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Multi-decadal lake-level dynamics in north-eastern Germany as derived by a combination of gauging, proxy-data and modelling

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Abstract

In the glacially formed landscape of north-eastern Germany pronounced hydrological changes have been detected in recent decades, leading to the general question how lake levels and related groundwater levels perform in a long-term perspective, i.e. during the last c. 100 years. But long-term lake-level records are rare; most observations do not start before the late 20th century.

Therefore, the potential of historic hydrological data, comprising drowned trees (as a geo-/bioarchive) and aerial as well as map imagery (as a document archive) was tested in order to derive discrete-time lake-level stands. These data are contrasted with lake-level simulations, obtaining a continuous-time series.

Two small glacial lakes without connection to the stream network (i.e. closed lakes) were investigated in the Schorfheide area, c. 70 km north of Berlin. Both are dominantly fed by groundwater and precipitation but differ in their hydrogeological and catchment characteristics. For one lake a c. 40 year-long gauging record is available, showing high lake levels in the 1980s followed by a lowering of c. 3 m till the mid-2000s. In both lakes submerged *in situ* tree remains were discovered and dated by dendrochronology, revealing low lake levels during the first half of the 20th century. One lake was almost completely dry until c. 1960. Aerial photos provided data on lake levels since the 1930s which are corroborated by evidence of topographic mapping. Combining the empiric data with retrograde lake-level modelling, a well-proven lake-level record can be established for one lake that covers the last c. 90 years. The same general lake-level dynamics could be reconstructed by means of proxy data for the other lake. In both cases climate has been the dominant driver of lake-level dynamics. Comparisons with other multi-decadal lake-level records from the region show that these differ, depending on the hydrological lake type which modifies water feeding and water level. The results clearly showed that lake levels exhibited substantial long-term changes that should be taken into account in future hydroclimatic and hydrological studies.

Keywords: lake-groundwater interaction, dendrohydrology, remote sensing, water budget, climate impact

1. Introduction

Despite the relatively early commencement of hydrological records in central Europe, monitoring data are often heavily constrained by the length of the observation period. While some gauging stations at large rivers and lakes as well as tidal gauges along the North and Baltic Sea coasts have operated since the 18th and 19th century (e.g. River Elbe/Magdeburg: 1727, River Rhine /Cologne: c. 1770, River Oder/Frankfurt O.: 1810, Lake Constance: 1816, Lake Müritz: 1879; Strigel et al., 2010; www.undine.bafg.de), gauging of low-order streams and lakes as well as aquifers and peatlands were established very late, i.e. mostly from the last third of the 20th century onwards. Furthermore, most hydrological monitoring sites are located along drainage networks and are thus heavily influenced by discharge regulation and other human impacts (e.g. hydromorphological change, intensive land use). These sites are less suitable for the tracing of long-term hydrological changes driven by climatic impact compared to pristine catchments.

While the empirical detection of hydrological changes is an indispensable prerequisite for environmental and climate impact research, the general challenge to develop long time series at suitable sites still remains. Long records generally help to identify trends and to separate short-term (i.e. high frequency) from long-term (i.e. low frequency) dynamics. This in turn is important for the attribution of the changes detected (Merz et al., 2012). Not all hydrological phenomena observed in a relatively short period can be unequivocally attributed to global (i.e. climate and land use) change. Some changes may even reflect periodic long-term natural processes (Blöschl and Montanari, 2010), basically driven by natural solar and atmospheric dynamics.

For the extension of hydrological time series into the past, a comprehensive bundle of well-developed historic-hydrological and palaeohydrological methods is required (e.g. Brown, 2002; Benito and Thorndycraft, 2005; Brázdil et al., 2006; Gregory et al., 2006; Meko, 2006; Baker, 2008). This historical or reconstructive perspective on (landscape) hydrology forms a research field usually established in geosciences/geography and palaeoecology including dendrohydrology. But even in central Europe, with its advanced hydrological, climatic and ecologic monitoring systems, a close linkage between observation data on the one hand and reconstruction data on the other is still rarely found (e.g. Schönfelder and Steinberg, 2004; Brazdil et al., 2005; Dressler et al., 2007; Hilt et al., 2008; Czymzik et al., 2010; Kämpf et al., 2012).

In this paper we present a case study on the nexus of observation and reconstruction from north-eastern Germany, where pronounced hydrological changes were observed during the last decades. Declining discharge or drying out of rivers and streams, lowering of groundwater and lake levels as well as shrinking peatlands indicate a period of two to three decades with decreasing water balances in the region, ending about 2010 (e.g. Germer et al., 2011; Kaiser et al., 2012a; Natkhin et al., 2012). Some hydrological phenomena are clearly related to direct human impact (e.g. drainage of peatlands; Merz and Pekdeger, 2011). Other 'drying-up' symptoms concern even near-natural ecosystems (e.g. decreasing lake levels within closed lake basins lying in forested catchments) and point to climatic impact on a large scale (Kaiser et al., 2014a). Furthermore, north-eastern Germany is one of the regions in central Europe which is most affected by climate change, as projected by model scenario studies (e.g. Jacob et al., 2008; Huang et al., 2010; Hattermann et al., 2011; Dietrich et al., 2012; IPCC, 2014).

Considering the available empirical database, the long-term hydrological variability on multi-decadal (50 to 100 years) to centennial scale (several hundreds of years) is poorly recorded and understood in that region so far. Knowledge is needed about the long-term dynamics of closed groundwater-fed lakes, which serve as 'sentinels' of the climate and human impact on the regional water balance (e.g. Mason et al., 1994; Williamson et al., 2008; Adrian et al., 2009; Rinke et al., 2013).

The focus of our study is on multi-decadal (last c. 100 years) lake-level dynamics of two closed lake basins. For Lake Redernswalder See (RS) a gauging record is available since 1976. Lake Krummer See (KS) is an ungauged lake (Fig. 1). For both lakes proxy data from archives exist (historic maps, aerial photos), potentially reflecting the local water-level history. Generally, these data are ubiquitous and easy to obtain for the lakes in the region, but have been rarely compiled and used for lake-level studies thus far. Drowned tree remains, however, which were discovered in both lakes in 2009 (Supplement 1), are a newly described and rare feature of inland lakes in the region. Furthermore, for RS water-budget and lake-level modelling covering the period 1958-2007 was performed recently (Natkhin, 2010; Natkhin et al., 2012), forming the base for retrograde lake-level modelling of the last 90 years. Combining all evidence we are able to establish a robust lake-level record for RS. If climate primarily drives the multi-decadal water-level dynamics of lakes and groundwater aquifers, one can assume that lakes of the same hydrological setting (groundwater-fed closed lakes) may respond in a fairly similar way. This should be true even if the catchment structure (geology, hydrogeology, soils, land-use/land-cover) is somewhat different. For that reason KS was included in our study. Further adjacent lake- and groundwater-level records were used for comparison (Fig. 1, Table 1).

2. Study sites

The study area, c. 70 km northeast of Berlin, is situated in the glacially formed north-eastern German lowlands in the Uckermark region, part of the federal state of Brandenburg. Since 1990 the area has been part of the UNESCO Biosphere Reserve Schorfheide-Chorin. This nature conservation status aims at the protection and development of the regional cultural landscape, consisting of typical and well-preserved lowland ecosystems (e.g. lakes, peatlands, flowing waters, deciduous forests).

The landscape is dominated by Pleistocene sandy and loamy sediments of glacial origin. Holocene organic sediments (mostly gyttja and peat) occur in lake basins, riversides and peatlands. Larger peatlands are drained and under agricultural grassland use. The wider study area (Fig. 1A) covers an altitudinal range from c. 1 to 140 m NHN (NHN is the German altitudinal reference system that is nearly equal to m a.s.l.). A prominent terminal zone of the last glacial Weichselian phase stretches through the study area (Gerswalde end moraine north of Angermünde; LGRB, 1997). The geology in the catchments of our two main study sites is rather diverse. The basin of RS, c. 55 ha in size, is embedded in glaciofluvial and well permeable sands of a slightly undulating outwash plain with accompanying till, aeolian sand and peat (Fig. 1B). The catchment of KS, with a lake size of c. 4 ha, is dominated by several and partly less permeable sediments of the hilly terminal zone (e.g. tills, glaciofluvial sands, erratic boulders; LGRB, 1997; Fig. 1C). Accordingly, the hydrogeological settings differ. The lake level of RS conforms to the water level of the first unconfined aquifer of the wider surroundings (supralocal aquifer), whereas KS lies in a small groundwater body of a small basin that is sealed by till (a local perched aquifer). Both lake basins, with maximum water depths of c. 13 m (RS) and c. 7 m (KS), were probably formed by the late Pleistocene/early Holocene melting of buried glacial ice (i.e. so-called ‘dead ice’; Kaiser et al., 2012b). For RS and KS bathymetric data (maps) are available that were obtained in 2002 and 2014, respectively.

RS and KS as well as Lake Rohrhahngrund (RG), whose gauging record is used for comparison, are located in closed basins with interior drainage. By contrast, Lake Jakobsdorfer See (JS), which is also used for comparison, has an artificial outlet. The lakes belong to different hydrological lake types (*sensu* Mauersberger, 2006; Tab. 1). But they are all dominantly fed by groundwater and precipitation. The surroundings of the lakes are drained either by the Rivers Welse and Sernitz, and thus to the Oder, or by the Ucker, draining northwards to the Baltic Sea.

Additionally, the groundwater-level record of Poratz (PZ) adjacent to RS was used for comparison.

The study area is located in the transition zone between maritime and continental climate. At the Angermünde station of the German Weather Service/DWD a long-term (1958-2007) mean annual precipitation sum of 529 mm, mean annual air temperature of 8.6 °C and mean annual grass reference evapotranspiration sum (after Penman-Monteith) of about 570 mm were recorded (Natkhin et al., 2012).

All lake catchments are forested. The surroundings of RS are dominated by plantations of Scots pine (*Pinus sylvestris*), whereas the surroundings of KS, RG and JS are covered by deciduous forests, dominated by beech (*Fagus sylvatica*) and oak (*Quercus robur*).

All the lake catchments are touched by the motorway A11 (Berlin-Szczecin) that was built in 1935/1936 (Gruber and Schütz, 2000). Despite a certain reshaping of the very local relief, no considerable impact of the road on the catchment hydrology is detectable. The rainwater collected on the road's surface is released in a widespread way into the surroundings, not channelled locally into the lakes. According to historical maps all lakes existed as early as the 18th/19th century, i.e. well before the road's construction (see section 4.3).

Further information on bathymetry, hydrology and limnology of the lakes as well as on geology and land-use of the catchments are given in Table 1.

3. Methods and data

3.1 Gauging

At RS lake-level gauging by an analogous graduated rod was established in January 1976, but there is a large data gap between January 1985 and December 1994. In February 2006, an additional automatic gauge with a data logger was installed. In 1995 and 2003, the location of the gauge was lowered because the water level fell below the measurement range. In June 2006 the gauge was levelled out to a fixed point. As a consequence, the zero point of the rod had to be corrected down by 0.81 m.

The Poratz (PZ) groundwater observation well at 4 km distance from RS is in operation since 1969. It gives an impression of the water-level dynamics of the upper confined aquifer that drives the lake level of RS as well (Lischeid et al., 2010; Natkhin et al., 2012). For KS no gauging record is available. Therefore, the gauging record from nearby RG, established in 2006 and located 2 km to the northeast, was used for comparison. In terms of hydrology, limnology and catchment properties this lake is very similar to KS. Further comparison is conducted with the gauging record of JS, located between KS and RS.

All gauging records are based on monthly readings. As the gauging data refer mostly to different reading dates and showed pronounced autocorrelation, similar to those reported by Lischeid et al. (2010), linear interpolation between the data points was applied.

3.2 Dendrochronology

Along the shore of RS nine stumps of black alder (*Alnus glutinosa*) were sampled in December 2009. Due to decreasing lake level the tree stumps had emerged recently. Since the stumps were still standing with their roots in the ground, it can be assumed that the trees grew *in situ* where they were found in 2009 (Supplements 1, 2, 3). A survey of the bottom of the lake did not reveal additional tree stumps.

Twenty-nine tree stumps of beech and oak were sampled at KS in September 2012. Similarly to RS, all samples were taken from *in situ* tree stumps in the lake or just outside of its water body (Supplements 1, 2, 3). It was observed that the deepest location of a tree stump within the lake was 5.1 m below the actual water level (January 2014). Six core samples of beech tree stumps were taken underwater in May 2014. All other samples from RS and KS were taken either with a handsaw or a power saw, cutting entire stem discs or parts thereof. All samples were identified with wood anatomical methods (Schweingruber, 1978).

The methods of dendrochronology applied in the current study follow the general methodology described in Fritts (1976), Schweingruber (1983), Cook and Kairiukstis (1990) and Speer (2010). Details on sample preparation, measuring, cross-dating and statistical sample treatment are given in Supplement 2.

3.3 Analysis of aerial photos and topographic maps

For the reconstruction of historic lake levels of RS and KS 16 maps dating between 1792 and 2008 are available. RS is additionally covered by 12 aerial photos and digital orthophotos (DOPs) since 1937 and KS by 11 aerial photos/DOPs since 1959. All data were provided in digital form. Whereas aerial photos and topographic maps needed pre-processing such as the assignment of coordinates (‘geo-referencing‘), DOPs were already geometrically corrected including topographic relief, lens distortion and camera tilt. Geo-referencing was based on the DOPs of 2007 and 2012, using ground control points (GCPs; cf. Anders et al., 1991; Hughes et al., 2006). All the topographic and remote sensing data, the metadata and the description of the pre-processing of aerial photos and topographic maps are given in Supplement 3.

Two approaches exist to estimate former lake levels based on aerial photos or topographic maps. The first is based on the reconstructed shoreline position and the second on the shape of the lake area. Both approaches require a high-resolution digital elevation model (DEM) covering the over- and underwater topography of the lake. The DEMs of RS and KS are mosaics of a laser survey DEM and bathymetric data of the lakes. Detailed descriptions of the DEMs and their pre-processing, e.g. the interpolation of the bathymetric data (cf. Furnans and Austin, 2008; Johnson et al., 2008), are given in Supplement 3.

For the first approach, we digitised manually former shorelines using the DOPs as well as the pre-processed aerial photos. These shorelines were merged with the DEM (cf. Hostache et al., 2009) to obtain the topographic heights of the shorelines (i.e. absolute lake levels). In an ideal case the merging of a shoreline with the DEM will return one height value (i.e. one absolute lake level), following the same contour line. However, in practice the merging returns a range of height values due to a number of cumulative inaccuracies (cf. Fisher and Overton, 1994), such as the geo-position errors of aerial photos, inaccuracies in the manual digitisation (interpretation problems due to e.g. vegetation) and inaccuracies of the DEM (Supplement 3). By averaging those varying height values of each shoreline, we derived as final result one estimated lake level per aerial photo/DOP.

For the second approach, the shapes of the lake areas of the topographic maps were compared with the shapes of modelled lake areas in the DEM (cf. Grandke, 2009). Different lake levels were simulated until the shape of the mapped and the modelled lake areas were very similar, e.g. concerning their numbers of bays and islands. This approach is suitable for a rough estimation of former lake levels despite geo-position errors (Choiński, 2009). The final result is one estimated lake level per topographic map.

