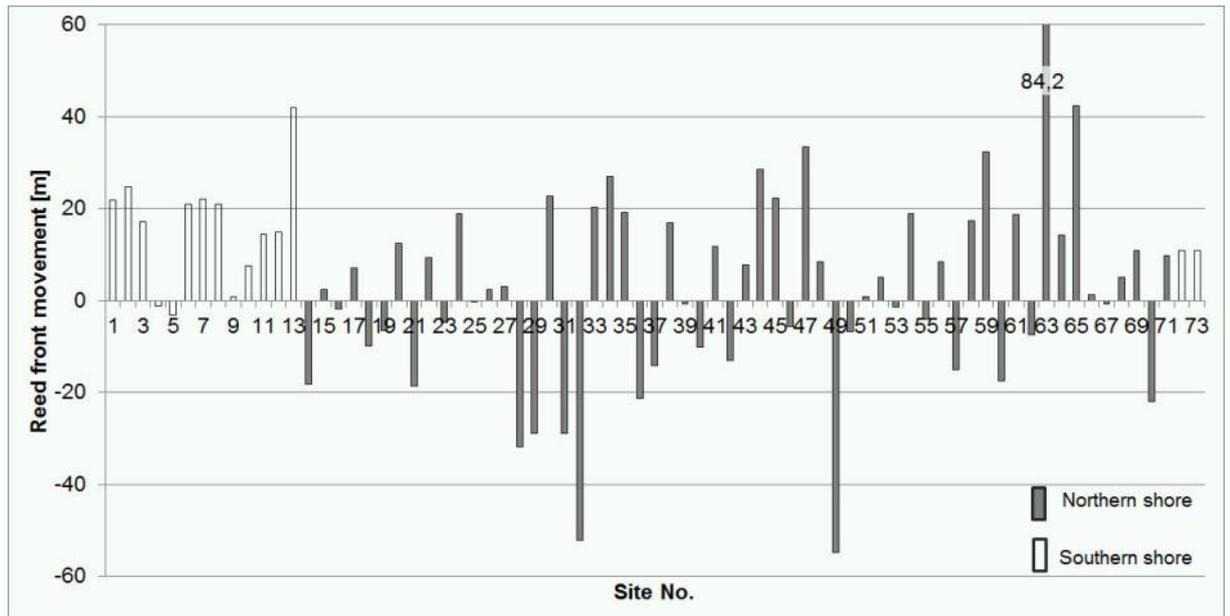


Fig. 34 Reed front movement index of study sites between 1987 and 2000.

Between 1987 and 2000 (Fig. 34), regression continued on 26 and progression started on 32 of the north shore sites, with a median front movement of +2 meters and no significant tendency. Sample sites in the northern part of the Keszthely basin and the east of the Szigliget basin hardly showed any change. More than -50 meters of reed die-back were measured at sites 32 and 49 in the Szemes basin. In the Siófok basin, at the redox measurement sites of the Limnological Institute (Herodek and Tóth, 2001), the healthy stand (site 58) grew +17 meters, and the neighbouring die-back stand lost -15. The most intensive growth, +84 meters was observed in the Siófok basin at site 63. During the previous period (1975-1987), this site lost -83 meters, so the extent in 1963 was re-established by 2000.

On the Southern shore the reed front progressed toward the open water at all except two sites with a median of + 15 m. The largest gain was +42 m near the mouth of Zala river.

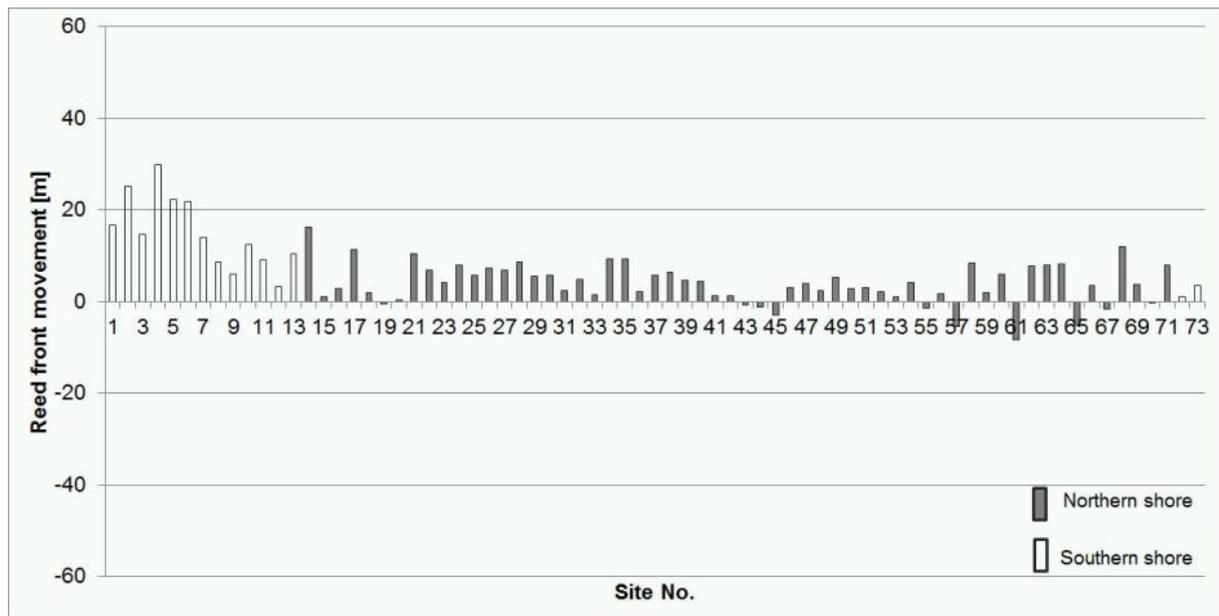


Fig. 35: Reed front movement index of study sites between 2000 and 2003.

Between 2000 and 2003 the reed increased significantly at 49 sites on the north shore (Fig. 34). Out of the other 9 stands only 3 regressed more than -2 meters. At site 57 in the fourth basin reed regeneration started to fill in the gaps in the reed, but the front retreated 5 meters because the toppling of the dying clumps. At site 58 the front progressed 8 meters. The median of reed front movement on the Northern shore was +4 meters. On the Southern shore all stands advanced with a median of +13 meters. During these three years the reed front of the sites on the Southern shore of the Szigliget basin near Balatonmárfürdő progressed 15-29 m towards the open water.

4.4.3 Comparison of the water level changes and reed front movements

The basis for this comparison was a dataset of water levels of Lake Balaton based on standard water gauge readings, and delivered to the Limnological Institute by the Central Transdanubian Water Authority (KöDTVizIg) on 3. August 2012 (Table 2, Fig. 36.). Water levels above +120 cm pose a serious flood risk to buildings on the shore, and regulations effectively avoided them from the 1950-s onwards, also excluding flood damage to the reeds. It is therefore not expected that the upper water level would have had an effect on the condition of the reed belt. The highest water level during the studied period was measured when the progression of reed was the strongest in 1951 (Fig. 36).

Table 2: Water levels and reed front movement in the studied periods (means \pm standard errors). *: Significant at $p<0.05$; Figures in bold are significant at $p<0.01$

	1951-1963	1963-1975	1975-1987	1987-2000	2000-2003
Max. water level [cm]	+125	+113	+110	+114	+111
Min. water level [cm]	+37	+42	+65	+57	+24
Average reed front movement [m], N shore	+23\pm2.6	+8\pm2.8	-25\pm3.6	+3 \pm 2.9	+4\pm0.6
Average reed front movement [m], S shore	+21\pm6.0	+12\pm3.5	+9 \pm 4.3*	+15\pm2.9	+13\pm2.1

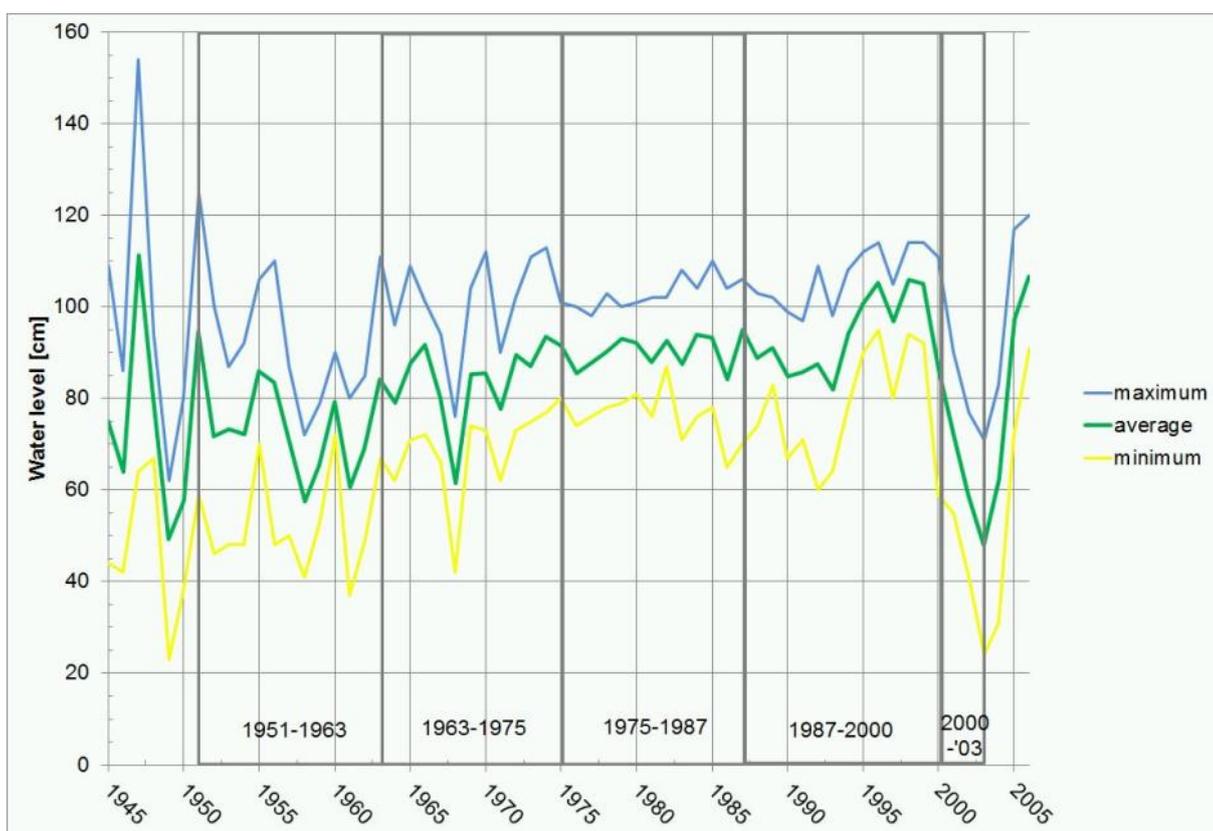


Fig. 36: Minimum, maximum, and average water levels of Lake Balaton during the studied periods.