3.4 Lake-level modelling of Lake Redernswalder See

In general, a changing lake level indicates a change of the water storage of a lake. Changing water storage is the outcome of the lake water balance over a given time interval. The lake water balance is driven by meteorological conditions, such as precipitation and evapotranspiration, as well as by surface and subsurface in- and outflow. In addition, these are dependent on catchment properties such as relief, pedologic and geologic conditions, land use or water management. The relationship between lake levels and the water balance is described in equation 1 in Supplement 4.

A total of five precipitation gauges near RS was taken into account for the analysis of the water balance. Three gauges were provided by the German Weather Service (DWD). They are located about 9 km east, 7 km west and 7 km northeast of RS. The time series were harmonised and homogenised. Gaps were filled by data from the Potsdam Institute for Climate Impact Research (PIK). Two of our own rain gauges (within 4 km distance from RS) were used to consider the local heterogeneity of the precipitation field. Linear regression with the Angermünde met station (DWD) was performed to fill the gaps in the precipitation time series. For that reason the mean of the factors from linear kriging from 20 surrounding precipitation stations and the correlation of the measured time series were used (Natkhin et al., 2012). Since precipitation data measured in the field need correction (HAD, 2003), we applied the regionally calibrated German standard method (Richter, 1995) for the correction of our precipitation time series.

The difference of precipitation and grass reference evapotranspiration (climatic water balance; reference evapotranspiration after Penman-Monteith; cf. Allen et al., 1998) was applied to consider changing climatic boundary conditions. The climatic water balance considers only meteorological conditions, but not the water-related properties and the water fluxes in the catchment. An empirical approach to model separately the lake-level dynamics was developed by Richter (1997) for another lake in the region (Lake Peetschsee). It uses terms of the water balance which are easy to determine (equation 2 in Supplement 4).

In addition to this model, we developed our own empirical approach to recalculate the lake-level fluctuation of RS (equation 3 in Supplement 4). Our approach considers both the changing climatic boundary conditions as well as the dampened and delayed subsurface exchange of water between the lake and its catchment. The subsurface lake outflow is calculated by an exponential function with a pressure gradient based on the lake level and the stable groundwater level of a lower hydraulic boundary. For RS the water level of the nearby Sernitz River (35 m NHN) was taken.

In general, an empirical approach requires information about the actual water balance in the catchment. An acceptable approximation can be obtained by means of the model WaSiM-ETH (Schulla and Jasper, 2007). The specific catchment model and the data basis used are described in Natkhin et al. (2012). The modelled time series of the lake level are originally given in daily time steps. These were aggregated to 7-day steps in order to obtain a suitable convergence with the monthly lake-level measurements.

As described by Natkhin et al. (2012), land-use/land-cover change (LUCC) in the forested catchment is important for the water balance. LUCC was considered for the period 1950-2010 as described in Natkhin et al. (2012). Because of the lack of data between 1901 and 1950, no LUCC could be modelled for this time. Thus the conditions of the 1950s were assumed to be consistently valid for the preceding period.

Calibration of the two empirical approaches for RS was undertaken with R-project software (R Development Core Team, 2006). To assess the quality of these approaches, the modelled and observed lake levels were compared based on the coefficient of determination (R^2) and Willmott’s index of agreement (Willmott, 1982).

4. Results

4.1 Gauging

The recorded lake levels of RS are partly inconsistent with the fact that 70 to 90 year old beeches are growing near the lakeshore. According to the lake-level record, they should have been flooded by c. 0.6 m during maximum water levels in the early 1980s for several months. This indicates that presumably a differing zero point was used at the reinstallation of the gauge board in 1995. To ensure consistency of the time series, the lake levels between 1976 and 1984 were shifted by minus 1 m. Accordingly, between the 1980s and 2007, the maximum decrease of the measured lake level was c. 3 m. Annual maxima occur usually in May, minima in October. The average intra-annual amplitude amounts to 0.3 m.

The gauging records shown in Figure 2 differ with respect to both the length of the observation period (7-45 years until 2013) and to the water-level amplitude in the respective period (0.6-3.0 m; Fig. 2, Table 1). The correlation coefficients between the records are rather high (0.6-0.9; Supplement 5) except between RS and JS, where a slightly negative coefficient (-0.12) is apparent. RS is the only one that did not exhibit a steep lake-level increase after 2010, whereas JS is the only one without a marked lake-level decrease before 2010. In contrast to the other lakes, lake-level increase at JS started clearly before 2010. Except for JS, the lake-level dynamics of closed lake basins in the region during the last decades were to a large degree synchronous. This can be illustrated by the lake-level dynamics after 2010. After a period of several decades of sinking or heavily fluctuating water levels, all of them rose again (Fig. 2). Even in the ungauged KS basin the lake-level dynamics clearly followed this regional development. In 2009, as we discovered the submerged tree remains, they partly rose up to c. 0.8 m above the lake level (Supplement 1) and were flooded again thereafter.

4.2 Dendrochronology

4.2.1 RS site

The tree-ring widths of the nine stumps of black alders could be cross-dated easily, since no false or missing rings were identified. The arithmetic mean of the nine series resulted in a floating site chronology of 30 years length (Fig. 3, Supplement 2). The dating of the otherwise difficult to determine alder samples was eased by the fact that stem discs rather than core samples were used for the analysis.

When the mean chronology was loaded into the Time Series Analysis Program (TSAP) the cross-dating statistics indicated the growth period 1923 to 1952 as the most likely position (Supplement 2). The decision of TSAP for this time period was based primarily on the Cross-Date-Index (CDI) value, which is a combination of the ‘Gleichläufigkeit’- (GLK-) and t-values. Other periods, though less likely, are also presented, but may have weaker t-values and/or GLK. Some relatively good dating statistics, such as for the period 1089 to 1118, are less plausible. Given the low altitudinal position (temperate water) and the trophic state of the lake (promoting potentially fast decomposition), the good quality of the alder sample material suggests that the trees were submerged only for a shorter period but not for almost 1000 years (for an opposite, high-elevated and cold-lake dendrochronological record see e.g. Kleppe et al., 2011).

Furthermore, the graphical comparison with the regional reference chronology also suggests that the period 1923 to 1952 is the most likely due to the synchronisation of several pointer years, such as the peak around the mid-1920s and the low in the 1930s (Supplement 2).

4.2.2 KS site

The number of tree rings found in the samples ranged from 10 to 75, while the diameter of the samples ranged from 10 to 90 cm. The larger tree stumps showed rather straight surfaces, indicating previous cuts by means of hand or chain saws. Four oak and nine beech samples could be dated, since they contained enough datable tree rings, that is, 30 to 82 years (Fig. 3). The other samples were not datable due to rotten wood or small amounts of tree rings visible.

The samples cover a growth period of 84 years, 1895 to 1979. The period of die-off or felling of the trees covers 20 years, 1959-1979 (Fig. 3). The growing period indicates drier site conditions in the past. Otherwise tree growth would have been impossible. A good indicator of the extent of the water-level fluctuations at this lake is the fact that the water depth at sample KRU1 and at samples UW1 to UW6 is currently c. 3 to 5 m. Since the trees were growing at these sites between 1879 and 1969, it is certain that this location must have fallen dry permanently during this period. Since the lake has a maximum depth of 7 m, and most of the lake is less than 3 m deep, it can be derived that most of the basin must have almost dried out during the last third of the 19th century and first half of the 20th century.

4.3 Aerial photos and topographic maps

Lake levels in the aerial photos/DOPs (Fig. 4) were estimated by merging the shorelines with the DEM. The results were ranges of height (i.e. lake-level) values due to a number of cumulative inaccuracies. Figure 5 shows an example for the spatial distribution along the shoreline and the range of water-level values for RS (2012-05-24) and KS (2014-01-14). The DOP of 2012-05-24 has a wider range of values than the GPS measurement on 2014-01-14. At KS, the outliers with very high lake levels are concentrated on one part of the shoreline. At RS, outliers with extraordinary small values area concentrated to one area as well, but in general the estimated range of lake levels is distributed over the entire shoreline and not significantly clustered in one part of the area.

Figure 6 shows the ranges of the lake-level values of each date of RS and KS as boxplots. For the following analysis of the lake level, we used the mean lake level calculated from the range of height values of each date. The quality of the estimated lake levels can be evaluated based on the interquartile range (IQR). The largest IQR ranges (c. 2 m) are illustrated for the oldest aerial photos (RS 1937; KS 1959 and 1970). The DOPs of the last decade have an IQR of c. 1 m. The aerial photo of RS 1987 and that of KS 1993 exhibited the smallest IQR range with less than 0.5 m. The GPS derived shoreline of KS 2014 has an IQR of only few centimetres.

The maps of RS and KS have, only a limited spatial and temporal reliability (cf. Suchożebrska and Chabudziński, 2007; Supplement 3) and could only be used for a very rough estimation of historic lake levels. The ‘Schmettausche Karte’ that was produced from 1767 to 1787 shows a maximum extension of RS. In that map the peninsula which is now visible in the south, was then an island. Three nowadays dry bays in the southern part of the lake were actually flooded. Using the DEM, modelled lake levels of RS between 55.5 m and 57 m NHN results in lakes which resemble the shape of RS drawn in the ‘Schmettausche Karte’ (see Grandke, 2009). However, the development of a very similar shape showing an island and three flooded bays is not possible based on the DEM. The island is either flooded at one point or one bay is dried out. The map of 1954 (DDR-TK25) of KS shows the lake as a wet area but not as a lake (Supplement 3). Such a complete dry out of KS occurs only when the water level falls below 79.5 m NHN.

Figure 7B shows the estimated lake-level changes (‘mean’, cf. Fig. 6) of RS between 1937 and 2012 using aerial photos/DOPs. The comparison of the estimated lake levels of RS obtained from aerial photos with the gauging data shows that both lake-level curves have the same tendency to fluctuations. For validation we calculated the difference between the estimated and the measured lake levels with a maximum time difference of one week because seasonal lake-level changes might be significant. The differences regarding the level range from -0.83 m to -0.24 m. On average, lake-level estimations based on aerial photos/DOPs underestimate the measured lake level by -0.41 m.

The estimated lake level of KS between 1959 and 2012 shows a similar trend as RS (Fig. 7C), with a very low lake level in 1959 and a high lake-level period between 1970 and 1993. The GPS measurement on the 2014-01-14 (Figs. 5, 6) illustrates a very high level again (86.5 m NHN). Supplement 3 demonstrates the lake-area changes. RS has its maximum lake area in 1987 with a total area of c. 62 ha and its minimum lake area in 2009 with c. 42 ha. KS is much smaller with a lake area of 4.1 ha in 1987. In 1959 the lake nearly dried out with an area of c. 0.1 ha.

4.4. Lake-level modelling of Lake Redernswalder See

The water-balance dynamics of both the catchment and the wider region were simulated from 1901 to 2010 (Fig. 7A). Distinct periods of relatively negative (e.g. 1940s/50s) and positive values (1960s) occurred parallel to low/decreasing and high/increasing lake levels (Fig. 7B), respectively. The time period 1976-2010 was primarily chosen for calibrating the model due to the availability of gauging data. Additionally, estimated lake levels from four aerial photos (1937, 1959, 1969, 1973) were used for calibration (Fig. 7B). These four lake levels were corrected by a systematic lake-level shift of -0.43 m, derived as the mean difference between data from aerial photos and gauging. Application of shorter time periods for model calibration (e.g. 1995-2011) resulted in unrealistically high lake levels in the past, e.g. 6 m higher than observed. By the recursive use of the previous water level (W_{i-1}) in our approach, the preliminary lead time decreased from 33 to 21 years, compared to the approach of Richter (1997). Thus, the lake level could be modelled over 12 more years until 1922. The goodness of fit was slightly higher in our approach (Supplement 4). But generally, both modelled lake-level time series are very similar at least over the observation period. Our approach operates in a smoother fashion compared to the approach of Richter (1997). Its short time dynamics are less distinct with intra-annual lake-level amplitude of 0.23 m *versus* 0.45 m (against 0.30 m of the observed gauging record). Furthermore, but not resolved in Figure 7B, the approach of Richter (1997) shows lake-level maxima in May and ours in March. Annual minima are passed in December and in September, respectively. During the late 1940s/early 1950s, significantly low values of the climatic water balance led to the lowest modelled lake levels over the whole record. This is also reflected in the approach of Richter (1997), which produced relatively higher lake levels throughout the pre-observation period. This may have been an outcome of the model's more pronounced response to fluctuations in the climatic water balance, neglecting the delay and damping caused by the catchment. According to our approach, the lake level until the mid-1960s amounts to around 52.5 m NHN and is characterised by markedly small amplitudes as compared to the later period (Fig. 7B). In this period the approach of Richter (1997) models higher amplitudes, but this can also be found in the observed period after 1995. The following pronounced lake-level rise lasting till the late 1980s is obviously induced by the positive water balance before 1970. In the 1980s the lake level fluctuates around the peak position of c. 55 m NHN, indicating the damping effect of a delayed recharge from the groundwater storage of the catchment (Natkhin, 2010). The absolute lake-level maximum of the model record was calculated to be 55.5 m NHN in 1988 according to our approach and 56.0 m NHN after Richter (1997). This peak follows the absolute maximum of the climatic water balance in 1987. Unfortunately, there is no observation to validate this absolute lake-level maximum. Following the course of relatively dry years starting in the early 1990s, the lake level decreased more or less continually by more than 3 m until summer 2006 (52.5 m NHN). Starting with the wet year 2007, the catchment water balance shows positive values again, resulting in a persistence of the lake level at a low position (c. 52.5 m NHN) so far.

5. Discussion

5.1 Comparison with long-term regional gauging records

Further gauges, located both in the same groundwater catchment as RS and in the whole Schorfheide area as well as beyond, verify a negative water-level trend for closed lakes since the mid-1980s and a positive trend from c. 2010 onwards (Natkhin, 2010; Germer et al., 2011; Kaiser et al., 2012a; Brothers et al., 2014; Figs. 2, 8A). Probably unique is the record from Lake Peetschsee, lying c. 50 km northwest of RS, which began in 1958 (Richter, 1997; Kaiser et al., 2014a). It shows that periods of relatively high and low lake levels regularly alternated in the last c. 50 years. If one includes the modelled lake-level from 1909 to 1957 (Richter, 1997), this periodicity becomes evident for the whole 20th century (Fig. 8B). Other lakes in the region suggest that periodic lake-level fluctuations with amplitudes of c. 1 to 3 m are characteristic for groundwater-fed (closed) lakes (e.g. Natkhin et al., 2012; Kaiser et al., 2014a). These dynamics primarily depend on climatic impacts, i.e. the periodic occurrence of wet and dry periods (Richter, 1997; Kaiser et al., 2014b). The long-term record of Lake Müritz (c. 11,700 ha), the largest lake in the German lowlands and located c. 80 km to the northwest, however, reveals other dynamics. This (open) lake, having several in- and outlets which are steered by weirs, is clearly controlled by water-level management, largely superimposing the climatic signal (Fig. 8C).

5.2 Drowned trees and peatlands as lake- and groundwater-level recorders

From an international perspective, several successful studies using both drowned (dead) and living trees for dendrohydrological studies were performed (Biondi and Strachan, 2012). With respect to groundwater- and lake-level fluctuations both short-term (e.g. Bégin, 2001; Xiao et al., 2005) and long-term dynamics (e.g. Loaiciga et al., 1993; Gunnarson, 2001; Hunter et al., 2006; Meko, 2006; Quinn and Sellinger, 2006; Jones et al., 2008; Wiles et al., 2009; Kleppe et al., 2011; Perez-Valdivia and Sauchyn, 2011) were the foci of the studies.

Drowned trees, as analysed in RS and KS, however, were rarely described in regional inland lakes or used as bioarchives thus far. One exception are small pine stumps (dating 1876-1893) that were found just below the present-day water level of Lake Kulowsee, c. 50 km northwest of RS (unpublished data). By contrast, submarine oak remains (*in situ* stems and stumps) were discovered along the German and Polish Baltic Sea coast, forming well-investigated geo-/bioarchives (e.g. Lampe, 2005; Uścinowicz et al., 2011). Furthermore, a multitude of archaeological construction wood exists which was retrieved from both inland lakes (e.g. Bleile, 2008) and terrestrial sites including river valleys and peatlands, contributing to long chronologies for different tree species (e.g. Brose and Heussner, 2002; Büntgen et al., 2011).

Our results on lake-level dynamics in RS and KS can be confronted with results from peat stratigraphy and wetland ecology of the nearby Barschpfuhl kettle-hole mire, located only c. 1 km north of RS. Here a high-resolution palaeoecological study was performed (van der Linden et al., 2008), using a 60 cm-thick peat layer from the surface (c. 60 m NHN). The peat chronology is based on radiocarbon wiggle-match dating and covers the time interval from AD 1705 to 2003, comprising c. 300 years. The peat stratigraphy at Barschpfuhl bears a noticeable layer of extremely decomposed peat (25-35 cm) that is encompassed by low and medium decomposed peat. As this layer comprises a time interval from 1790 to 1960, it might represent a dry phase similar to what we reconstructed at least for the 1870s to 1960s for RS and KS. Furthermore, local water-table reconstruction by using testate amoebae (i.e. microfaunal fossils) indicates periods of lower (e.g. 1950, 2003) and of higher (ground-) water levels (e.g. 1964, 1990) at Barschpfuhl. However, all fluctuations are in a range of 5 cm only, and no long-term trends in the data exist. Considering the peatland type (i.e. kettle-hole mire) with its ecological and hydrological characteristics (Timmermann and Succow, 2001), obviously a hydraulic buffer effect is present which decouples the very local (peatland-) from the supra-local (ground-) water level. Indeed, the surface of a kettle-hole mire is often partially ‘floating’ on a subsurface water lens (i.e. a perched aquifer; van der Linden et al., 2008). This peatland geoarchive hardly reflects the hydrological changes in the wider groundwater catchment that includes RS and the Poratz groundwater well. Both show maximal water-level amplitudes of c. 3 m from the 1980s to 2000s and 1960s to 2000s, respectively.

For the last c. 20 years kettle-hole mires around RS, including Barschpfuhl, have revealed different reactions of the local groundwater levels, depending from the hydrogeological setting (Luthardt et al., 2010). According to these observations, one can conclude that there is no spatially uniform hydrological cause-response relationship at present, pleading for a careful interpretation even of records of the past.

5.3 Aerial photos and topographic maps

Aerial imagery is the only remote sensing data category that has a high resolution and remained consistent from the 1930s/1950s to the present (e.g. Gerard et al., 2010). Therefore, it is ideal for the long-term monitoring of the landscape dynamics, including lake-level and lake-area changes. Aerial photos were already used successfully for the distinction of former shorelines of lakes, in synthesis with tree ring and lake sediment analysis (Shapley et al., 2005), and for the analysis of lake-area changes due to climatic change (e.g. Klein et al., 2005; Papastergiadou et al., 2007). The retrieval of a water level based on the extracted contours of a water body from a DEM were mostly used for the estimation of flood-water levels so far (e.g. Puech and Raclot, 2002). Our study shows that the approach applied here is also valuable for the estimation of lake levels. The accurate geo-referencing of the aerial photos is time consuming, but the quality difference between the lake levels extracted from DOPs and aerial photos seems not as large as was first expected. Dense vegetation along the shoreline is the challenging obstacle for an accurate estimation of the lake level. For example, the DOP of RS (2012-05-24) has high pixel position accuracy, but nevertheless shows a wide range of lake level values (Figs. 5, 6). For KS, fieldwork in summer 2012 revealed a strong influence of vegetation on the analysis of remote sensing data. The corrected shoreline based on this expert knowledge can be noted in the corresponding subset of DOP (2012-05-24) in Figure 4. Thus, the lake level of KS (2012-05-24) is of limited reliability. A much higher water level (c. 86 m NHN) would be realistic. The continuous increase of the lake level of RS in 2012 supports this reasoning.

The smallest IQR was assigned to the GPS measurement of KS 2014. None of the indirect reconstructed shorelines reaches its precision. However, it must be considered that a longer shoreline potentially has a wider range of lake-level values: RS is much larger than KS and an increasing lake level results in a longer shoreline. For studies at other lakes we recommend the use of subsets of the shoreline with shallow topography and without interfering vegetation to ensure a reliable digitisation of the shoreline for the lake-level estimation.

Maps are a valuable tool to trace earlier landscape changes. In the region their records reach back to the 16th century at the earliest for certain small areas (Cordshagen, 1986) and to the second half of the 18th century for the entire area (Kressner, 2009). However, spatial and temporal inaccuracies limit their use as a precise hydrological proxy (e.g. Marszelewski and Adamczyk, 2004; Choiński, 2009). The changing appearance of peninsulas, islands and dried out bays/wet areas are good indicators for lake-level changes, but this evidence is of only limited suitability for quantitative estimations. Spatial inaccuracies can be bypassed partly by the modelling of historic lake levels based on the shape of lake areas drawn in a map (e.g. Grandke, 2009). However, this method provided only very rough results for RS, probably due to an altered topography since the 18th century.

5.4 Lake-level modelling of Lake Redernswalder See

So far, several studies to model the water-balance and lake-level of closed lakes were performed throughout the world (e.g. Legesse et al., 2004; Vallet-Coulomb et al., 2006; Troin et al., 2012). Our approach to calculate lake levels for RS based on water-balance modelling was the most comprehensive applied in the region so far. The combination of a sophisticated model for calculating the catchment water balance (WaSiM-ETH; Schulla and Jasper, 2007) and an empirical approach to model the lake-level dynamics is innovative for the analysis of closed lakes interconnected with groundwater in central Europe.

The model approach after Richter (1997) shows a good fit to the observed lake levels of RS, as good as Richter (1997) showed for Lake Peetschsee. Nevertheless, our own approach performs better for RS (Supplement 4). A general methodical advantage of our approach is its proximity to the full water balance equation and the connection to the lake level of the previous time step (Supplement 4). The adaptability and modelling quality for different lakes was clearly not in the focus of this work. But for further application the local complexity in coupling between meteorology, hydrogeology and hydrological lake dynamics as well as land use/land cover characteristics must be carefully considered.

However, the results obtained for RS are accompanied by some obstacles. The first one is the relatively short period of the gauging record, comprising a lack of data from 1985 to 1994. Secondly, with a view to the completeness of meteorological data, an imbalance exists in the gauging record, leading to uncertainties in the calibration of the parameters used for the empirical model approaches. The extrapolation of an empirical model into the past without any observation data generally increases uncertainty (Refsgaard and Henriksen, 2004). Some modelled lake-level extremes of RS occur in periods without gauging record. Based on a short-term calibration period (1995-2010) high lake levels in the beginning of the reconstruction period and a lake-level decrease over most of the time afterwards were confirmed. But insufficient observation data were available for periods of a predicted lake-level rise. To solve this problem, the lake-level data retrieved by some aerial photos were additionally used for calibration. In addition, detailed information on historical land use (i.e. a changing forest structure) could not be obtained. Thus the land-use change before 1950 could not be implemented into the model.

There are some further uncertainties caused by methodological shortcomings pertaining to the regional hydrology of groundwater dominated systems. Most of them were recently evaluated and discussed for the wider study region by Thomas et al. (2012). In particular, the problem of correctly quantifying the local climatic water balance still exists. There are well-proven empirical procedures for correcting measured precipitation (e.g. Richter, 1995). But, calculation of the daily evapotranspiration still remains difficult due to the low density of meteorological stations with the full set of input data. In addition, there are different approaches for calculating the actual evapotranspiration. They differ especially for forested catchments, lakes, riparian vegetation or groundwater-dependent systems, which are abundant in the RS catchment.

5.5 Synthesis

Compiling all the lake-level evidence from RS, the varying conformity of the records for certain periods becomes evident (Fig. 7B). The best match of the records is from 1976 to the present where the lake-level curves tend to merge. Prior to that the lake-levels derived from modelling and aerial photos were (correctly) widely below the level defined by the dendro-record of samples Red1-3. This dendro-record generally reflects a maximal possible lake level for the period 1923-1952. In comparison with aerial photos and with lake-level modelling after the approach of Richter (1997), our modelled lake-level before 1976 is constantly lower in a range of

0.25 to 1.6 m. A systematic deviation is also found between observed lake levels and lake levels derived from aerial photos.

The same general dynamics with low lake levels in the first half of the 20th century, a rise afterwards up to the mid-1980s and a following decline is proven by the KS proxy record (Fig. 7C), consisting of dendrochronologically dated tree remains and lake-level reconstruction by means of aerial photos. Thus two consistent multi-decadal lake-level records of different temporal resolution were established.

The dimension of the local hydrological and ecological changes and, consequently, of the suitability/sensitivity of the geo-/bioarchive (i.e. preservation potential for submerged tree remains) clearly differ, depending from a faster reaction time and larger amplitude of the lake level in KS compared to RS (Fig. 9).

Thomas et al. (2012) found that the long-term dynamics of precipitation and evapotranspiration do not differ significantly at distances as short as in this study. In spite of that, time series of groundwater or lake levels can differ substantially even for adjacent sites. Lischeid et al. (2010) analysed time series of various groundwater wells and lakes in the study area, though a much shorter time period was covered. They could assign most of the spatial variance of the observed dynamics to different degrees of damping of deep seepage. This in turn seems to be related to a differing depth to the groundwater and to different soil substrates. The same was found for another data set, measured about 50 km further to the southeast (Lischeid et al., 2012).

Our study revealed drastic changes of lake levels that were rarely reported from natural lakes for other parts of northern central Europe. In fact, the study region is sensitive to minor changes of the water balance. In general, plants are very effective in ensuring their need of water, resulting in fairly stable annual rates of evapotranspiration in spite of substantial interannual fluctuations of precipitation. Consequently, groundwater recharge can be regarded as the residual of precipitation minus plant water uptake and evaporation. In the study region groundwater recharge amounted to 83 mm/year on average for the 1983-2007 period, which was only 16 % of the mean annual precipitation of 529 mm/year (Natkhin et al., 2012). Thus, the low groundwater recharge would be drastically reduced even by an only slight decrease of annual precipitation, resulting in a drastic change of groundwater and lake levels.

Broadening the perspective, scenario analyses that assess the effect of single anthropogenic measures (e.g. land-use change, construction of barrages) or of climate change on landscape hydrology are usually based on the implicit assumption that stationarity is the norm for remote, undisturbed (i.e. near-natural) hydrosystems. Only recently have scientists challenged this, showing a multitude of anthropogenic effects on hydrological processes (e.g. Milly et al., 2008). Our results clearly revealed that in addition to seasonal lake-level dynamics fluctuations at a scale of decades need to be considered in this region. In fact, clear evidence exists that low-frequency fluctuations have always been an intrinsic property of the climate and related hydrological conditions and should be taken into account for further hydroclimatic and hydrological studies (Clarke, 2007).

6. Conclusions and outlook

Knowledge on multi-decadal lake-level and groundwater-level dynamics is very much helpful to understand the long-term landscape water budget and its effects in northern central Europe and beyond. Incorporating not only present and future perspectives, but also focus on historic hydrology and palaeohydrology, resulted into new insights concerning the dynamics and thus assisted us with both hydrological process understanding and the evaluation of hydrological proxy data.

For the first time evidence from a geo-/bioarchive and remote-sensing were jointly exploited in the region, revealing their high potential for lake-level studies. By applying a combined approach of gauging and proxy-data analysis and of retrograde modelling we were able to establish two consistent lake-level records that cover the last c. 90 years in maximum. Thus a quasi-continuous, c. 40 years long time series of observation data could be extended c. 50 years further into the unobserved past. In general, our results reveal non-stationarities of the landscape water budget at a scale of decades that should be taken into account for future hydroclimatic, hydrological and climate impact studies in the region.

This study also contributes to the question how centennial- to millennial-scale lake-level records can be interpreted, using the dynamics of the recent past as a key to understanding. As the last c. 100 years for RS show, there are several low-magnitude fluctuations with amplitude of c. 1 m and one high-magnitude fluctuation with amplitude of c. 3 m. Further multi-decadal records from the region reveal considerable variability, depending on the hydrological lake type which modifies water feeding and water level.

Ongoing work in the surroundings of the lakes examined aims, on the one hand, to realise a detailed study of structures (landforms, soils, vegetation) along shorelines that have been affected by water-level changes over the last decades. On the other hand, an analysis of sub-littoral sediment cores is under way for the same lakes, and this aims to generate millennial-scale lake-level records. Combining all evidence, i.e. monitoring data, proxy-data analysis and further modelling efforts, we aspire to establish a long-term lake-level history for the region, covering the whole Holocene.

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Figures

Fig. 1: Sketch maps with the sites investigated. A – Overview on the study area with the main sites investigated and with further sites used for comparison. B – Drainage network and geology in the surroundings of Lake Redernswalder See (after LGRB, 1997, modified). C – Drainage network and geology in the surroundings of Lake Krummer See (after LGRB, 1997, modified).

Fig. 2: Gauging time series of the main sites investigated (Lakes Redernswalder See and Krummer See) and of further sites used for comparison (Lakes Jakobsdorfer See and

Rohrhahngrund, groundwater observation well Poratz; data provided by Rüdiger Michels, Angermünde). The diachronous onset of the gauging record is given each by the blue date (year). The onset (2010) of the present period of rising lake and groundwater levels is marked by the grey dashed line.

Fig. 3: Overview of the dendrochronological records in the basins of Lakes Redernswalder See and Krummer See.

Fig. 4: Selected aerial photos of Redernswalder See (left) and Krummer See (right). The blue lines represent the shorelines of the lakes that were extracted from the aerial photos. At Lake Krummer See we digitised a land bridge based on the digital orthophoto 2012-05-24. However, fieldwork in summer 2012 showed that it was only dense vegetation in and on the water. Thus the corrected shoreline based on this additional knowledge is illustrated in light blue.

Fig. 5: Range of lake-level values for Lake Redernswalder See on 2012-05-24 (left) and Lake Krummer See on 2014-01-04 (right) gained by merging the manually digitised shoreline with the high-resolution digital elevation model (DEM). Above – Shoreline height values. The 1-2 pixel broad line is enlarged for illustration purpose. Below – Histograms of the height values with resulting mean lake levels.