The minimum water level, however, apparently has a strong effect on reed dynamics on the Northern shore. The strongest progression of the reed front (+19 m) was between 1951 and 1963, when the minimum water level was +37 cm. During the next period, when the lowest water level was only slightly higher, reed progress slowed but continued. Between 1975 and 1987, when the water level never dropped below +65 cm, reed die-back started on the north shore, and the mean front movement became strongly negative. Between 1987 and 2000, while water levels dropped slightly below regulation levels because of droughts,

some stands still retreated, others progressed, adding up to a mean front movement of +2 meters on the Northern shore.

During the extreme low water level period between 2000 and 2003, when water levels reached half a meter below the regulation limits, nearly all reed sites regenerated, creating a mean front movement of +4 meters on the Northern shore, and this was reached in a remarkably short time (3 years) compared to the previous periods (10-12 years).

The front of the Southern shore stands showed continuous progress, with no reed die-back symptoms. The rate of average front progress decreased from the first to the third period, then increased again. The growth was most intensive in the stands near the Zala mouth in the first period and on the Southern shore of the second basin in the last one.

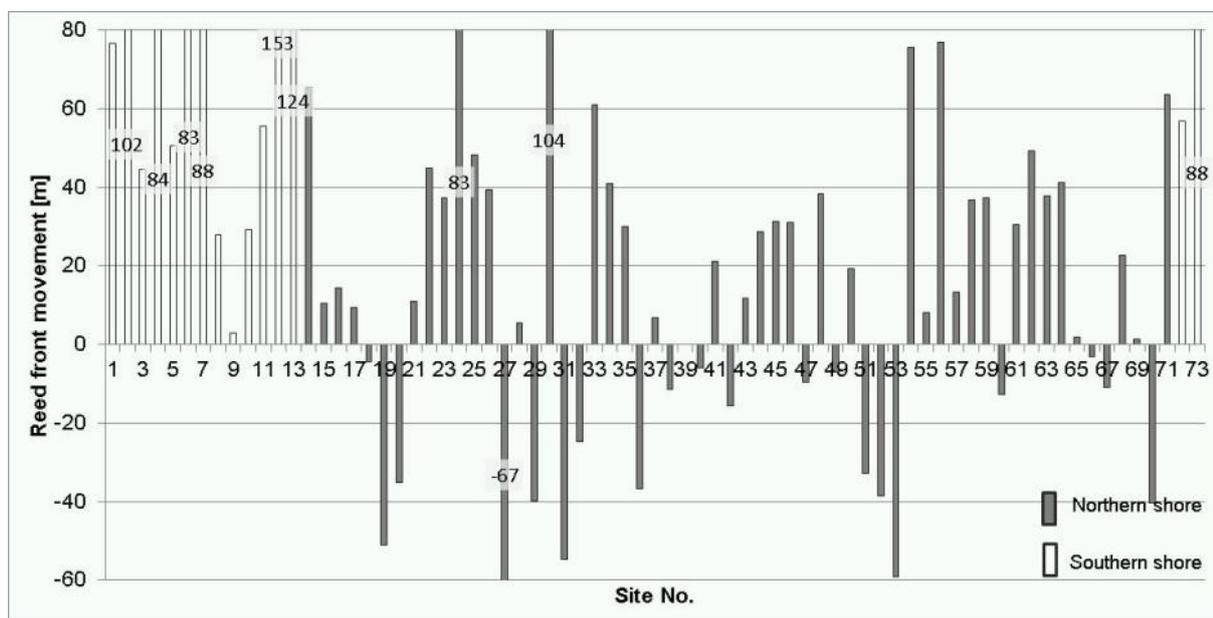


Fig. 37: Comparison of reed area at study sites in 1951 and 2003.

Between 1951 and 2003 (Fig. 37), the summed reed front movement was +23 meters, so despite the die-back of the 1970s and 1980s, the current area of the reed belt is larger than during the initial stage. On the north shore, the average width (perpendicular to the shore) of the reed in the sampled sites was approximately the same as in 1963. On the Southern shore, a cumulative reed front progress of +65 meters was measured for the whole time scope of the measurements. This corresponds to a 6% increase on the northern and to an 80 % increase on the Southern shore respectively.

4.5 Novel ALS-based wetland vegetation mapping method

4.5.1 Results of visual interpretation of the Airborne Laser Scanning Data

The airborne survey of Lake Balaton successfully covered the full shoreline and the Kis-Balaton wetland system, creating a novel vegetation map of nearly 1000 km² with a spatial resolution of 1 m or 2.5 m. Initial 3D views of the point cloud showed that many characteristics of the vegetation are well represented in the vertical distribution and echo intensity of the ALS points.

Quality control of the points revealed that in most cases, echoes from water were lost due to specular reflection and that the canopies were not fully penetrated by the pulses. Multiple echoes were only recorded in trees, as the canopy height of reed vegetation rarely exceeded the minimum vertical distance needed for separation of subsequent echoes of a single pulse. Visual quality control of the resulting maps (Fig. 21) showed that wetland recognition does not miss any known wetland areas but also classifies agricultural fields as wetlands in some cases. Since the main objective of the process was not to mark wetlands in the landscape but to classify their vegetation, these were not removed manually yet.

Flat areas and water were well mapped including small lagoons within wetland areas but artificial elevated structures such as piers, platforms and moored boats under a certain size were misidentified as wetland.

Table 3: Confusion matrix of vegetation categories and accuracies

classified as	reference field photographs									Totals	User's accuracy
	Typha	Carex	Die-back reed	Stressed reed	Ruderal reed	Healthy reed	Tree	Water/artificial	Scirpus		
Typha	78	7	6	7	0	8	0	1	0	107	72.90
Carex	1	29	0	1	1	0	0	3	0	35	82.86
Die-back reed	7	0	75	16	2	13	0	6	1	120	62.50
Stressed reed	0	3	6	78	1	5	2	2	0	97	80.41
Ruderal reed	0	5	0	1	33	0	0	0	0	39	84.62
Healthy reed	2	4	11	4	5	109	0	0	1	136	80.15
Tree	0	0	0	0	0	0	99	0	0	99	100.00
Water/artificial	0	0	0	0	0	0	0	104	1	105	99.05
Scirpus	0	0	0	0	0	0	0	1	36	37	97.30
Totals	88	48	98	107	42	135	101	117	39	775	
Producer's accuracy	88.64	60.42	76.53	72.90	78.57	80.74	98.02	88.89	92.31		

Total accuracy	Cohen's Kappa
82.71 %	K 0.80

Trees and shrubs were accurately categorized but in some rare cases, waves were misclassified as *Scirpus* or *Carex*, especially in the centre of the strips where water reflections were the most intensive (Fig. 21). The patterns of the wetland vegetation classification showed striking similarity to the patterns of vegetation patches observed in the field or on aerial photographs. The overlapping areas of strips showed high similarity except for some edge effects.

4.5.2 Metrics of classification accuracy

The accuracy of the classification was summarized in a confusion matrix, showing the number of reference photographs representing each vegetation class in the columns and the number of tested pixels belonging to each category of the map in the rows (Mather, 2006). The cells show how many instances of a particular vegetation type were classified as members of each map category, with the number of the correctly identified map cells in the main diagonal. Omission errors are when pixels that should belong to a given category according to the reference photos are misidentified and classified to a different category on the map. Commission errors are when pixels that should not belong to the class in focus are erroneously included.

Different indices of classification accuracy exist, representing different potential applications and calculation methods. The following were used for this thesis:

- The User's accuracy for each category, showing how many percent of pixels mapped to a given vegetation class are correct
- The Producer's accuracy for each category, indicating how many percent of the sites on the reference photographs were found to have been classified correctly
- The Total Accuracy for the whole classification system, representing the ratio of correct pixels (the sum of the main diagonal) to all checked pixels
- Cohen's Kappa, which quantifies the selection accuracy of the confusion matrix relative to random guessing, and is thus influenced by the number of categories and their success.

4.5.3 Numeric quality control

For the class "wetlands" (Table 3), the User's accuracy was 97.1% and the Producer's accuracy 100%, indicating that all ground truth points that belonged to wetlands were successfully categorized and only very few non-wetland points were mistaken, mainly open water patches. Therefore, the area of wetlands was only very slightly overestimated.

Trees and shrubs were recognized with a User's accuracy of 100% and a Producer's accuracy of 98.0% (Table 3). Classifying low trees or shrubs as reed was the only source of omission errors and no commission errors were present. No other vegetation was classified as trees and therefore the area of trees and shrubs was minimally underestimated.

The *Scirpus* class has a User's accuracy of 97.3% and a Producer's accuracy of 92.3%, but since this is a relatively rare vegetation type in the study area, only 39 ground truth points could be used (Table 3). Omission errors are caused by classification as die-back reed, healthy reed or water, while the single commission error was a misclassification of open water (waves). The area of *Scirpus* is slightly underestimated.

Water/artificial has a User's accuracy of 99.0% and a Producer's accuracy of 88.9% (Table 3). The only commission error was a *Scirpus* patch misidentified as water but several omission errors were found, mainly because this category also contained artificial structures such as boats and platforms. In the cases when these were not correctly recognized, they were mainly misclassified as die-back reed because they were close to dropout points (open water). Occasionally this class is also falsely determined as *Carex* due to the relatively low height. Since omission errors were more frequent than commission errors, the area occupied by water/artificial surfaces was somewhat underestimated.

User's accuracy for *Typha* was 72.9%, while Producer's accuracy was 88.6% (Table 3). The number of ground truth points found was slightly lower than the 100 used for most categories. Dark coloured reed patches were a source of commission errors, which were also caused by young (bright and low) and dense *Typha* growth categorized as *Carex*. Omission errors were nearly all caused by *Typha* patches and gaps of open water being interpreted by the algorithm as die-back reed. *Typha* was underestimated as shown by the relatively low User's accuracy.

The performance of the *Carex* class could only be tested in 48 control points. User's accuracy was 82.9%, while Producer's accuracy was only 60.4%, the lowest of all classes (Table 3). While commission errors were relatively rare, they strongly affected the calculated accuracy because of the low number of points, with the most important problem being the categorization of artificial structures as *Carex* because of their low height. Omission errors were more frequent, as some of the test points were from exceptionally high *Carex* stands (as revealed by field notes) and classified as reed, while others probably had a low density and thus lower reflectance and were classified as *Typha*. This also meant that the presence of *Carex* in the sites used for ground truthing was strongly underestimated by this classification scheme. If the two non-reed wetland vegetation classes were merged,

misclassifications between them were not counted as errors (Table 4), and this single class would have a User's accuracy of 80.1% and a Producer's accuracy of 84.6%.

Table 4: Classification accuracies of summed vegetation categories.

	number of reference points	correctly classified	ommission errors	commission errors	user's accuracy [%]	producer's accuracy [%]	grouped from original classes:
wetland class	518	518	0	16	97.00	100.00	<i>Typha</i> , <i>Carex</i> , Healthy reed, Stressed reed, Die-back reed, Ruderal reed
reed class	382	359	23	10	91.58	93.98	Healthy reed, Stressed reed, Die-back reed, Ruderal reed
unhealthy reed	205	175	30	12	80.65	85.37	Stressed reed, Die-back reed
wetland not reed	136	115	21	6	80.99	84.56	<i>Typha</i> , <i>Carex</i>

The category reed (including all four reed health categories) had a user's accuracy of 91.6% and a producer's accuracy of 94.0% (Table 3). The main source of commission errors were patchy *Typha* areas classified as die-back reed, and very tall *Carex* stands categorized as healthy or ruderal reed. The main source of omission errors was dark coloured (low-density) reed being categorized as *Typha*. However, since the producer's and user's accuracy was relatively close, the overall area occupied by reed was only marginally overestimated.

Healthy reed had a user's accuracy of 80.2%, and a producer's accuracy of 80.7% (Table 3). Both commission and omission errors were mainly caused by misidentification of die-back reed, and sometimes created by misclassification of stressed reed. The small difference in accuracies suggested that the overall area occupied by healthy reed was correctly measured.

Die-back reed was classified with a user's accuracy of 62.5% and a producer's accuracy of 76.5% (Table 3). Commission errors were abundant as water reflections caused by waves could influence the relatively simple dropout counting algorithm. In these cases, the boundary of wetland vegetation was categorized as die-back reed. Artificial gaps in vegetation or artificial structures creating a patchy pattern were often misclassified as die-back reed. Omission errors were mostly die-back reed being categorized as healthy reed. The current algorithm strongly overestimated the presence of die-back reed.

Stressed reed had a user's accuracy of 80.4% with a producer's accuracy of 72.9% (Table 3). The main source of errors was the uncertain separation of die-back and stressed reed, while some omission errors were a result of misclassification as *Typha*. High grid variance introduced by the vicinity of trees also resulted in some artefacts: in these cases healthy reed was misclassified as stressed. The relatively lower producer's accuracy compared to user's accuracy shows that the area of stressed reed was overestimated. If die-back and stressed reed were merged to a single category, the corresponding user's and producer's accuracy was 80.7% and 85.4%, respectively. This implied that the recognition of reed stress itself was relatively reliable, while quantification of the level of damage was uncertain.

Ruderal reed was recognized with an 84.6% user's and 78.6% producer's accuracy, although the number of ground truth points was relatively low (Table 3). Commission errors were mainly caused by false identification as *Carex*, while omission errors usually involved misclassification as healthy reed. This category was slightly underestimated.

The total accuracy of the survey over the full area of the tested strips was 82.7%, with a Cohen's Kappa of 0.80. This indicated that although errors and artefacts were still present, the general reliability of the classification process was good, with a strong correspondence between ground truths and the classified map.

4.6 New GIS datasets

Through application of GIS methodology to historic maps and airborne remote sensing images and points, a continuous time series spanning several centuries was created. The first results presented in the following sections certainly do not exploit the full information content available, with many possible applications outside the focus of this dissertation.

Land cover changes derived from the historic maps georeferenced for this thesis can be compared to hydrological fluctuations, while historic wetlands could be separated into subunits and their habitat functions assessed with landscape indices. Also, more detailed elevation data and the development of anthropogenic pressure on the landscape could be quantified through time.

The historic aerial photograph series can also serve as a basis for a multitude of ecological studies beyond the scope of this thesis. The change of wetland forest patches, which are highly valuable habitats, can be followed, the increase in the numbers of angling and bathing platforms can be surveyed and, perhaps, accurate comparison with contemporary ground-surveyed vegetation maps would allow separation of historic aerial

photographs into vegetation classes within wetlands. Focusing on smaller regions of the lake, aerial photographs from even more years are available (which did not have full coverage of the lake), and based on the data created for this thesis, more refined investigations can be made.

Detailed botanical studies of the wetland map compiled from ALS are also beyond the scope of this thesis. The first wetland vegetation map with full coverage of Kis-Balaton and the shore of Lake Balaton can most probably serve as a basis for habitat quality studies, ornithological and herpetological investigations and long-term protected area management. Potential applications include quantitative studies of the preferred abiotic conditions of reed, *Typha* and *Carex*, and the fine differences in habitat use of key protected wildlife species between these vegetation categories.

5. Discussion of new methods developed and used during the study

5.1. Georeferencing historic maps

5.1.1 Historic maps as data sources for ecology

In order to understand the ecological role and spatial and temporal dynamics of the reed wetlands in and around Lake Balaton, the ecohydrological history of the catchment had to be investigated, as recommended by Ostendorp (1989). Several possible data sources exist, including historic text documents (Bendefy and V. Nagy, 1969; Virág, 2005), geomorphology, pedology (Lóczy, 1920), and also historic maps. Out of these possible options, historic maps were selected as a main data source because they are detailed and spatially accurate enough, cover the whole study area, and their date and interpretation is relatively clear, especially compared to the other possible sources.

During the processing of these maps, their original purpose and mapping method had to be taken into account. Our analysis was aided by the existence of the original documentation collected during mapping, either in original language (Krieger, 1776a) or in translation (Dobai, 1983). Published studies of military and engineering history also supported the interpretation (Bendefy, 1972, 1973; Virág, 2005; Jankó, 2007).

5.1.2 Georeferencing methods and accuracies

Georeferencing is always a trade-off between creating an ideal fit to the control points of the reference system and preserving the positional consistency of the features on the original map. An ideal fit can be achieved by triangulation (also called rubbersheeting),

where the triangles defined by the control points are distorted one by one with separate parameters, ensuring a perfect fit at all points. If the mapping projection is absent or inconsistent, and if all reference points are correct, then this is a suitable method.

For the maps georeferenced in this study, the mapping projection could be assumed to be consistent (representing a local cylindrical projection), while the control points were not regarded as perfect. In this case, a polynomial, 2 dimensional transformation function was applied based on least-squares optimizing of fit to the ground control points, and leaving a residual error of fit (linear for the Krieger map, cubic for the First Military Survey). This method corrects the systematic errors in mapping, but does not affect the local mapping errors that have random directions. In case of the 50 neighbouring map sheets of the First Military Survey, the difficulty lay in ensuring the seamless fit of the neighbouring map sheets while using separate transformation parameters for each map sheet. The constrained polynomial georeferencing method developed by Gábor Molnár solved this problem successfully (Molnár, 2010). The average RMS error of the >500 points was 140.8 meters, the standard deviation of the RMS errors was 131.8 meters, the minimum error is 3 meters and the maximum error is 707.9 meters. The errors are smaller with this method than those experienced by Podobnikar (2009) using rubbersheeting and somewhat smaller than the average errors measured by Zimova et al. (2006) who used separate transformation parameters for each map sheet, and also smaller than the errors experienced by Dömötörfy et al. (2003) in the Kis-Balaton area, who used a polynomial fit but a lower number of control points.

5.1.3 Georeferenced historic maps as documents of historic conditions and as data sources for further investigation

On a long-term perspective, one of the most important outputs is the existence of a consistent time series of georeferenced historic maps for the Lake Balaton watershed. The originals and paper copies of these maps have been studied in detail by previous authors, but this was always limited by the condition of the maps and the problems of handling the paper sheets. The spatial accuracy of products derived from paper-based maps (e.g. by planimetry) was uncertain, and error assessment was hardly possible. It is also known that several invaluable copies of the Krieger map were lost after the Second World War. Digital archiving of multiple copies could possibly avoid such losses in the future (Virág, 1998), and integration in a GIS allows easy access and accurate analysis. With the georeferencing of the First Military Survey completed for all map sheets with a part inside the Lake

Balaton watershed, a time series of nearly 250 years with a spatial scale of at least 1:28800 has been established.

5.1.4 Method for estimating water levels

Water level fluctuations are a main driver of shore vegetation dynamics and also influence ecological and biogeochemical processes in the open water (Coops et al., 2003; Mitsch and Gosselink, 2003). Accurate measurements of lake water levels are usually available in Europe for several centuries but, beyond this, or where such records are completely absent, other data sources have to be used. Features of shore topography reflect prehistoric or historic conditions but they take decades to form, are affected by later tectonic movements and are usually not more accurate than a few meters. Records of levelling surveys are sometimes available and while they can prove to be very accurate (Lotz, 1973), their recalculation and subsequent interpretation is ambiguous in most cases. The newly developed method used for historic water level reconstruction on the basis of bathymetric contour lines produces strong results since the use of several thousand data points means that the error of the measurement can be well quantified.