Fig. 6: Ranges of height (i.e. lake-level) values gained by merging the extracted shorelines with the high-resolution digital elevation model (DEM) for Lake Redernswalder See (left) and Lake Krummer See (right). The shoreline of Lake Krummer See on 2014-01-14 was measured by GPS device. The rhomb illustrates the mean value, the dark line the median. The grey box is the

interquartile range (IQR) that is the range in which 75 % of the lake-level values of each date fall. The whiskers in the boxplot mark values within 1.5 IQR. Extreme outliers are not plotted.

Fig. 7: Synoptic overview on multi-decadal climatic and lake-level dynamics in the study area. A – Catchment water balance und climatic water balance for Lake Redernswalder See and Angermünde meteorological station, respectively. B – Lake-level dynamics of Lake Redernswalder See according to different evidence. C – Lake-level dynamics of Lake Krummer See according to different evidence.

Fig. 8: Multi-decadal lake-level records from north-eastern Germany. A – Lake Redernswalder See with gauging data since 1976 and lake-level modelling since 1922 after the own approach introduced in this study. B – Lake Peetschsee with gauging data since 1958 (data provided by Anke Pingel, Potsdam) and lake-level modelling from 1908 to 1997 after Richter (1997). C – Lake Müritz with gauging data since 1879 (data provided by Peter Stüve, Neustrelitz). Unlike Redernswalder See and Peetschsee which are (groundwater-fed) closed lakes, Müritz is an open lake having several in- and outlets that are controlled by weirs.

Fig. 9: Synoptic sketch showing the local water-level dynamics at Lakes Redernswalder See and Krummer See for selected years with related vegetation changes at the shoreline and taphonomic processes of the tree remains investigated.

Tables

Table 1: Characterisation of the lakes under study and of further sites and its catchments (data from Mauersberger and Mauersberger, 1996; LGRB, 1997; Luthardt et al., 2009; and from own compilation).

Supplements

Supplement 1: Photos and images of the sites investigated and of further sites. A – In-situ tree remains of alder rooting at the northeastern shore of Lake Redernswalder See that are exposed by a low lake level in September 2009 (Photo: K. Kaiser). B – In-situ tree remains of alder in the aggradation fringe at the northern shore of Lake Redernswalder See exposed by a low lake level in December 2009 (Photo: I. Heinrich). The stems are sawn off by woodsmen in the 1950s and subsequently flooded by the lake. After exposure of the site in the late 1990s/early 2000s a new tree generation mainly of birch has developed. C – In-situ tree remains of beech and oak at the western shore of Lake Krummer See exposed by a low lake level in September 2009 (Photo: K. Kaiser). D – In-situ tree remains of beech and oak at the northwestern shore of Lake Krummer See in September 2009. Some stems were cut by woodsmen before flooding by the lake in the 1960s (Photo: K. Kaiser). E – Detail of a cut oak stem at the eastern shore of Lake Krummer See in September 2009 (Photo: K. Kaiser). The diameter of the stem is c. 40 cm. F – Side sonar image of the southwestern part of Lake Krummer See (January 2014) showing a broken tree with branches (red arrow) in a water depth of 5.1 m (Image: J. Becker). G – Submerged tree base of beech in a water depth of c. 3.5 m rooting in the lake bottom (May 2014). The diameter of the stem is c. 25 cm (Photo: S. Oldorff). H – Submerged tree stem of beech in a water depth of c. 2.5 m rooting in the lake bottom (May 2014). The diameter of the stem is c. 50 cm. The stem was cut by woodsmen before flooding by the lake in the 1950s/60s (Photo: S. Oldorff).

Supplement 2: Supplementary material on dendrochronology.

Part 1: Dendrochronological methods.

Part 2: Synchronised tree-ring series of black alder from Lake Redernswalder See; individual trees in black, mean chronology in red.

Part 3: Synchronised tree-ring series of beech from Lake Krummer See; individual trees in black, mean chronology in red.

Part 4: Dating statistics for the ten best fits of samples from Lake Redernswalder See to the black alder reference chronology (period 1036-2007).

Part 5: Dating statistics for the ten best fits of samples from Lake Krummer See to the beech reference chronology (period 400-2011).

Part 6: Comparison of the tree ring series of Lake Redernswalder See (red line) with the regional chronology of black alder (black line).

Part 7: Comparison of the tree ring series of Lake Krummer See (red line) with the regional chronology of beech (black line).

Supplement 3: Supplementary material on remote sensing.

Part 1: Detailed description of the pre-processing of aerial photos and topographic maps.

Part 2: List of aerial photos and digital orthophotos of Lake Rederswalder See and their metadata.

Part 3: List of topographic maps of Lake Rederswalder See and their metadata.

Part 4: List of aerial photos and digital orthophotos of Lake Krummer See and their metadata.

Part 5: List of topographic maps of Lake Krummer See and their metadata.

Part 6: Selected maps of Lakes Redernswalder See (left) and Krummer See (right) after the pre-processing.

Part 7: Detailed description of the digital elevation models (DEMs) and their pre-processing.

Part 8: Digital elevation models (DEMs) including over- and underwater topography of Lakes Redernswalder See and Krummer See.

Part 9: Area of Lake Redernswalder See and its change in comparison to the newest date (2012-05-24).

Part 10: Area of Lake Krummer See and its change in comparison to the newest date (2014-01-14).

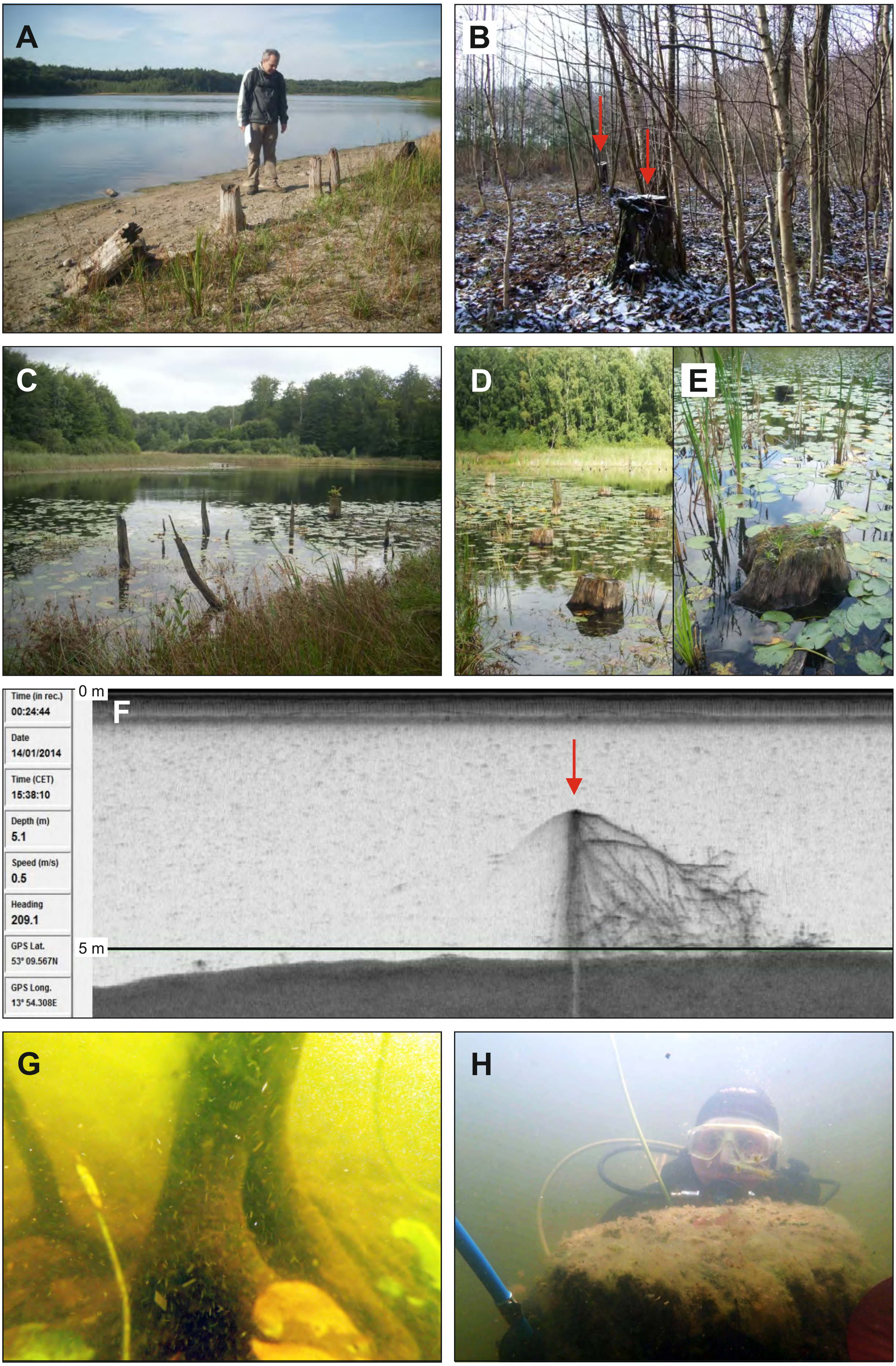
Supplement 4: Supplementary material on hydrological modelling.

Part 1: Equations used for lake-level modelling.

Part 2: Empirical and quality parameters for the modelling approach according to Richter (1997) and for our own approach presented in this study.

Supplement 5: Supplementary material on hydrological gauging.

Correlation matrix for the gauging records under study. As different gauging periods exist, the correlation pertains to the overlap period each.


A
B
C
D
E
Time (in rec.)
00:24:44
Date
14/01/2014
Time (CET)
15:38:10
Depth (m)
5.1
Speed (m/s)
0.5
Heading
209.1
GPS Lat.
53° 09.567N
GPS Long.
13° 54.308E
0 m
5 m
F
G
H

Supplement 1: Photos and images of the sites investigated and of further sites

A – In-situ tree remains of alder rooting at the northeastern shore of Lake Redernswalder See that are exposed by a low lake level in September 2009 (Photo: K. Kaiser). B – In-situ tree remains of alder in the aggradation fringe at the northern shore of Lake Redernswalder See exposed by a low lake level in December 2009 (Photo: I. Heinrich). The stems are sawn off by woodsmen in the 1950s and subsequently flooded by the lake. After exposure of the site in the late 1990s/early 2000s a new tree generation mainly of birch has developed. C – In-situ tree remains of beech and oak at the western shore of Lake Krummer See exposed by a low lake level in September 2009 (Photo: K. Kaiser). D – In-situ tree remains of beech and oak at the northwestern shore of Lake Krummer See in September 2009. Some stems were cut by woodsmen before flooding by the lake in the 1960s (Photo: K. Kaiser). E – Detail of a cut oak stem at the eastern shore of Lake Krummer See in September 2009 (Photo: K. Kaiser). The diameter of the stem is c. 40 cm. F – Side sonar image of the southwestern part of Lake Krummer See (January 2014) showing a broken tree with branches (red arrow) in a water depth of 5.1 m (Image: J. Becker). G – Submerged tree base of beech in a water depth of c. 3.5 m rooting in the lake bottom (May 2014). The diameter of the stem is c. 25 cm (Photo: S. Oldorff). H – Submerged tree stem of beech in a water depth of c. 2.5 m rooting in the lake bottom (May 2014). The diameter of the stem is c. 50 cm. The stem was cut by woodsmen before flooding by the lake in the 1950s/60s (Photo: S. Oldorff).

Supplement 2: Supplementary material on dendrochronology

Part 1: Dendrochronological methods

The surfaces of the core samples were smoothed with a belt-sander using paper grit size of 240 according to routine sample preparations (Bowers, 1964) followed by an orbital sander treatment with paper of increasingly fine grit size up to 1200 (Pilcher, 1990), facilitating easier analyses of the tree-ring boundaries (Cook and Kairiukstis, 1990). Individual samples were checked in advance under low magnification for problematic zones such as narrow or false rings. Tree-ring widths were measured with a resolution of 1/100 mm by means of the measuring system TSAP (Time Series Analysis Program). The system consists of a moving table, a binocular and a PC with TSAP (Rinn, 2007). The synchronisation of the individual samples was achieved by visually and graphically crossdating them in TSAP.

The new site chronologies were compared with regional chronologies of black alder, beech and oak covering the last millennium (Brose and Heussner, 2002; Büntgen et al., 2011).

In TSAP, two main concepts are used to express the quality of synchronisation between time series: ‘Gleichläufigkeit’ (GLK) and t-values. While the t-statistic is a test for the significance of the correlations between the individual time series, the ‘Gleichläufigkeit’ was developed as a special tool for cross-dating of tree-ring series (Eckstein and Bauch, 1969).

The t-value t is based on the product moment correlation coefficient, and measures the significance of the correlation of two series in relation to their overlap length and should not drop below a value of 3 (Baillie and Pilcher, 1973). The t-statistic is expressed as:

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}}$$

with
N: degrees of freedom,
r: product moment correlation coefficient

The GLK indicates the level of agreement between consecutive ring-width slopes. The degree of similarity between two series based on the positive (upward) or negative (downward) trend of each width is expressed as a percentage of the number of intervals (Speer, 2010). The GLK is expressed as:

$$\Delta_i = (x_{i+1} - x_i)$$

when

$$\Delta_i > 0: G_{ix} = +1/2$$

$$\Delta_i = 0: G_{ix} = 0$$

$$\Delta_i < 0: G_{ix} = -1/2$$

then

$$G_{(x,y)} = \frac{1}{n-1}\sum_{i=1}^{n-1}\left|G_{ix} + G_{iy}\right|$$

with
Δi: Change in ring width,
xi: ring width in year x,
xi+1: ring with in the following year,
Gix: value added to the G-score, reflecting whether ring with is increasing, staying the same or decreasing in each interval for series x,
Giy: value added to G-score for series y

These concepts are characterised by different sensitivities to tree-ring patterns. While ‘Gleichläufigkeit’ represents the overall accordance of two series, t-values are more sensitive to extreme values, such as event years. A combination of both is realised in the Cross-Date-Index (CDI):

$$CDI = \frac{(GLK - 50 + 50 * \sqrt{\frac{overlap}{maxoverlap}}) * t}{10}$$

with
GLK: Gleichläufigkeit,
t: t-value

The threshold for the CDI is defined to be greater than 10. Since the CDI is a very powerful parameter in cross-dating, the possible dating matches are ordered by descending CDIs in the TSAP output file (Rinn, 2007).