The similar method used for categorizing the tributary wetlands on the basis of their elevation produces qualitative but not necessarily quantitative results: the topography of land is more detailed than the lake floor, and the number of data points is much less than for bathymetry. Therefore the effects of georeferencing errors can sometimes conceal the profile. A more detailed approach based on interpolation of the elevation points of the boundaries and also on the use of present-day digital elevation models was attempted by the author but this was discontinued because elevation model interpolation artefacts produced errors with an effect similar to the inaccuracies of the profiling method. Nevertheless, the interpretation of the valley profiles is possible and the results are distinct enough for categorizing the wetlands and drawing ecological conclusions.

5.2 Archive aerial photography

Aerial photographs have been used for decades in reed research and the time series approach clearly offers the possibility of correlation with environmental changes. Historic aerial photographs are usually a relatively cheap data source and are often the only available information with sufficient coverage and accuracy from certain periods. Many European countries conduct regular nation-wide aerial photography surveys, which produce datasets similar to those used for this study. The method or the accuracy of georeferencing and orthorectification is often not dealt with in the literature (Maemets and Freiberg, 2004;

Sickel et al., 2004; Hellsten et al., 2006; Whyte et al., 2008). Some notable exceptions are Csaplovics (1982); Rucker et al. (1999); these studies give detailed descriptions of the method used.

The altitude and spatial coverage of the aerial photos used was sufficient to cover the reed front and also artificial objects on every image for ground control. Using a digital elevation model of the lake shore as an input dataset for orthorectification increased accuracy, especially where the relief of the terrain was high. Automatic edge detection was attempted in order to obtain more reproducible area measurements but the difference in the colour of water and reed was not sufficient in most images (green on green). Manual on-screen digitizing is not free from operator errors but it is also still a reference standard in classification evaluation, e.g. Eysn et al. (2012). In case of this dissertation, all manual digitizing was done by the same operator (the author), ensuring some consistency. The number and distribution of sample sites selected provided a good representation of the spatial pattern of reed die-back and regeneration on the whole shoreline of the lake. Differences between the North and South shore were demonstrated together with the similarity between different basins of the lake. The large scale (high resolution) of digitizing enabled detection of subtle changes, and these were successfully correlated with environmental variables to identify the key driving factor of reed area change.

The most important drawback of manual image georeferencing and digitizing is its labour intensity and thus high cost and time demand. This also means that it is not realistic to use manual processing of aerial photography over large areas for near-real time monitoring. Multi- or hyperspectral imagery can often be classified automatically and the increasing resolution of satellite images means they are often a substitute for dedicated airborne surveys.

5.3 Airborne Laser Scanning

There is an increasing demand for a wetland mapping method that is accurate to the level of a few meters, involves fully automatic processing, uses data that are easily available and does not require a dedicated survey. Airborne Laser Scanning was expected to fulfil all three criteria: spatial resolution is typically at a meter or sub-meter level, a software package is available that supports automatization of the processing chain, and many countries and regions have already organized full surveys of their territory.

5.3.1 Planning of the survey flight

In the case of Lake Balaton, there was no ALS dataset readily available, so the planning and setup of the airborne survey had to deal with a number of trade-offs due to limited flight time and ground resources. The main problem was the decision between full coverage of the study area with a limited ALS ground sampling density or, alternatively, only partial coverage with high ALS point density. In order to survey the whole shoreline of the lake with at least the typical resolution of regional-level surveys (1 pt/m^2), the flight pattern was set to have only single-line coverage of most of the shore areas (Fig. 15). Due to this flight pattern, instead of the typical 50–20% overlap between neighbouring (parallel) ALS strips, in most cases the surveyed ALS strips overlapped with their neighbours at the ends only (2–10% overlap, see Fig. 15). This compromised the absolute positioning accuracy of the data in the vertical sense, creating errors in the range of 10–50 cm between strips. Although the classical parallel block pattern may seem redundant for lake shore surveys as the majority of the surveyed area is open water, it has the advantage that overlaps between strips can facilitate accurate relative and absolute georeferencing (Ressl et al., 2011). The sinusoid scan pattern of the Leica sensor resulted in slightly uneven point densities (<1%) across track and this sometimes created artefacts in the surface variance and Sigma Z layers near the strip edges.

The ALS sensor used works with an Automatic Gain Control that modulates the recorded echo intensity to keep it within the range of data representation (8 bits). Due to the fact that the exact gain function was unknown, Lehner et al. (2011) tested a linear and an exponential gain function based on homogeneous reflecting areas. The exponential function was found to characterize the gain control better and was therefore utilized within the calibration procedure. However, in some regions the calibration method could not reproduce the real surface reflectances due to the time necessary for the gradual adjustment of the gain control voltage.

As the aircraft moved along the shore, most flown strips started or ended with the full width occupied by open water. In the cases where this was the start, the gain control was initially adjusted to the low reflectance of water, and as the plane moved in over the coast, the gain control took about one second of time to reach the values necessary for recording the higher intensity dry land echoes. The first scan lines covering the shore were thus collected using gain control values which were too high; therefore the echo amplitude oversaturated the receiver. The radiometrically calibrated reflectances of these echoes were erroneously low (since they were normalized by the high gain control) and did not represent

the real reflection properties of the surfaces. In these areas, the vegetation was typically (incorrectly) classified as non-wetland for 100–200 m along the shore (reflectances lower than the minimum of the “wetland” category), and classified as *Typha* for the next few hundred metres approximately, as this was the darkest vegetation category. Since the algorithm was applied to each ALS strip separately, and the ends of the flown strips always overlapped along the shore (Fig. 15), this did not have strong influence on the resulting vegetation map.

Surface reflectance reference values have not been measured with an active reflectometer (Briese et al., 2008; Lehner and Briese, 2010) but with a passive spectroradiometer. Despite these difficulties, the reflectance range of the reference areas was sufficient for empirical estimation of the gain control function, which could then be included in the radiometric calibration scheme.

5.3.2 Parameter calculation and classification algorithm

The radiometric correction algorithm proved to work adequately for the echo amplitudes and gain control values usual for wetland vegetation. The resulting reflectance values were successfully used for separation of artificial and vegetated surfaces as well as wetland categories. The water surface recognition algorithm was simple and robust but also introduced errors in areas where waves created ALS echoes from open water. Therefore, the number of dropout points did not only depend on the vegetation pattern but also on the presence of waves, so if a single threshold value was applied to all flown ALS strips, die-back reed was overestimated on flight strips with waves and underestimated on flight strips without waves.

One of the advantages of the classification algorithm presented here is that the decision steps leading to the categorization of pixels are relatively simple to build and understand based on the signature analysis, and can all be directly explained on the basis of the vegetation structure observed in the field. Artefacts often follow the scan pattern and are, therefore, easy to find during image interpretation, while advanced multivariate image classification methods (especially neural networks) can sometimes be a “black box” where errors are difficult to resolve (Mather, 2006). Contrary to the automatic selection of discriminatory parameters and values of multivariate methods, the signature analysis performed here is clear, relatively robust and easy to adapt. Compared to remote sensing methods that are mainly based on spectral parameters, this ALS-based algorithm relies on geophysical quantities such as NDSM height, elevation variance and surface reflectance

(including dropouts) and is thus theoretically independent from many of the mission parameters (flying height, swath width *etc.*). The thresholds and parameters were set based on a detailed understanding of the structure of the different vegetation classes and the representation of this structure in the point cloud. Some threshold values could need adjusting if a completely different point density or footprint size is used, or if the scale of vegetation units is different. It can therefore be expected that the proposed method including ground truthing, signature analysis and decision tree algorithms can be relatively easily adapted to other campaigns.

5.3.3 Selection of categories

The categories were selected before the airborne survey in order to provide ecologically relevant information at the finest detail possible without the need for species-level identification in the field. The selected categories provide a strong representation of the health status of shore wetland vegetation. In the case of reed, quantitative mapping of vegetation health in an ecophysiological sense was realized, with four categories describing the status. In the case of the other categories and the habitat in general, the zonation and patch structure of the wetlands can be visualized and used to represent ecosystem health.

The question whether the information in the ALS point dataset can be mapped to a sufficient number of independent variables for classifying to a relatively high number of vegetation genus and health categories is highly relevant to this study. Identifying further categories numerically representing vegetation structural variables (such as height, density or biomass) would probably have been feasible but was not the focus of this study. The moderate density, discrete echo dataset and the simple decision tree algorithm performed adequately for most categories but, as expected, reducing the number of categories by merging increases overall accuracy values. If *Carex* and *Typha* are merged to “non-reed wetland” and stressed reed and die-back reed are merged to “unhealthy reed”, the overall classification accuracy is 86.6% with a Cohen’s Kappa of 0.85, and these categories are still relevant for conservation ecology. These accuracy levels are probably more suitable for detailed quantitative investigations but the information which would be lost through merging is valuable for the purpose of change detection, monitoring and ecological mapping.

5.3.4 Accuracy of classification categories

The classification of non-wetland categories and wetlands themselves was more accurate than expected with values mostly well above 90% (Table 3). Actually, the overall accuracy

produced and the reliability of the different classification categories can be compared to the repeatability of some completely field-based vegetation mapping surveys (Stevens et al., 2004; Vanden Borre, 2009), which is also regularly between 80–90%. Although the algorithm still identifies some agricultural areas as wetlands (including certain cereal fields and vineyards), it can be used on its own to locate wetland patches in the rather complex landscape of the study area if some data on the location of agricultural areas are accessible. This can help identification of small wetland pockets near the main lake that can have high conservation value as ecological corridors or sanctuaries (Gibbs, 1993; Standovár and Primack, 2001). Vineyards, harbour piers, boats and platforms misclassified as wetland vegetation are a limitation of the point density and not the classification method. Several algorithms have been tested to remove row crops or boats with masts but these were not found reliable enough and would have introduced their own artefacts. The problem of the waves on the lake surface being classified as wetland vegetation could have been eliminated by setting a minimum elevation threshold that corresponds to the water level of the lake. However, this was not attempted because of the inaccuracies of absolute georeferencing in the vertical sense (see Section 3.5.4), and also because some wetlands in the surrounding landscape have lower elevation than the water level of the lake.