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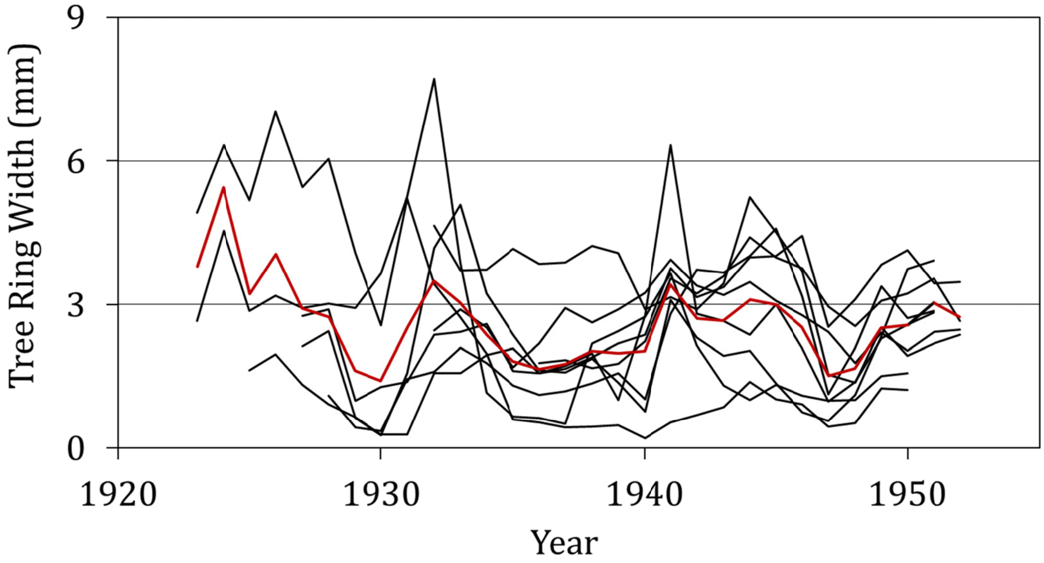
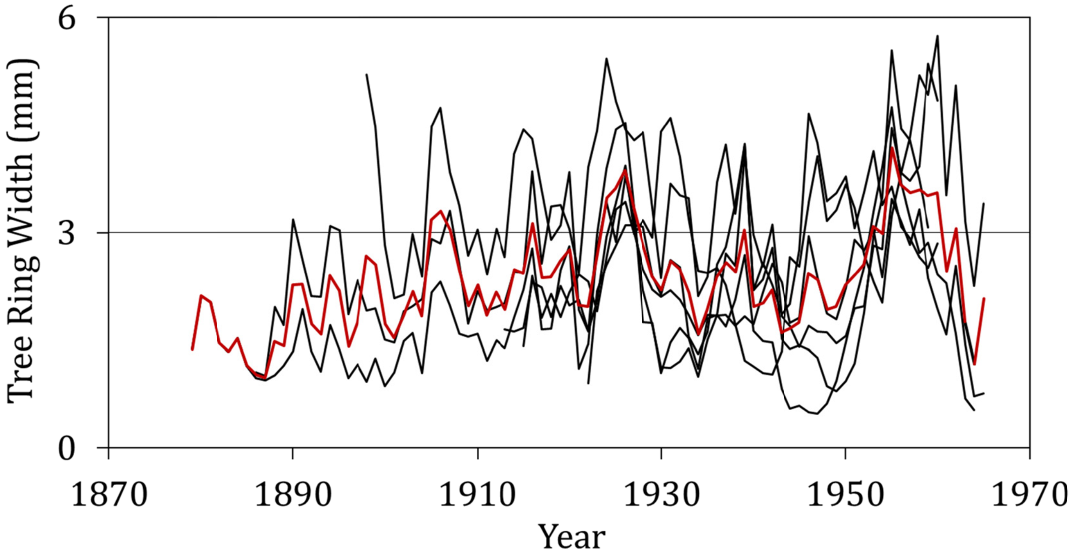
Part 2: Synchronised tree-ring series of black alder from Lake Redernswalder See; individual trees in black, mean chronology in red.



Part 3: Synchronised tree-ring series of beech from Lake Krummer See; individual trees in black, mean chronology in red.



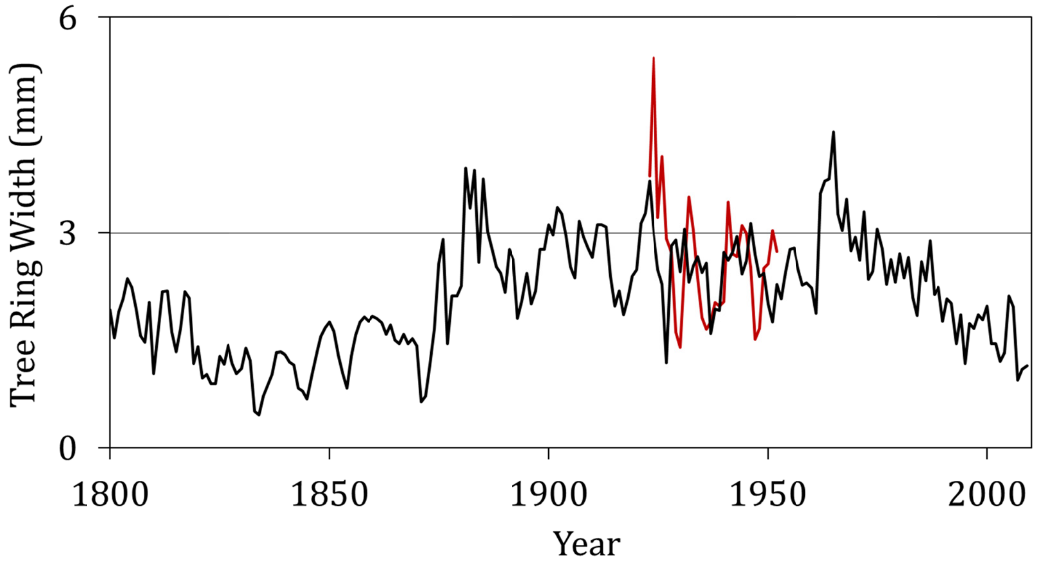
Part 4: Dating statistics for the ten best fits of samples from Lake Redernswalder See to the black alder reference chronology (period 1036-2007).

Glk	TVBP	CDI	start-date	end-date
71	5,0	27	1923	1952
79	3,9	24	1089	1118
66	3,4	20	1534	1563
59	2,6	20	1868	1897
75	3,0	19	1957	1986
79	3,8	17	1095	1124
61	4,6	17	1037	1066
66	2,8	16	1316	1345
61	2,6	15	1361	1390
55	2,3	15	1516	1545

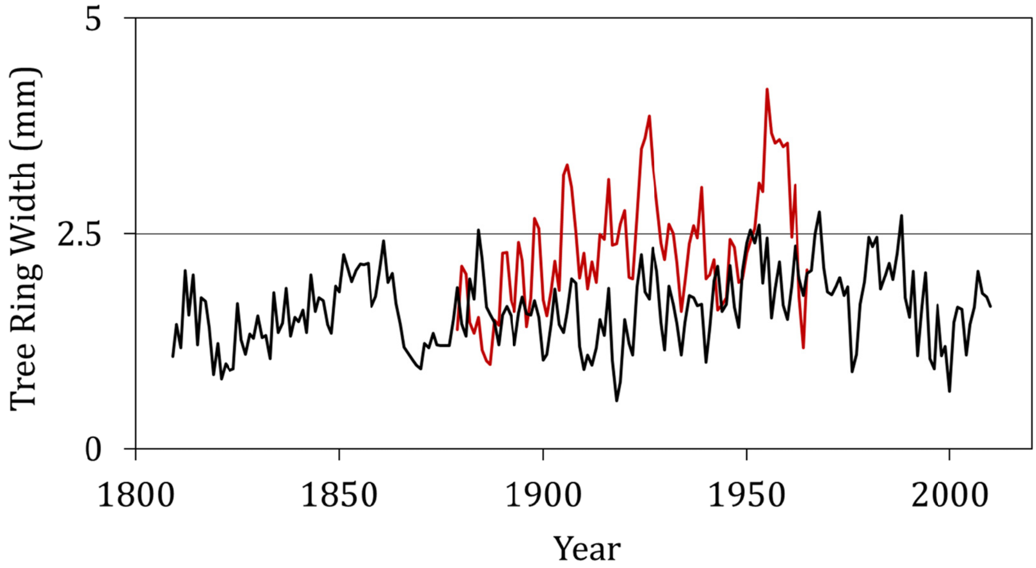
Part 5: Dating statistics for the ten best fits of samples from Lake Krummer See to the beech reference chronology (period 400-2011).

Glk	TVBP	CDI	start-date	end-date
80	5,2	28	1879	1965
60	4,0	18	747	833
59	3,8	17	1041	1127
59	4,6	15	1905	1991
63	3,5	14	1355	1441
61	3,8	14	1934	2020
61	3,7	13	485	571
59	2,3	13	1400	1486
49	3,7	13	487	573
59	3,6	12	1698	1784

Part 6: Comparison of the tree ring series of Lake Redernswalder See (red line) with the regional chronology of black alder (black line).



Part 7: Comparison of the tree ring series of Lake Krummer See (red line) with the regional chronology of beech (black line).



Supplement 3: Supplementary material on remote sensing

Part 1: Detailed description of the pre-processing of aerial photos and topographic maps.

The pre-processing of the aerial photos and topographic maps comprises mainly the assignment of coordinates, called “geo-referencing”. The geo-referencing is based on the two digital orthophotos (DOPs) of 2007 and 2012 with precise geographical information. For the assignment of coordinates common points, so called ground control points (GCPs), are marked in the aerial photo/map and in the DOPs. Functional GCPs that were used for the geo-referencing were road crossings or other characteristic landmarks.

In the aerial photos we set in average 12 GCPs per image (cf. Suppl. 3, Parts 2, 4). In the topographic maps, we set between 14 and 55 GCPs per map (cf. Suppl. 3, Parts 3, 5). Based on the GCPs, the aerial photos and maps were transformed. For the aerial photos, we mostly used a second-order polynomial transformation that ensures the general accuracy of the corrected aerial photos (cf. Hughes et al., 2006). In one aerial photo (1970-6-9) only 6 GCPs could be set, thus, second-order polynomial transformation was not feasible and we used a first-order polynomial transformation instead. For the topographic map, we used the spline transformation (a ‘rubber sheeting’-method).

The quality of the geometrical correction depends on the distribution and quality of the GCPs, the transformation used, as well as the quality of the aerial photos/maps (cf. Anders et al., 1991; Hughes et al., 2006). For evaluation purposes we calculated the total root mean square error (RSME) of the aerial photos as the sum of squares of difference (in meter) between the actual location of a GCP and its predicted location based on the transformation and the residual GCPs. The RSME of the aerial photos are listed in the metadata of the data (cf. Suppl. 3, Parts 3, 5).

Geo-referencing of the aerial photos was reliable with mostly low RSME (< 2 m). Challenging were (1) the small coverage of some photos, with a depiction of only lake and forest areas; (2) the distinct changes of the landscape structure that reduced the number of suitable GCPs and decreases the accuracy of GCPs (e.g. 1959); (3) the blackening of military areas in one photo (1981-05-13, KS); and (4) the significant lens distortion (1973-05-30, RS and KS).

The interpretation of the aerial photos and the clear distinction of the water-land-border are challenged by reed growing in the lake, swimming plants, overhanging trees at the shoreline and sun glint on the water surface in the case of the image of RS 1993-04-27. Field observation in 2012 showed a significant floating vegetation cover in KS. For the lake-level estimation of RS in 1969 only a part of the shoreline was used as the aerial photo does not cover the entire lake. For the year 1959 two aerial photos had to be combined to facilitate the extraction of the entire lake area of RS.

For the very old historic maps (before 1900) the possible GCPs were too coarse. Thus the actual position of the shorelines could not be extracted. Additionally, the temporal accuracies were low. Old maps were often developed step by step over several years and the date of publication differed from the date of the measurements or the update of old measurements. We noticed that even when maps were published in an updated format, lakes and forests were often just copied from the old maps.

References

Anders, F., Byrnes, M., 1991. Accuracy of shoreline change rates as determined from maps and aerial photographs. Shore and Beach 59, 17-26.

Hughes, M.L., McDowell, P.F., Marcus, W.A., 2006. Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. Geomorphology 74, 1-16.

Part 2: List of aerial photos and digital orthophotos of Lake Rederswalder See and their metadata.

The metadata of remote sensing data of Lake Redernswalder See include the acquisition date of the digital orthophotos (DOPs) and aerial photos, the nominal scale/resolution and the source of the images. For the aerial photos we listed the number of GCPs and the transformation used, and the resulting root mean square error (RSME) in meter. The RMSE is the sum of deviations between predicted and actual position of the GCPs.

Date	Nominal scale/ resolution	Source	# of GCPs	Trans-formation	RMSE (m)
2012-05-24	20 cm	Landesvermessung und Geobasisinformation Brandenburg (LGB)	DOP	-	-
2009-04-24	20 cm	Landesvermessung und Geobasisinformation Brandenburg (LGB)	DOP	-	-
2007-04-14	40 cm	Landesvermessung und Geobasisinformation Brandenburg (LGB)	DOP	-	-
2003-08-09	100 cm	Landesvermessung und Geobasisinformation Brandenburg (LGB)	DOP	-	-
1993-04-27	1:18000	Landesvermessung und Geobasisinformation Brandenburg (LGB)	14	2nd Order	4.15436
1987-05-10	1:18000	Landesvermessung und Geobasisinformation Brandenburg (LGB)	12	2nd Order	3.66549
1978-05-04	1:12700	Bundesarchiv	12	2nd Order	3.26063
1973-05-30	1:12500	Bundesarchiv	12	2nd Order	5.66798
1969-09-08	1:10500	Bundesarchiv	10	2nd Order	1.48932
1959-06-01	1:10000	Bundesarchiv	9	2nd Order	2.40953
1959-06-01	1:10000	Bundesarchiv	10	2nd Order	4.65904
1937-07-00	1:25000	Landesvermessung und Geobasisinformation Brandenburg (LGB)	DOP	-	-

Part 3: List of topographic maps of Lake Rederswalder See and their metadata.

The metadata of topographic maps of Lake Redernswalder See include the date when the maps were published (and last updated), their name with information about the scale and the source of the maps.

Date	Name	Source
2008 (updated 2005)	TK25 (ATKIS)-2849 Warnitz	vom GFZ (Geo-Basis)
1998 (updated 1994)	TK25-2849 Warnitz	HNE Kartenarchiv
1997 (updated 1994)	TK10- 2849 NW Warnitz	Kartenarchiv Humboldt-Universität
1990 (updated1978)	DDR-TK25 (AS): N-33-100-D-b (Greiffenberg),	Bundesarchiv, Geo-Basis Potsdam
1985 (updated 1981)	DDR-TK25 (AS): N-33-100-D-b (Greiffenberg),	Bundesarchiv, Staatsbibliothek Potsdamer Str.
1981	DDR_TK10-0609_421 Warnitz-Grünheide	Kartenarchiv Humboldt-Universität
1976 (updated 1974)	DDR-TK25 (AS): N-33-100-D-b (Greiffenberg),	Bundesarchiv
1957 (updated 1954)	DDR-TK25 (AS): N-33-100-D-b (Greiffenberg),	Bundesarchiv
1936 (updated 1890)	Messtischblatt 1402 (2849) Polssen	Bundesarchiv
1932 (updated 1890)	Messtischblatt 1402 (2849) Polssen	Staatsbibliothek Berlin, Potsdamer Str.
1924	Militärkarte Angermünde West	Militärgeschichtliches Forschungsamt
1919 (updated1888)	Messtischblatt 1402 (2849) Polssen	Bundesarchiv
1890 (updated 1888)	Messtischblatt 1402 (2849) Polssen	Staatsbibliothek Berlin, Unter den Linden (SBB_IIIC_Kart. N 730), Bundesarchiv
1827	Urmesstischblatt 1402 Polssen	Staatsbibliothek Berlin, Unter den Linden (SBB_IIIC_Kart. N 729)
1767-1787	Schmettausche Karte 36 Tempelin	Staatsbibliothek Berlin, Unter den Linden (Kart. L 5420)
1792	Charte der Uckermark	Deutsches Historisches Museum (Do 2006/508)

Part 4: List of aerial photos and digital orthophotos of Lake Krummer See and their metadata.