Typha and *Carex* are recognized by this basic decision tree algorithm with moderate numerical reliability in the case of the ground control dataset used (60–88%). The pattern of *Typha* and *Carex* patches identified still suggests that major typical stands are correctly recognized, but exceptions to the simple rules applied here cause errors. The main problem source, artificial structures misclassified as *Carex*, can compromise direct quantitative use, but these can usually easily be recognized when viewed as a map and removed or labelled manually if necessary. In some cases, the misclassification of tall *Carex* stands as reed, or low density reed stands as *Typha* has some ecological relevance, since similarity between the vertical structure of these confused vegetation types also means that they form similar habitats.

The presence of reed, the macrophyte with the highest conservation value, is recognized by the algorithm with considerable accuracy (>90%) (Table 4). The identification of reed is balanced in terms of under- or over-estimation and reed is rarely mistaken for other macrophytes. This implies that ALS time series can be used for automatic detection of subtle changes in the area occupied by reed, such as those caused by water level fluctuations (Dienst et al., 2004).

The identification of healthy reed areas is also balanced and relatively accurate. Classifying healthy reed areas in the last step of the decision tree algorithm (“all areas previously unclassified”, Section 3.5.7) was expected to be a source of error, since this means many exceptions to rules are classified as healthy reed. Since healthy reed is the most abundant vegetation category on the lake, it was assumed that this class would be the least compromised by such criteria, and this is proven by the satisfactory accuracy.

Since reed die-back is well known to affect the stand structure of reed, while the effect of reed stress on ecophysiological properties (and thus radiometric properties) at the stand level is not fully understood (van der Putten, 1997), ALS holds a strong potential for monitoring reed health. Although numerical quality control showed that reed die-back is overestimated by the set of parameters used, these artefacts are often easy to locate during interpretation as only a narrow strip on the immediate border to water is labelled as die-back. Artificial objects and structures classified as die-back reed, such as boats or fishing platforms, can be more difficult to recognize, but since their area is relatively small, they can be assumed to have a negligible contribution to the summed area.

The identification of stressed reed (as defined in Section 3.5.2) was more accurate than die-back reed, as the data parameters used here were less influenced by artefacts.

Finally, ruderal reed could also be identified with adequate accuracy even though it is a rare category and separation from other reed types is often not evident in the field. Misidentification as *Carex* is explained by the field observations that vertical growth of reed stalks is often impaired by competition of other species present (creating low vegetation heights similar to *Carex*), and *Carex* also tends to form mixed stands with ruderal reed.

Selecting larger cell sizes might also have enhanced the classification quality, but since change detection is one of the planned applications, spatial resolution had to be kept within the expected range of short-term relocations of vegetation boundaries. The hybrid approach of using 2.5 m cells for wetland classification and masking this with a 1-m raster of non-wetland categories allowed accurate detection of changes in wetland area without creating redundantly high resolution data from low resolution input rasters.

5.3.5 *Quality control method*

The usual method for quality control is cross validation: separating the ground truth polygon dataset, reserving some pixels for automatic validation and using the rest for calibration (Mather, 2006; Wang et al., 2007; Artigas and Pechmann, 2010). In this case, a

different approach was chosen because the relatively low spatial resolution ($2.5 \text{ m} \times 2.5 \text{ m}$) of the output wetland classification raster restricted the number of pixels available from the $10 \text{ m} \times 10 \text{ m}$ area of the ground truth polygons. Since the number of pixels used for algorithm calibration is a crucial factor of the classification accuracy (Pal and Mather, 2003), all of these were used for signature analysis in case of this study. Although field-based information can be slightly less objective, the ground image-based validation provided widespread spatial coverage and a full range of vegetation types. However, since quality control was not automatically performed, errors of the operator cannot be completely excluded.

5.4 Comparing ALS classification accuracy with other studies

5.4.1 Multispectral and hyperspectral surveys

The classification accuracy reached in this study is clearly lower than the maximum possible accuracy achievable by multivariate processing of hyperspectral data, but many wetland hyperspectral surveys have produced similar or lower accuracy and Cohen's Kappa values (Wang et al., 2007; Burai et al., 2010; Hunter et al., 2010). The overall accuracy of 99.2% has been reached during classification of ROSIS imaging spectrometer data to five vegetation categories in a saltmarsh (Belluco et al., 2006). Other studies of hyperspectral classification of wetland vegetation show accuracies from 90% (Kappa = 0.87) for six classes (Artigas and Pechmann, 2010) and 91% (Kappa = 0.87) for five classes (Wang et al., 2007), to 78% (Kappa = 0.63) for six main dominant littoral vegetation genera (Burai et al., 2010) and 78.3% (Kappa = 0.72) for five wetland vegetation growth-form classes mapped by 15 selected hyperspectral bands (Hunter et al., 2010).

5.4.2 Combined ALS-multispectral surveys

The accuracy of the current survey is also within the range of some multispectral-ALS fusion studies: the dendrogram-based classification of fused Compact Airborne Spectrographic Imager and ALS data yielded an overall accuracy of 74% (Kappa = 0.66) for six classes (Verrelst et al., 2009). Object-oriented classification of ALS data fused with QuickBird satellite images identified six main land cover categories in a riparian savannah setting with an overall accuracy of 85.6% (Arroyo et al., 2010) (Kappa not published). By fusing a simple ALS-derived canopy height mask with selected bands of a hyperspectral dataset, detection of reed stands could reach an accuracy of 94% for two classes (Kappa not published) (Onojeghuo and Blackburn, 2011). In case of forests, the fusion of ALS with

aerial photographs or multispectral images also produced accuracies above 95% (Holmgren et al., 2008). Identifying 3 natural and 5 artificial classes in an insect habitat mapping context was possible with an overall accuracy of 89,2% (Kappa = 0.88) by fusion of multispectral images with a LIDAR-derived canopy height model (Hartfield et al., 2011).

5.4.3 ALS-based vegetation surveys

An ALS-based study aiming at detecting a single invasive genus (*Spartina* sp.) found that the accuracy reached by vegetation filtering of the point dataset was sufficient for identification of stand expansion and sediment accumulation (Rosso et al., 2006). A comparable study of vegetation mapping in an intertidal environment based on dual-wavelength ALS provided a remarkable overall accuracy of 91.89% (Kappa = 0.91), based on vegetation cover estimation using the reflectance ratio of the two bands in addition to vegetation structure (Collin et al., 2010).

In forests, the accurateness of vegetation categorization based on ALS can be similar to this study: separating coniferous and deciduous trees is possible on the basis of full-waveform data with 85% overall accuracy (Hollaus et al., 2009), while the identification of the three main deciduous tree genera had an accuracy of 64% (Kappa values not published) (Brandtberg, 2007).

These studies indicate that hyperspectral surveys, combined hyperspectral-ALS classification or dual wavelength ALS can sometimes provide better accuracies than single-band ALS, both in forests and wetlands. It is not to be overlooked, however, that most comparable studies use less categories for classification. Single-band ALS-based classifications have similar reliability in forests and wetlands, which is explained by the fact that homogeneous patches in wetlands can have horizontal extents similar to or larger than trees, and thus the units of classification are in fact often larger compared to the ALS point density in wetlands.

In addition to classification accuracy, many other factors have to be considered during survey planning: constraints on flight or ground truthing time, weather, or funding can mean that in some cases, classification of single-band ALS data can be the most efficient method.

5.5 Applicability of the new method for regional and local scale wetland vegetation mapping

The fact that ALS surveying is often carried out in preparation for major construction projects means that the method presented can potentially be applied in rapid impact

assessment involving wetland areas, providing information not only on the area but also on the condition of the wetlands that are to be affected. The potential of ALS data for accurate topography mapping and change detection was also recognized by several national and state governments in the last decades (Surveying and Mapping Authority of the Republic of Slovenia, 2010), leading to full surveys of regions or states (Flood, 2001; Briese et al., 2007; Hoffman et al., 2012; Lysell, 2012). These datasets are widely used for forest monitoring, natural hazard recognition, infrastructure planning, geomorphologic investigations and even change detection in the regions that have now been surveyed several times (Fritzmann et al., 2011). ALS data are thus already available for large areas including many of the largest European lakes (Austria, Switzerland, southern Germany, southern Sweden, Norway and Finland, the Netherlands, major Hungarian lakes). Since these regions have been surveyed with ALS settings similar to those used for this study, it can be expected that wetland maps based on the regional datasets would also have similar accuracy. Even if the created maps would not necessarily correspond to the immediate present, they would support the creation of wide-scale wetland inventories such as Oberleitner and Dick (1996); Zalidis and Mantzavelas (1996) and hold valuable information for change monitoring, habitat assessment and theoretical ecology.

6. Discussion of results

6.1 Reed wetlands and water level variations in the history of Lake Balaton

6.1.1 Wetlands and water levels before the regulation of the water level

During the 18th century, especially the Southern shore and tributaries were relatively sparsely populated. Until the end of the Ottoman occupation of present-day Hungary (closed by the Treaty of Karlowitz in 1699), the Southern side of Lake Balaton was an active border zone with regular military action. Resettlement and clearing of agricultural land took place during the 18th century but this probably did not have a major effect on the existing wetlands for some time. The water level of the lake was unregulated except for a mill dam across the outflow, and according to our measurements was not more than 2 meters above the current water level. Previous authors (Bendefy and V. Nagy, 1969) generally describe a higher water level on Lake Balaton for this period, around 110 m ASL, mostly based on the maximum or mean elevations of the inundated area of the valleys.

Calculations of a hydrological equilibrium also have suggested this water level for the balance of inflow and evaporation. While this latter is mainly controlled by the surface of the water, it has been shown that high water levels in the tributary valleys do not necessarily have to result in high water in the lake as well, since not all valleys are in a close hydrological connection with the lake. No levelling-based calculations of the water level of Lake Balaton support floods above 108 m to the best knowledge of the author in studied time frame.