The metadata of remote sensing data of Krummer See include the acquisition date of the digital orthophotos (DOPs) and aerial photos, the nominal scale/resolution and the source of the images. For the aerial photos we listed the number of GCPs and the transformation used, and the resulting root mean square error (RSME) in meter. The RMSE is the sum of deviations between predicted and actual position of the GCPs.

Date	Nominal scale/ resolution	Source	# of GCPs	Trans- formation	RMSE (m)
2012-05-24	20 cm	Landesvermessung und Geobasisinformation Brandenburg (LGB)	DOP	-	-
2009-04-12	20 cm	Landesvermessung und Geobasisinformation Brandenburg (LGB)	DOP	-	-
2007-04-14	40 cm	Landesvermessung und Geobasisinformation Brandenburg (LGB)	DOP	-	-
2003-08-09	100 cm	Landesvermessung und Geobasisinformation Brandenburg (LGB)	DOP	-	-
1993-04-01	1:18000	Landesvermessung und Geobasisinformation Brandenburg (LGB)	9	2nd Order	1.72782
1987-03-23	unknown	Landesvermessung und Geobasisinformation Brandenburg (LGB)	10	2nd Order	0.56343
1981-05-13	1:80000	Landesvermessung und Geobasisinformation Brandenburg (LGB)	9	2nd Order	1.50877
1978-05-04	1:12700	Bundesarchiv	11	2nd Order	1.46313
1973-05-30	1:12500	Bundesarchiv	31	2nd Order	6.13806
1970-06-09	1:7000	Bundesarchiv	6	1st Order	3.43973
1959-06-19	1:10000	Bundesarchiv	7	2nd Order	2.12637

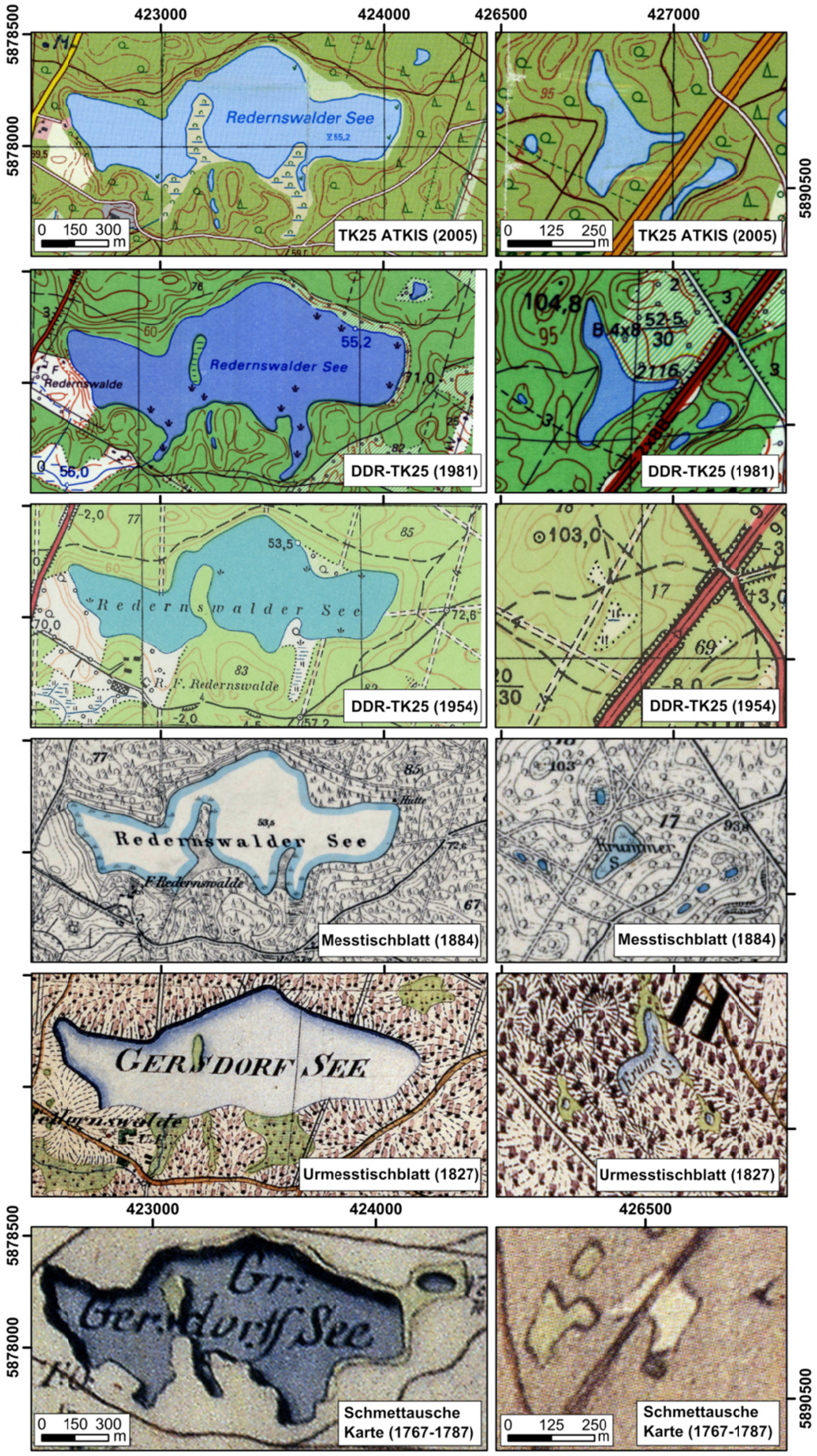
Part 5: List of topographic maps of Lake Krummer See and their metadata.

The metadata of topographic maps of Lake Krummer See include the date when the maps were published (and last updated), their name with information about the scale and the source of the maps.

Date	Name	Source
2008 (updated 2005)	TK25 (ATKIS)-2949 Greiffenberg	vom GFZ (Geo-Basis)
1997 (updated 1994)	TK25 2949 Greiffenberg	HNE Kartenarchiv
1997 (updated 1994)	TK10 2949-SW Wolletz	Kartenarchiv Humboldt-Universität
1990 (updated1978)	DDR-TK25 (AS): N-33-100-D-b (Greiffenberg),	Bundesarchiv, Geo-Basis Potsdam
1985 (updated 1981)	DDR-TK25 (AS): N-33-100-D-c (Parlow-Glambeck)	Bundesarchiv, Staatsbibliothek Potsdamer Str.
1979	DDR_TK25 (AV)_0609-43_Parlow-Glambeck	HNE Kartenarchiv
1976 (updated 1974)	DDR-TK25 (AS): N-33-100-D-c (Parlow-Glambeck)	Bundesarchiv
1957 (updated 1954)	DDR-TK25 (AS): N-33-100-D-c (Parlow-Glambeck)	Bundesarchiv
1936 (updated 1884)	Messtischblatt 14082(2949) Greiffenberg	Bundesarchiv
1928 (updated 1882)	Messtischblatt 14082(2949) Greiffenberg	Bundesarchiv
1924	Militärkarte Angermünde West	Militärgeschichtliches Forschungsamt
1908 (updated 1884)	Messtischblatt 14082(2949) Greiffenberg	Staatsbibliothek Berlin, Unter den Linden (SBB_IIIC_Kart. N 730),
1890 (updated 1884)	Messtischblatt 14082(2949) Greiffenberg	Staatsbibliothek Berlin, Unter den Linden (SBB_IIIC_Kart. N 730),
1826	Urmesstischblatt 1482 Greiffenberg	Staatsbibliothek Berlin, Unter den Linden (SBB_IIIC_Kart. N 729)
1767-1787	Schmettausche Karte 51 Liebenwalde (L5420)	Staatsbibliothek Berlin, Unter den Linden (Kart. L 5420)
1792	Charte der Uckermark	Deutsches Historisches Museum (Do 2006/508)

Part 6: Selected maps of Lakes Rederswalder See (left) and Krummer See (right) after the pre-processing.

The dates in brackets are the year of the last update, not the year when the maps were published. ‘Gr. Gersdorff See/Gersdorf See’ is the name of Lake Rederswalder See in the late 18th to early 19th centuries. Map ‘Schmettausche Karte’ could not be accurately geo-referenced, thus, the geo-position of the lakes is shifted massively.



Part 7: Detailed description of the digital elevation models (DEMs) and their pre-processing.

The DEMs of Lakes Redernswalder See (RS) and Krummer See (KS) are mosaics of a laser survey DEM and bathymetric data of the lakes. Following data were used for processing the DEM:

Data	Date	Source	Accuracy
DEM of RS with lake surface	2011-01-29/ 20011-02-12	Landesvermessung und Geobasisinformation Brandenburg (LGB), Laserscanning	The resolution is 1 m x 1 m with an vertical and horizontal accuracy of 0.3 m
DEM of KS with lake surface	2011-03-30	Landesvermessung und Geobasisinformation Brandenburg (LGB), Laserscanning	The resolution is 1 m x 1 m with an vertical and horizontal accuracy of 0.3 m
Bathymetric point data of RS	2002-06-11	Landesamt für Umwelt, Gesundheit und Verbraucherschutz (Brandenburg)	The measurements were performed in rows with circa 50 m distance with insufficient distribution of points.
Shoreline of RS	2002-06-00	Not measured at the date of the bathymetric survey, thus, the shoreline was estimated based on the in situ measured lake level (53.38 m NHN at 2002-06-13) plotted in the digital terrain model, supported by an Landsat 7 satellite image (2002-06-01, panchromatic band: 15 m resolution)	
Bathymetric point data of KS	2014-01-14	Measured within the framework of this study	Good distribution and very high number of points in relation to the area of the lake.
Shoreline of KS	2014-01-14	Measured within the framework of this study using a GPS handheld device	

First, we interpolated the bathymetric point data using triangulation. In this interpolation method, triangles are placed between three non-uniformly spaced points and a height gradient is calculated between them. This method is frequently used for the interpolation of bathymetric maps (e.g. Furnans and Austin, 2008; Johnson et al., 2008). The shorelines are included in the interpolations of the bathymetric point data. Because of the small number of data points of the bathymetric survey of RS and their uneven distribution, the underwater topography of RS shows artefacts and stair-like structures.

The relative bathymetric maps are transformed into absolute height maps using the absolute lake levels at the date of the bathymetric survey. For RS we took the *in situ* lake level, for KS we used the estimated mean lake level based on the GPS derived shoreline and the DEM.

The DEMs of the laser survey are terrain models and show the bare ground without vegetation. Those DEMs were combined with the interpolated bathymetric maps. The final DEMs of RS and KS illustrate the over- and underwater topography (‘terrain’) with 1 m resolution.

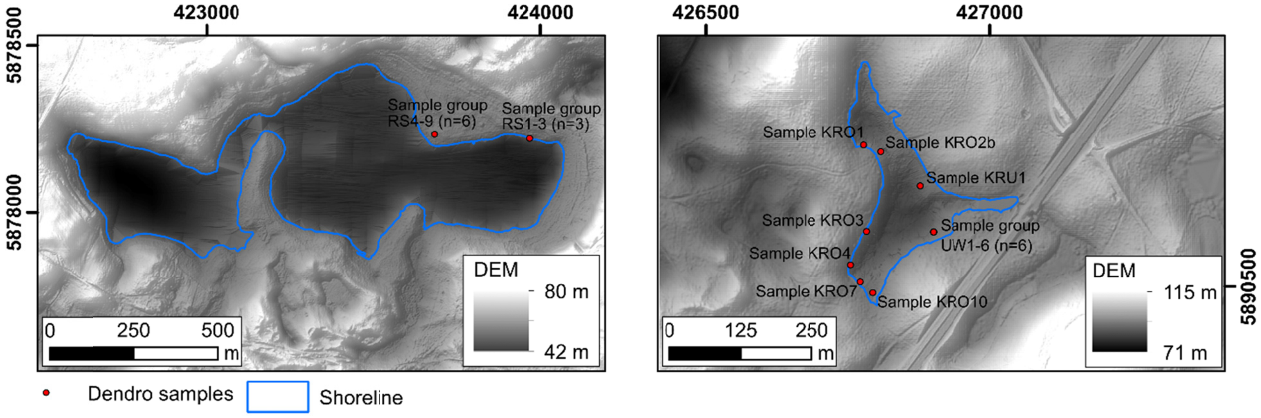
References

Furnans, J., Austin, B., 2008. Hydrographic survey methods for determining reservoir volume. Environmental Modelling & Software 23, 139-146.

Johnson, M.R., Andersen, M.J., Sebree, S.K., 2008. Hydrographic surveys for six water bodies in eastern Nebraska, 2005-07. U.S. Geological Survey, Scientific Investigations Report 2008-5048, U.S. Geological Survey, Reston/Virginia

Part 8: Digital elevation models (DEMs) including over- and underwater topography of Lakes Redernswalder See and Krummer See.

The digital elevation models (DEM) illustrate the over- and underwater topography of Lakes Redernswalder See (left) and Krummer See (right). The blue line represents the shoreline of the lakes extracted from the aerial photo for Lake Redernswalder See (2012-05-24) and measured by GPS device during a field campaign for Lake Krummer See (2014-01-14). The red dots mark the dendrochronological sampling sites.



Part 9: Area of Lake Redernswalder See and its change in comparison to the newest date (2012-05-24).

Date	Lake area [ha]	Lake area change [%]
2012-05-24	42.58	0
2009-04-24	41.57	-2
2007-04-14	41.87	-2
2003-08-09	43.55	2
1993-04-27	52.62	24
1987-05-10	61.91	45
1978-05-04	59.84	41
1973-05-30	54.94	29
1969-09-08	46.06	8
1959-06-01	46.06	8
1937-07-15	42.83	1

Part 10: Area of Lake Krummer See and its change in comparison to the newest date (2014-01-14).

Date	Lake area [ha]	Lake area change [%]
2014-01-14	3.63	0
2012-05-24	1.37	-62
2009-04-12	2.76	-24
2007-04-14	2.55	-30
2003-08-09	1.51	-58
1993-04-27	3.88	7
1987-03-23	4.13	14
1981-05-13	3.49	-4
1978-05-04	3.12	-14
1973-05-30	3.19	-12
1970-06-09	2.75	-24
1959-06-19	0.13	-97

Supplement 4: Supplementary material on hydrological modelling

Part 1: Equations used for lake-level modelling.