6.1.2 Categorization of tributary wetlands

Based on the results of this thesis, an important change in perspective can be made regarding the tributaries of Lake Balaton: Many previous studies discuss the water levels and connections of these wetlands in general, but it has been clearly shown that not all wetland basins connected to Lake Balaton behaved in the same way during history. Although this is not a surprise, it cannot be emphasized enough that ecohydrological conservation measures require a different approach for each of these areas. Evaluation of the slopes and water levels of the tributary valleys often agree with results obtained from different studies. The Western Kis-Balaton has hardly any slope, but it is important to note that this area was never an integral part of Lake Balaton because it is separated from the Eastern Kis-Balaton and the lake by an elevated ridge which is cut through by the Zala river. During the investigated period the Western Kis-Balaton had a mean elevation 3.5 meters higher (110 m ASL.) than the 18th century elevation of Lake Balaton (106.5 m ASL). The sediments of the main part of the Tapolca Basin have been proved by pollenstratigraphic investigations to be of fluvial and not lacustrine origin (Zólyomi and Nagy, 1991), and the geological map of Lóczy (1920) also clearly marks the border of lacustrine-type sedimentation. The Nagy-Berek wetland is somewhat different from most wetlands because it is separated from the lake by a sandbar which reaches a width of 1 kilometer in some areas, and is only crossed by the rivers flowing into the lake. According to Józsa (1899) this sandbar has an older (“diluvial”) compacted core which is less penetrable to water, so Lake Balaton only influences the water levels of the wetland through the inflowing river. Most of the areas of these major wetlands lie in higher elevations than the 18th century water level of the lake. The investigated part of the Sió valley lies between the mouth of the River on the shore of the lake and a bottleneck of the valley between Mezőkomárom and Szabadhídvég. Cholnoky (1918) describes this basin of the Sió river to have been an integral part of the lake based mainly on geomorphological

investigations but also on the fact that he found no fluvial deposits in the valley between Mezökomárom and the lake. The geomorphology of most of these valleys allows for a strong connection with the water system of the lake, although the deeper layers of the sandbar along the Southern shore act as a barrier according to Józsa (1899). The flow of water along the fluvial-type wetlands is unidirectional but in the small lacustrine-type valleys along the Southern shore, especially the Szemes valley, floods of the lake can drive the lake water upstream and into the wetlands as described by Cholnoky (1930) and also observed by the author, sustaining very strong hydrologic connections.

6.1.3 Human influence on wetland hydrology

Between the late 18th and the early 19th century, 39% of the wetlands were drained according to the First and Second Military Survey. These changes happened before the first documented lowering of the lake level in 1848, which means that, contrary to the most widespread opinion (Lotz, 1978), the lowering of the water level of Lake Balaton was not the primary cause of wetland loss on the watershed. Mainly the upstream part of the valleys was affected through canalization of the tributary rivers and demolition of mill dams. While this change probably did not influence the functioning of the wetlands in the ecosystem of Lake Balaton, it must have significantly affected their role as ecological corridors.

Between the early and late 18th century, parallel to the opening of the Sió canal, mostly small wetland patches were lost, 30 km² altogether. The areas closest to Lake Balaton in elevation and distance remained wetlands to the present day or were converted to fishponds. The connection between these wetlands and the lake itself was mainly influenced by the development of shore resorts, the regulation of the inflows and the building of road and railway embankments. The water level changes initiated during the 19th and 20th century on the watershed also affected the water balance of the lake: on one hand, one third of the historic surface area of the lake-wetland system was lost, decreasing evaporation and increasing outflow; on the other hand, the total amount of water stored upstream of the Lake on the watershed was reduced by approx. 15%, possibly leading to larger fluctuations in the water regime of the lake.

6.1.4 Water levels of Lake Balaton

Analysis of maps and levelling archives showed that the water level of the lake underwent the following changes before and during regulation (Fig. 28), (Sági, 1968; Lotz, 1973): firstly there was a general trend of decreasing water level during the 18th and 19th century that started around 107 in 1776 and receded with fluctuations of a meter annually

and 2-3 meters on a decadal scale to 105 m ASL by the start of the regulation. Neither the demolishing of the Siófok mill nor the opening of the Sió sluice showed an effect on water level for more than a decade: the capacity of the Sió canal had to be enlarged in several steps before it could play a significant role in flood control.

As the water level reached a long-term minimum of 103 m ASL in the 1860s, the previously established reed stands ran dry for several years, while new reed vegetation was established on the newly uncovered sediment surfaces. After the water level returned to 105 m, which became the regulation maximum, these reed stands were under up to 2 meters of water, which approximately corresponds to the depth limit of reed on the Lake. Since the germination of the seeds requires dry land with abundant subsurface water (Engloner, 2009), these conditions could have been ideal for the establishment of the present-day stands from windblown seeds. The area of the lakebed that was probably uncovered during this low water level event is thus probably the same surface that is today covered to maximum water depth of 2 meters including most present-day reed stands. This implies that the bulk of the reed areas around Lake Balaton must have been established before or during the mid-19th century.

The discharge capacity of the Sió canal was increased in several steps between 1900 and 1976 but, during this period, floods higher than the regulation maximum could not be efficiently avoided. Due to the lack of aerial images before 1951, the effect of these high water levels on the reed stands can only be assumed. The rapid growth of the reed areas observed on the aerial images between 1951 and 1963 was probably partly a consequence of widespread reed losses induced by the last major flood of the lake (105.64 m ASL) in 1949.

Parallel to the expansion of the Sió canal, the priorities of water level management also changed. Until 1970, the most important goal of water regulation was to avoid damage from floods. The reduction of maximum water levels was a consequence of increasing discharge of the sluice and also improving weather forecasts. In order to maximize profit from tourism, the water level regulation of the lake was subordinated to the new goal of keeping stable and high water. Until 1975, the official mean water level was +75 cm (104.84 m ASL), and the official minimum and maximum +40 and +100 cm; after this, different regulation levels were introduced for each calendar month but the overall planned mean water level was +100 cm and the minimum regulated to +85 cm in some months. This change in policy effectively halved the water level fluctuation range of the lake (from

60 cm to 30 cm) and increased the average level by 25 cm (nearly 10% of the mean depth of the lake!).

6.2 The causes and dynamics of reed die-back and regeneration on Lake Balaton and other lakes

6.2.1 The possible causes of reed die-back other than eutrophication and water level changes

The similarity of reed die-back symptoms across many European lakes suggests a common cause. According to the review of van der Putten (1997), the indirect effects of eutrophication, enforced by water regime management are the most important factor. However, since reed is a very widespread species inhabiting different biotopes (Rodewald-Rudescu, 1974), reed stands in different locations are subject to many different damaging processes. The review of Ostendorp (1989) of reed die-back on 35 different European lakes lists many different causes that were associated with reed loss according to the local research or management in addition to eutrophication and water regime changes.

The first group of them is the direct destruction of reed. On Lake Balaton, littoral vegetation was removed during the construction of harbours or beaches, or damaged by the deposition of dredged sediment. Luckily, this only affected a small part of the reed area, and is now prohibited by law.

Mechanical damage is listed as the next category. However, motor boats are not allowed on Lake Balaton, freight traffic is also absent and passenger ship routes are far from the shore, therefore, waves generated by vessels are not expected to affect the reed. Drifting wood is rare on the lake and could not have had a direct effect, but drifting ice could be an important factor occasionally.

Herbivory certainly affects reed on Lake Balaton, but no major effects of this could be demonstrated, nor any correlation with the dynamics observed during this study.

The muskrat (*Ondatra zibethicus*), was first observed on Lake Balaton in the 1930's (Entz and Sebestyén, 1942) and is still present on the lake, but not in large numbers. The grass carp (*Ctenopharyngodon idella*) entered Lake Balaton during the 1970-s, and is known for grazing its own weight of macrophytes every day in summer. According to fishery records, some 59 tonnes of this fish were caught from the lake between 1981 and 1995 (Virág, 1998). Several parasitic insect and fungi species were identified on Lake Balaton reed, but there is no evidence of spatial and temporal patterns that would explain these processes.

6.2.2 *Eutrophication and reed die-back*

During the early years of reed die-back research, eutrophication was often mentioned as the main cause (Schröder, 1987; van der Putten, 1993; Klötzli, 2005). This seemed self-evident as eutrophication strongly influenced the ecology of the affected lakes, and reed loss often happened before or during eutrophication events.

In Lake Balaton the primary production of the phytoplankton was similar in all four basins during the 1960s, and corresponded to a mesotrophic level (Böszörményi et al., 1962). By the next decade, the production increased by a factor of eight in the Keszthely basin, four in the Szigliget basin, three times in the Szemes, and doubled in the Siófok basin (Herodek, 1977). Due to this gradient the effects of trophic changes can be studied both in space and time in this lake. The very short turnover times of orthophosphate in the water indicated that the trophic state is determined by the phosphorus supply of the lake (Herodek, 1986). A large scale eutrophication remediation program started in 1983, and reduced the phosphorus load to its half until 1993 (Herodek et al., 1995). The water quality improved and is close to pre-1970s values since 1995.

The chlorophyll content of the water is measured bi-weekly by the Central Transdanubian Water Authority since 1975. According to these data the Keszthely basin could be classified as hypertrophic between 1975 and 1995 and eutrophic after that. The Szigliget basin fluctuated between hypertrophy and eutrophy between 1975 and 1995, then it became moderately eutrophic. The Szemes basin is continually eutrophic, the Siófok basin mesotrophic since 1975.

Focusing on each of the basins separately, it would seem that reed die-back started after eutrophication, and the stands regenerated after the water quality improved. However, at the scale of the whole lake, reed die-back was observed in the Siófok basin under mesotrophic conditions, and intensive regeneration was measured in the other three basins while the water remained eutrophic. As the spatial distribution of reed die-back does not reflect the pattern of water quality, eutrophication cannot be a major factor of reed die-back in this lake. This is in agreement with the results of Ostendorp et al. (2001), who, after comparing reed performance with trophic indices from 51 European lakes and wastewater treatment wetlands, concluded that trophicity can not be a major factor of reed die-back.

6.2.3 *Water level changes and reed stands*

Water level changes can be different in their duration, frequency and amplitude (Coops et al., 2003; Leira and Cantonati, 2008), and are known to have a fundamental influence on the distribution, composition and succession of shore vegetation (Mitsch and Gosselink, 2003). The optimal water depth for reed is 0.5-1 meter (Haslam, 1972), so rising water levels cause problems on the open water side, and falling water levels on the shore side. The maximum water depth tolerated by reed for longer periods is usually 1.5 meters in the temperate latitudes and higher in the Mediterranean region and the tropics (Rodewald-Rudescu, 1974).

Culms growing in deeper water need more reserve carbohydrates (Crawford, 1992), meaning that fewer resources remain for rhizomes and roots responsible for nutrient uptake, clonal expansion and fixation of the plant (Asaeda et al., 2006), and shallower water means the horizontal expansion of the rhizomes and, therefore, the increase in reed area is much faster (Weisner and Strand, 1996). On Lake Garda, aerial images showed decreasing shoot density of reed stands during periods of water levels 40-50 cm higher than average (Bresciani et al., 2011).

Water levels high enough to completely submerge the stalks impair CO₂ uptake from air and also oxygen transport to below-ground organs. Widespread loss from such events is well documented (Rücker et al., 1999; Ostendorp et al., 2003).

Reed can survive on dry land provided the groundwater table is high enough to be reached by roots. Of course, heavy droughts can cause water loss too severe to be tolerated by reed. On dry land, however, it is more common that established reed stands are replaced by other plants. Trampling and grazing of livestock or herbivory by birds can also induce reed loss on land (Rodewald-Rudescu, 1974; Coops et al., 2004).

Stable water levels are demanded by ship transport, recreational activities and other human uses of water. During the last decades, many lakes have been affected by the stabilizing of water levels that caused degradation and loss of reed stands (Rücker et al., 1999; Dienst et al., 2004; Gigante et al., 2011). In these cases, the problem for reed is not the high water level but the lack of occasional low water levels.

Many studies show that artificial or natural water level drops temporarily uncovering the sediment surface have a positive effect on the reeds (ter Heerdt and Drost, 1994; Maemets and Freiberg, 2004; Papastergiadou et al., 2006; Whyte et al., 2008; Liira et al., 2010). The seeds of reed are unable to germinate if covered by water. Young seedlings are very vulnerable to flooding (Baldwin et al., 2010) and dry lake bed surfaces with no vegetation

are ideal for them. Another advantage of low water levels is the good ventilation of the soil in contact with air promoting a faster decomposition of the organic matter and the vegetative spread of the reed (Weisner, 1996). Rea (1996) suggested that stabilised water levels are contributing to reed decline through a lack of vegetative and generative reproduction.

6.2.4 Changes of reed stands on Lake Balaton after 1951

The extent of reed on the lake was estimated on the basis of aerial images by previous studies for the purpose of hydrographic mapping and commercial harvesting of reed. However, the detailed results and maps were not published, only the total areas covered by reed on each shore (Virág, 1998). According to this source, area of reed on the north shore of the lake was 11.32 km² in 1958, 14.6 km² in 1968, 13.07 km² in 1975, 9.82 km² in 1984, and 8.99 km² in 1993. On the Southern shore, 2.34 km² of reed stands were documented in 1958, 4.01 km² in 1968, 3.72 km² in 1975, 2.89 km² in 1984, and 2.3 km² in 1993. The author of the cited study draws attention to the uncertainties of these datasets himself, because the images were not orthorectified but optically-mechanically processed, and because all vegetated areas inside the shoreline (not only reeds) were considered reed stands before 1984.

The actual change in the area of shore reed is a sum of the changes on the shore and lakeward side. Since European reed die-back is characteristic to the water side (while changes of the shore limit are governed by many other processes), this study focuses on the lakeward front of reed. This excludes any uncertainties that would be introduced by changes of species composition on the shore side that are more difficult to quantify.

On the Northern shore, comparing previously published areas with those measured for this study, the period between 1951 and 1963 shows synergy between the datasets, (increase in reed area and movement of the reed front towards the water), while between 1963 and 1975, the previous data indicate loss of reed area while our results prove that the reed front continued to advance. Again, the previous assessments imply a slight decrease of reed area between 1975 and 1993, while our results show severe regression of the reed front between 1975 and 1987.

On the Southern shore, previous data suggest that the area of reed decreased between 1963 and 1993, but our results show continuous progression of the reed front towards the water.

For the period between 2000 and 2003, no previously published datasets are known to the author, but the quick regeneration of reed can easily be explained by the recovering oxygenation of the sediment. This short drought period acted as a natural experiment: after the time between 1975 and 1987 demonstrated that the lack of low water levels is detrimental to reed, it was observed from 2000 to 2003 that a drop in water level benefits the health of reed. The uninterrupted increase of reed along the Southern shore can easily be explained by relatively recent establishment of reed, the low slope and the low organic content of the sediment of the lake shore, as the stands have not yet reached water depths (and thus redox potentials) that limit their growth.

6.2.5 How the lack of low water periods can lead to reed die-back

In anaerobic sediments, phytotoxins are formed which injure the ventilation system of the rhizome as proven by detailed laboratory studies (Weisner, 1996). The death of the apical buds on the horizontal rhizomes allows activation of the secondary buds on the vertical rhizomes, thus resulting in the typical clumped growth (Armstrong et al., 1996b). Studies describing actual redox potential measurements in the sediment of natural reed stands are rare (Armstrong et al., 1996b; Fogli et al., 2002), but it is reasonable to assume that anaerobic conditions are responsible for reed die-back.

It is easy to understand the favourable effect of low water periods on sediment redox potential if these are low enough to uncover the sediment and allow direct contact with air. However, in Lake Balaton, the lakeward edge of the stands (where die-back and regeneration occurred) remained covered by water even during the low water level period. Weisner and Strand (1996) elaborate the connection between reed expansion and water levels: low water levels mean shorter oxygen transport pathways within the reed stalk and rhizome, and thus provide an opportunity for intensive growth of the horizontal rhizomes. This is probably enhanced by the reduction in the oxygen demand of the sediment that was measured by Herodek and Tóth (in prep) in connection with low water levels: if oxygen loss to the sediment is lower, the horizontal rhizome tip receives more oxygen regardless of the water depth, and thus advances and colonizes new areas faster.

The redox conditions can be influenced either by changes to oxygen supply or organic matter removal. In shallow water, oxygen supply is facilitated by the shortening of the diffusion path between the atmosphere and the sediment through the water column. Currents near the sediment are typically more intensive than in deep water, enabling more oxygen transport from well-oxygenated open water (Schröder, 1979a). However, the near-

sediment currents in shallow water may be most important in removing the accumulated organic debris from the reeds during seiche movement.

While the connection between reed area loss or regeneration and water level changes has been discussed by previous authors, this thesis presents a quantitative study on a spatial scale finer than any previous investigation known to the author. This is enabled by the accuracy of georeferencing and the high resolution of the digitizing process. The large number of measurement sites cover different conditions within a major lake, allowing the exclusion of some factors previously suspected, and providing statistically sound results. The use of archive aerial images provides coverage of a period long enough to include different water regulation regimes.

6.2.6 Different periods of reed growth on Lake Balaton

According to these datasets, five different periods of reed growth can be distinguished on Lake Balaton. Before 1863, the practically unregulated water level of the lake caused reed to occupy a higher elevation range than during present times. Between 1863 and 1951, periodic floods limited the distribution of reed. Between 1950 and 1975, the capacity of the Sió canal was high enough to prevent floods and thus open the previous limit, and the minimum levels regularly reached +40 cm, low enough to allow expansion of reed practically everywhere around the lake. After 1975, when the minimum water level was raised to +70 cm, the accumulation of organic matter in the sediment became more intensive and reed die-back started on the waterward front of the North shore reeds, while the Southern shore reed belt continued to expand. Finally, during the extreme low water levels of 2000 and 2003, the reed belt rapidly regenerated and regained some of its lost area.

6.3 Management aspects

6.3.1 Problems of lake management

From the water resource management perspective, the most important question is whether it is indispensable to lower the minimum water level to stop die-back. As the reed front retreats, the edge arrives in shallower and shallower water. It is unknown whether this process is sufficient to stop reed loss by itself after reaching a steady state. If this is not the case, and drawdowns are necessary, then their timing and extent remain to be optimised. The results suggest that lowering the water level in autumn to +40 cm every 4-5 years would sustain healthy reeds. The concern is whether precipitation would be sufficient for

the water level to return to +100 cm by the tourism season of the next years. The probability of a drought as extreme as between 2000 and 2003 is minimal (Honti and Somlyódy, 2009), but individual dry years could also cause water shortage.

6.3.2 Recommendations to lake management

According to the results obtained from historic maps, the water regime of some tributary wetlands is independent from the lake in many cases and, therefore, their reconstruction could be possible without interfering with the water level of the lake, often simply by changing the regulation scheme of the drainage canals. In case of the rest, opening the drainage channel banks and recreating a more natural flow would allow periodic high levels of the lake to have more influence on the water level of the wetlands. Such reconstruction efforts should focus on the wetlands that are closest in elevation to the present-day water level of the lake in order to ensure a good hydrological connection: these would be the tombolo triangle of Szántód, the valley between Balatonszemes and Balatonlelle, and the outflowing valley of the Sió river. As shown by the success of the Kis-Balaton restoration project, ensuring a suitable hydrological regime allows the succession of natural vegetation to lead to habitats of high natural value. In the cases where these wetlands still exist, their connection to the water system of the lake should be maintained by fish ladders, wildlife crossings and constructed wetland corridors. Pollution and degradation of these existing wetlands should be monitored and controlled, while the entry of farmed fish into the water system of Lake Balaton has to be avoided.

While on-site protection of the reed belt on Lake Balaton has to be continued, water level management should consider lowering the water level of the lake to ca. +40 cm approximately every five years, if natural water level fluctuations do not provide a similar effect. The building of platforms and jetties in the reed should be controlled, especially on the Southern shore. The extent of healthy and die-back reed should be regularly monitored, together with the spread of *Typha* and the decline of *Carex*. Regular ALS campaigns perhaps every ten years would supply this information and could also be used for other purposes.

7. Conclusions

- The earliest accurate measurement of the historic water level of Lake Balaton was identified as 107.0 meter above the Adriatic benchmark, as a medium water level in 1776. The difference between two independent measurements of the water level

elevation derived from two different elevation contours (thus two independent measurements) was 53 cm, the standard deviation of the measured values were lower than the documented average annual water level fluctuation of the lake during the studied period. This is in agreement with previous studies, which reconstructed the water level of Lake Balaton based on recreation of precise levellings, but contradicts other authors who assumed the water level of the lake to be the same as the water level of the surrounding wetlands, which then estimated higher elevations for this period.