Equation 1:

$$W_{(i)} = W_{(i-1)} + Prec_{(i)} - EvaLake_{(i)} + \frac{Q_{inflow\,(i)} - Q_{outflow\,(i)}}{A}$$

with
$W_{(i)}$ – water level of time interval i in mm
$W_{(i-1)}$ – water level of previous time interval in mm
$Prec_{(i)}$ – precipitation in mm
$EvaLake_{(i)}$ – evaporation from lake surface in mm
$Q_{inflow(i)}$ – surface and subsurface inflow into lake during time interval i in dm³
$Q_{outflow(i)}$ – surface and subsurface outflow of lake during time interval i in dm³
A – surface area of the lake in m²

Equation 2:

$$W_i = a + b\frac{1}{m}\sum_{k=i-m}^{i}(Prec_k - EvaLake_k) + c\frac{1}{n}\sum_{o=i-n}^{i}(Prec_o - EvaCatch_o)$$

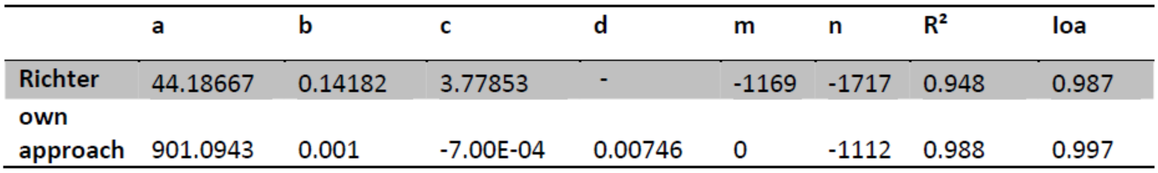
with
n – timelag1
m – timelag2
a, b, c – empirical parameters used for calibration
EvaCatch – (actual) evapotranspiration from catchment area in mm

Equation 3:

$$W_i = W_{i-1} + bPrec_i + cEvaLake_i + d\frac{1}{n}\sum_{k=i-n}^{i}(Prec_k - EvaCatch_k) + (1 - \mathrm{e}^{\frac{W_{i-1}-\mathrm{BC}}{\mathrm{a}}})$$

with
n – first interval of the analysed time period
BC – groundwater level of the lower boundary condition with 35 m a.s.l.
a, b, c, d – empirical parameters used for calibration

Part 2: Empirical and quality parameters for the modelling approach according to Richter (1997) and for our own approach presented in this study.

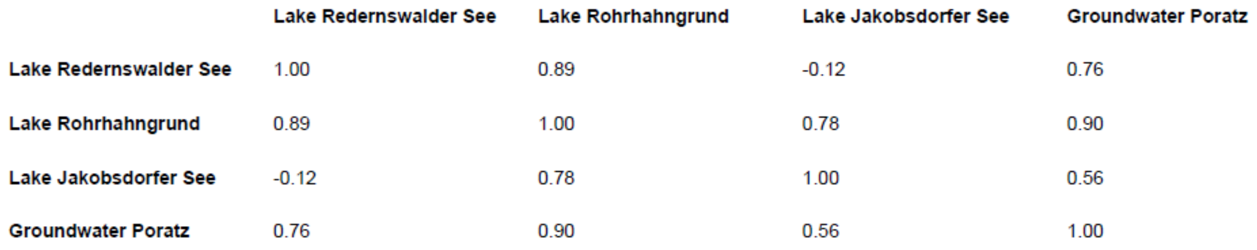


	a	b	c	d	m	n	R²	Ioa
Richter	44.18667	0.14182	3.77853	-	-1169	-1717	0.948	0.987
own approach	901.0943	0.001	-7.00E-04	0.00746	0	-1112	0.988	0.997

a, b, c, d – empirical parameters used for calibration
m – timelag2
n – timelag1
R^2 – coefficient of determination
Ioa – Willmott's index of agreement

Supplement 5: Supplementary material on hydrological gauging

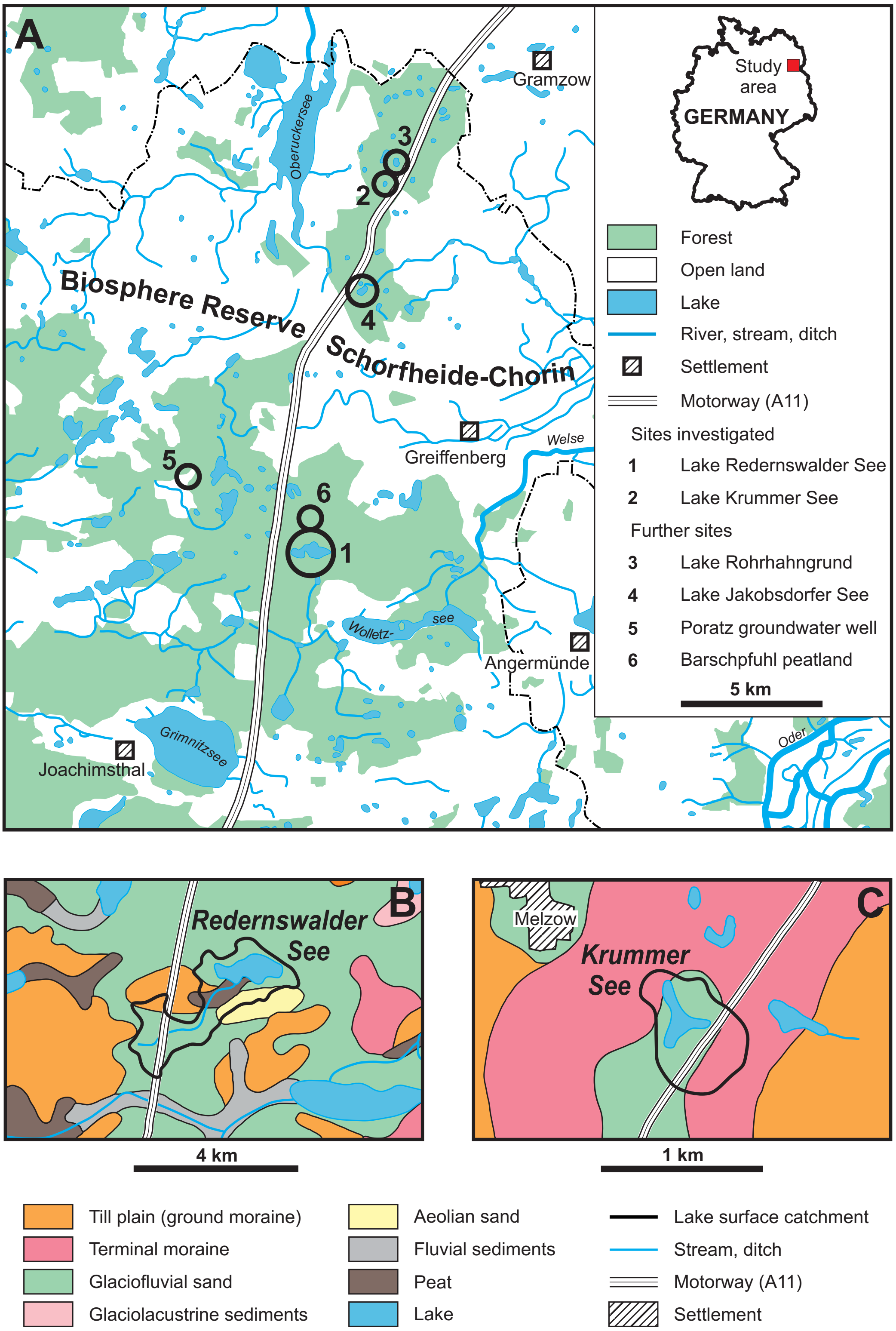
Correlation matrix for the gauging records under study. As different gauging periods exist, the correlation pertains to the overlap period each.

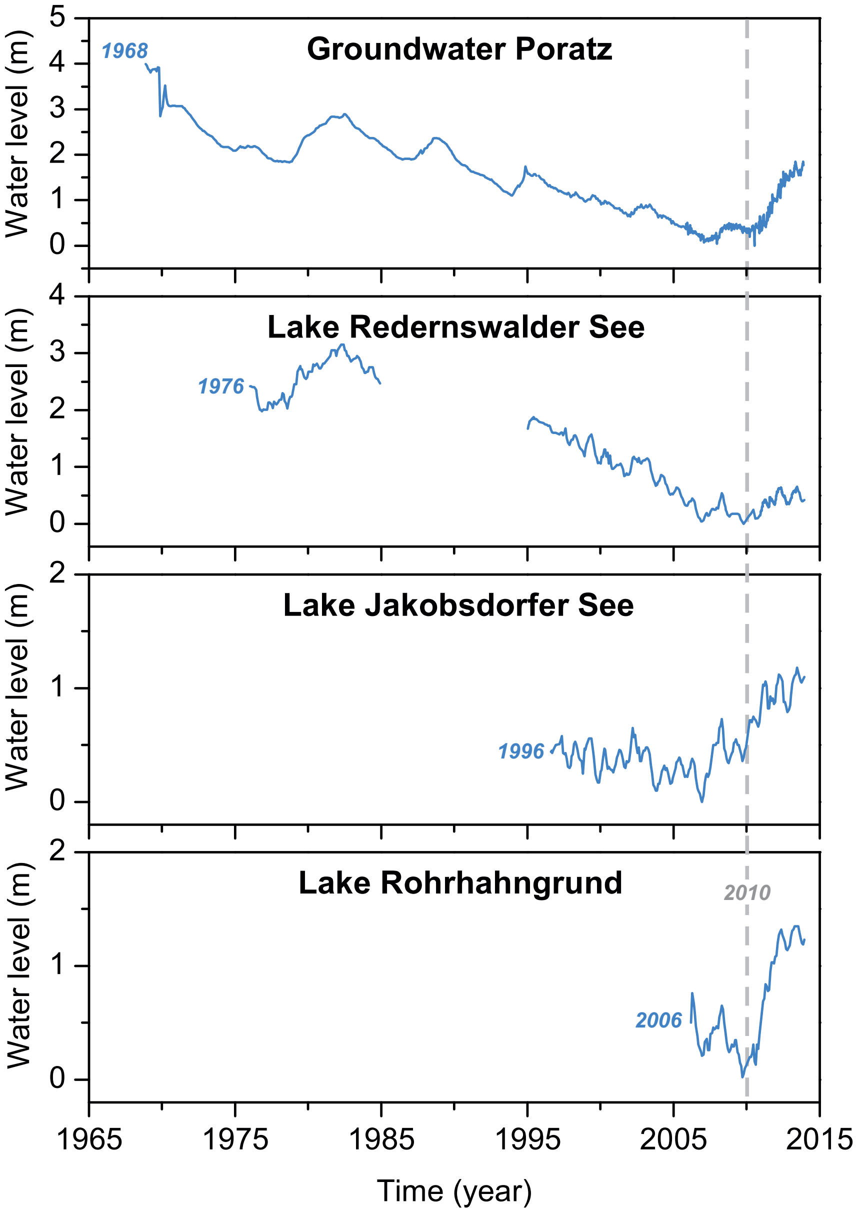


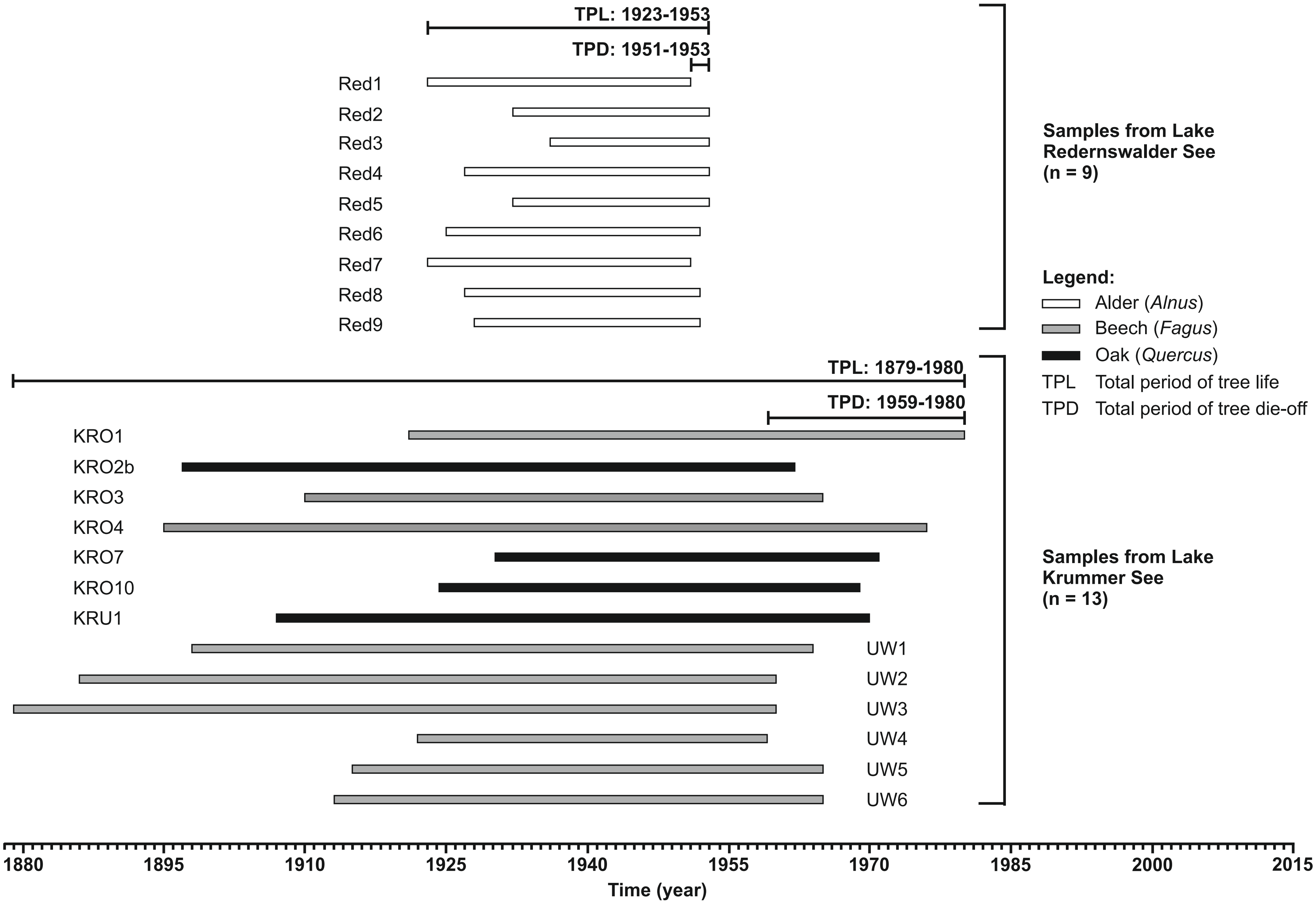
	Lake Redernswalder See	Lake Rohrhahngrund	Lake Jakobsdorfer See	Groundwater Poratz
Lake Redernswalder See	1.00	0.89	-0.12	0.76
Lake Rohrhahngrund	0.89	1.00	0.78	0.90
Lake Jakobsdorfer See	-0.12	0.78	1.00	0.56
Groundwater Poratz	0.76	0.90	0.56	1.00