- Reed wetland vegetation extents were mapped and measured on the georeferenced First, Second and Third Habsburg Military surveys (1780s, 1830s and 1870s, respectively). The area of wetlands on the 5771 km² drainage area of the lake changed from 361 km² during the late 18th century to 217 km² during the early 19th century (before the water level of Lake Balaton was lowered) and then to 186 km² by 1870. Most of the surface lost was in the upstream part of the wetlands, where the water was retained by vegetation despite the considerable slope of the valleys until they were artificially drained.
- The main cause of reed wetland area loss around Lake Balaton was identified to be the canalization and drainage of wetlands. It was clearly demonstrated that nearly half of the wetland area on the Lake Balaton watershed was lost before the first documented direct human influence on the water level of the Lake. This process mostly affected the upstream part of the historic wetlands, while the areas closest to the lake in distance and elevation exist to the present day.
- The tendencies of reed area change within the lake between 1951 and 2003 were measured for a network of 73 sample sites of 200 meters (along shore) each, adding up to 17% of the total reed belt. A time series of 1951, 1963, 1975, 1987, 2000, and 2003 was set up, with a measurement accuracy of +/- 1 meter for reed front movement. During the studied period, reed stands on the Southern shore of the lake between the Zala river mouth and Balatonfenyves showed continuous expansion, and a similar tendency was observed for reed stands on the North-eastern shore of the lake or at sites where large-grained sediment is being deposited by tributaries or currents. The reed belt of the Northern shore bays and coves lost 16% of its area between 1975 and 1987, then regained 5% of its area between 2000 and 2003.
- Reed area loss is obviously caused by many direct human activities on Lake Balaton at a local scale. However, the spatial extent of reed area loss and regeneration indicates a

general controlling factor that acts in the same sense across the whole lake. Damage from fungal diseases, parasitic insects or grazing by muskrats, swans or grass carp have been observed on Lake Balaton, but since no large-scale fluctuation in their activity has been documented parallel with the reed area changes measured, they could not have been this key factor. Eutrophication of the lake was suspected to cause die-back but the spatial trophic gradient along the axis of the lake did not induce a similar gradient in the health of reed stands. Reeds standing in eutrophic waters in the first basin of the Lake in 2000 grew vigorously, while reed areas under mesotrophic conditions in the fourth basin in the 1970-s died back. Between 1975 and 1987, the minimum water level of the lake was raised by 30 cm (10% of the average water depth). Between 2000 and 2003, the water level of the lake reached a 50-year minimum 60 cm below regulation levels. The changes of reed health and area on the Northern shore of the lake reflect these changes in water level, while the low water depth of the Southern shore stands explains why they were not affected. Therefore, it is concluded that the lack of periodic low water levels is the key factor of reed die-back on Lake Balaton and should be addressed by a change in water level management for the benefit of the reed habitats.

- The literature of the symptoms identified as “European reed die-back” was reviewed and the suggested causes of reed loss or regeneration were compared at a European scale. Water level regulations were identified as the key factor of reed die-back and regeneration on Lake Balaton, which is in agreement with the combined conclusions of recent European studies. In particular, the lack of low-water periods has proved to be a cause of die-back over the whole north shore of the Lake, while below-average water levels allow stabilization of the reed front and extremely low water coverage initiates regeneration of the reed belt. Measurements of redox potential carried out by BLRI staff between 2000 and 2004 have shown lower redox potentials in the sediment of reed stands affected by die-back than in the sediment of healthy stands, with low water levels inducing higher redox potentials that diminished this difference. According to the literature, water level acts by controlling the availability of oxygen for the decomposition of organic matter in the submerged sediment. The oxygen demand of the sediment limits the distance oxygen can travel along the aerenchyma of the rhizome, and thus the availability of oxygen to the apical rhizome meristems. Oxygen shortage of the rhizome tips slows horizontal expansion, the death of the bud inhibits apical dominance, activating dormant buds on the vertical rhizomes and

resulting in clumped growth. While this mechanism has been suggested by laboratory experiments, it has not been proven before through measurements in a natural setting involving both high and low water levels. Previous studies have identified the beneficial effect of water level drawdowns on reed if the sediment of the wetlands was completely uncovered by water. Flooding has been known before to cause reed area loss. However, the current study shows the negative effect of the lack of low water levels without actual flooding, and also the positive effect of low water levels without the sediment of the stands being uncovered. The results are expected to be applicable to other European lakes, where reed die-back has also been observed and water levels are often regulated, and thus could be a general basis for dealing with European Reed die-back.

- A novel method for reed wetland vegetation genus and health mapping on the basis of Airborne Laser Scanning (ALS) has been developed. An ALS survey of Lake Balaton was planned and carried out and an algorithm developed that automatically classified the ALS dataset to a map of nine categories: *Phragmites*, *Carex*, *Typha* and *Scirpus* dominated wetlands; and healthy, stressed, ruderal and die-back *Phragmites* areas, and non-wetland areas covered by *Schoenoplectus*, trees and shrubs or artificial surfaces. Accuracy was tested against an independent dataset and was found to be 82.7% with a Cohen's Kappa of 0.80 for the 9 classes involved. This is comparable to or better than hyperspectral imaging, ALS fused with multispectral data or field mapping studies. The use of single-channel airborne laser scanning is completely new for ecological mapping in wetland environments but the classification accuracy is satisfactory and the method proposed is expected to be robust enough for application in other study sites. The connection between the measured data parameters and the actual structure of the studied vegetation classes in the field is well understood. The relatively easy access to ALS data facilitated by nationwide surveys means this method has a high potential for cheap, quick and accurate mapping of wetland presence, structure and health.

8. Summary

Reed (*Phragmites australis*) is the most widespread emergent shore macrophyte in Europe, and has been affected by die-back in many major lakes in the last decades. Lake Balaton is a large and shallow lake sustaining 11 km² of reed within its shores and is connected to several tributary rivers which also supported wetlands in historic times. The focus of this thesis was to quantify the areal extent of these wetlands before major human interventions with the hydrology of the watershed and their connections to the water level of the lake, to survey the reed belt of Lake Balaton in the time before reed die-back, to identify the key factor of reed area loss on the lake and to develop a novel method for mapping, monitoring and early warning.

Based on scanning, georeferencing and GIS processing of historic maps, the 18th century water level of the lake was reconstructed to be 2 meters higher than the present average and compared with the water levels and slopes of the tributary wetlands. The valleys which had the tightest ecohydrological connection to the lake were identified. The changes in wetland area throughout the watershed during the 18th and 19th centuries were measured. It was proven that most of the wetland loss described by previous authors as a result of the regulation of Lake Balaton in fact happened before the water level of the lake was lowered.

Archive aerial photographs were georeferenced and the reed-water boundary was digitized at 73 measurement sites around the lake, for images collected during 1951, 1963, 1975, 1987, 2000 and 2003. Reed stands on the Southern shore growing in shallow water and on large-grained sediment poor in organic matter showed continuous expansion during this period. On the Northern shore, most sample sites also increased in area between 1951 and 1975. Between 1975 and 1987, widespread die-back was observed with symptoms similar to other European lakes, and the reed area decreased. Between 1987 and 2000, no strong trend could be identified on the Northern shore, but between 2000 and 2003, nearly all study sites showed regeneration. Die-back after 1975 can be explained by a major change in water regulation policy cutting the water level fluctuation, and regeneration between 2000 and 2003 by low water levels. Redox potential measurements of the submerged sediment explain this: oxygen depletion caused by decomposing organic litter is known to limit rhizome growth, and was proved to be a result of high water levels.

In order to support future monitoring of reed vegetation health, a new automatic mapping method based on Airborne Laser Scanning was developed.

8.2 Összefoglalás

A nád Európa legelterjedtebb vízparti emergens növénye. Az elmúlt évtizedekben a nád nagyarányú pusztulása volt megfigyelhető számos Európai tavon. A Balaton területén 11 km² nádas található, és a történelmi időkben ennél jóval nagyobb nádasok csatlakoztak hozzá a befolyók berkeiben. Jelen munka célja volt a tóhoz kapcsolódó mocsarak történelmi nagyobb emberi beavatkozások előtti területének kiszámítása, a tóval való kapcsolatuk vizsgálata, a Balaton nádasai nádpusztulás előtti kiterjedésének feltérképezése, a nádpusztulás okának azonosítása és a jövőben használható olcsó és automatikus térképezési módszer kidolgozása.

Történelmi térképek térinformatikai feldolgozása alapján megállapítható volt, hogy a Balaton 18. századi vízszintje csak 2 méterrel lehetett magasabb a mostani átlagnál. Azonosításra kerültek a Balatonnal legszorosabb ökohidrológiai kapcsolatban lévő berkek, és a mocsarak területének változása a 18. és 19. században. Bebizonyosodott, hogy a korábban a Balaton lecsapolásának következményeként számon tartott területcsökkenés már a Sió-zsilip megnyitása előtt bekövetkezett.

Archív légifelvételek segítségével kiszámítottuk 73 mintahelyen a nádas területének változását 1951, 1963, 1975, 1987, 2000 és 2003 évek között. A déli part homokos üledékén, sekély vízben álló nádasok folyamatos növekedést mutattak a vizsgált időszakban. Az északi part szegélynádasai 1951 és 1975 között növekedtek, 1975 és 1987 között viszont pusztultak, más európai tavakon is megfigyelt tünetekkel. 1987 és 2000 között stabilizálódott a front, 2000 és 2003 között viszont intenzíven növekedtek a nádasok. Ez megmagyarázható a vízszint változásaival: az 1970-es években megemelték az átlagos vízszintet és leszűkítették az engedélyezett ingadozási tartományt. 2000 és 2003 között extrém alacsony vízállás alakult ki. A vízszint befolyásolta az üledék redox potenciálját, mivel hosszan tartó magas vízállás során a vízlengés nem tudja a nádasból a bomló szerves üledéket eltávolítani. Az oxigénhiányos üledék akadályozza a rizómák növekedését és így a nádas terjeszkedését.

A nádas állapotának gyors és pontos térképezése érdekében LIDAR-alapú új módszert fejlesztettünk, és légi felmérést hajtottunk végre a Balaton teljes partvonalán. A növényzet osztályozásának pontossága összevethető volt más hiperspektrális vagy a kombinált LIDAR-multispektrális alapú térképezési módszerekkel.

9. References

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