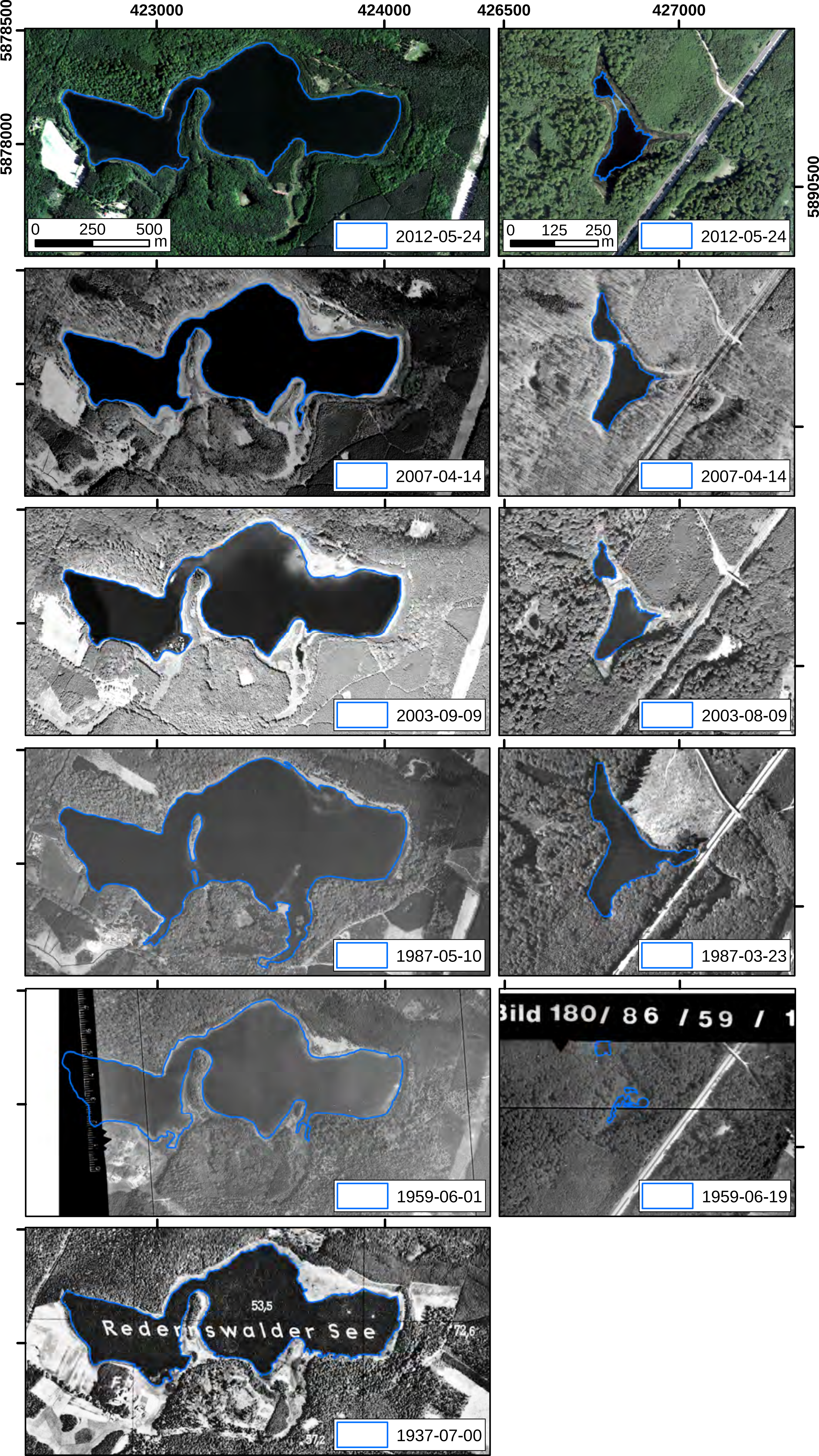
Site name	**Site ID and data**	**Northing** [Dec°]	**Easting** [Dec°]	**Altitude** [m NHN]	**Lake area** [ha]	**Max. lake depth** [m]	**Hydrological lake type** [sensu Mauersberger, 2006]	**Gauging since** [year]	**Max. water-level amplitude** [m]	**Trophic state**	**Catchment area** [ha]	**Catchment geology** [prevailing]	**Catchment land-cover** [prevailing]
Lake Redernswalder See	RS[1,2,3,4,5]	53.046940	13.857089	55	55	13	Endorheic lake	1976	3,2	mesotrophic	390	Outwash plain	Coniferous forest
Lake Krummer See	KS[2,3,5]	53.159979	13.905887	85	4	7	Groundwater lake	-	>5.0	eutrophic	30	Terminal moraine	Deciduous forest
Lake Rohrhahngrund	RG[1]	53.176824	13.917912	76	5	6	Groundwater lake	2006	0,6	eutrophic	45	Terminal moraine	Deciduous forest
Lake Jakobsdorfer See	JS[1]	53.131995	13.892590	60	23	10	Spring lake	1996	1,2	mesotrophic	120	Terminal moraine	Deciduous forest
Poratz groundwater well	PZ[1]	53.063524	13.787774	56	-	-	-	1968	4,0	-	-	Outwash plain	Arable land

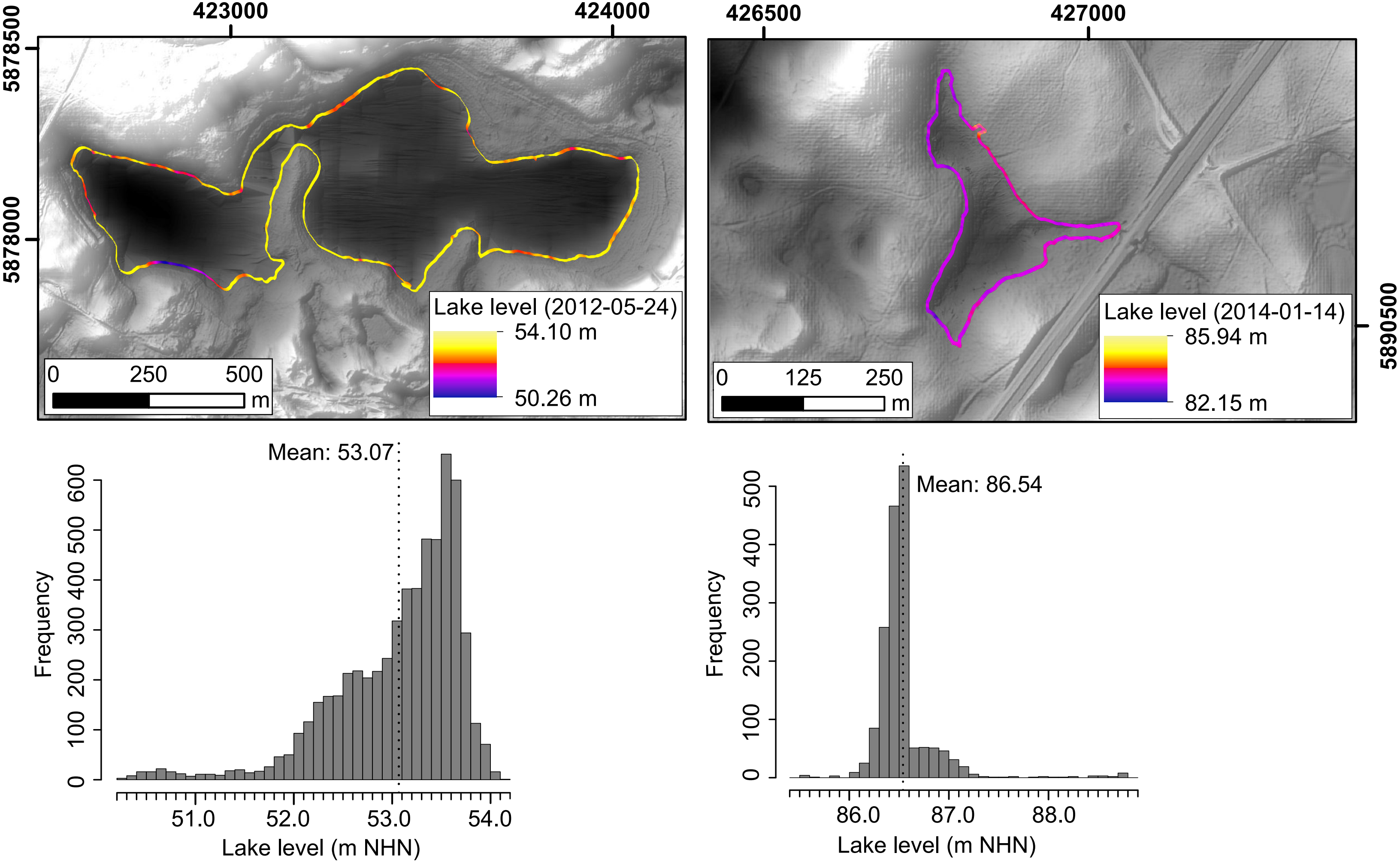
[1] gauging data
[2] dendrochronological data
[3] remote sensing data
[4] modelling data
[5] bathymetric data

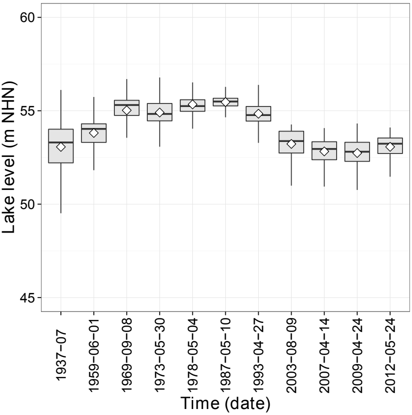

A
Study area
GERMANY
Forest
Open land
Lake
River, stream, ditch
Settlement
Motorway (A11)
Sites investigated
1 Lake Redernswalder See
2 Lake Krummer See
Further sites
3 Lake Rohrhahngrund
4 Lake Jakobsdorfer See
5 Poratz groundwater well
6 Barschpfuhl peatland
5 km
Gramzow
Oberuckersee
Biosphere Reserve Schorfheide-Chorin
Greiffenberg
Welse
Angermünde
Wolletz-see
Grimnitzsee
Joachimsthal
Oder
1
2
3
4
5
6
B
Redernswalder See
4 km
C
Melzow
Krummer See
1 km
Till plain (ground moraine)
Terminal moraine
Glaciofluvial sand
Glaciolacustrine sediments
Aeolian sand
Fluvial sediments
Peat
Lake
Lake surface catchment
Stream, ditch
Motorway (A11)
Settlement

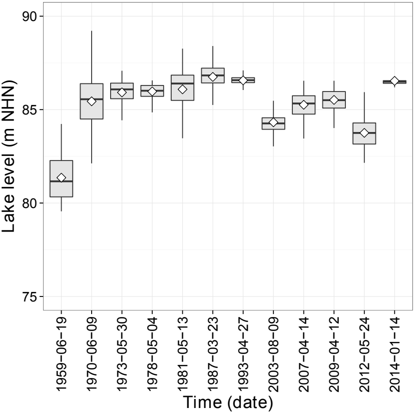

5
4
3
2
1
0
1968
Groundwater Poratz
Water level (m)
4
3
2
1
0
Lake Redernswalder See
1976
Water level (m)
2
1
0
Lake Jakobsdorfer See
1996
Water level (m)
2
1
0
Lake Rohrhahngrund
2010
2006
Water level (m)
1965
1975
1985
1995
2005
2015
Time (year)

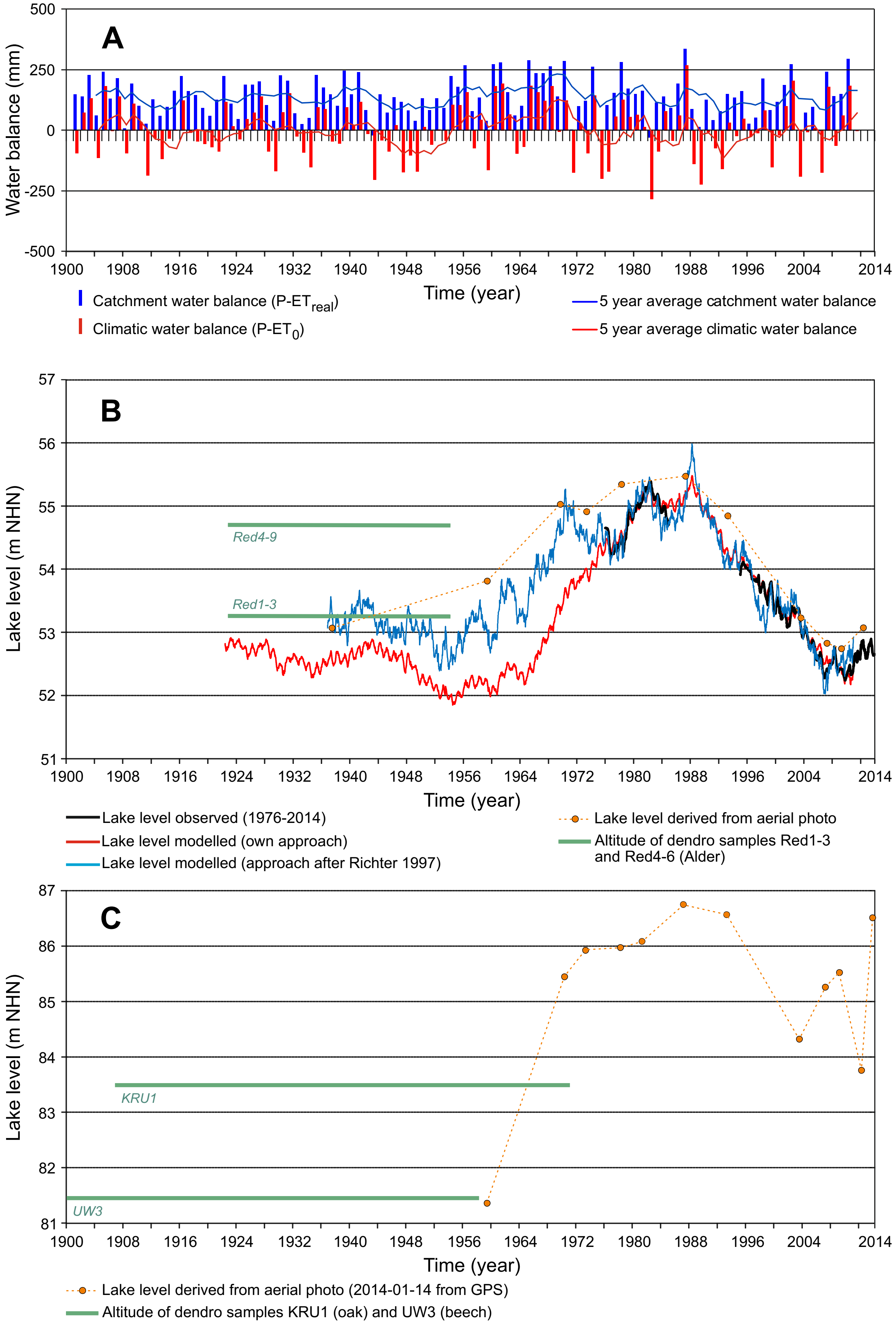

TPL: 1923-1953
TPD: 1951-1953
Red1
Red2
Red3
Red4
Red5
Red6
Red7
Red8
Red9
Samples from Lake Redernswalder See (n = 9)
Legend:
Alder (*Alnus*)
Beech (*Fagus*)
Oak (*Quercus*)
TPL Total period of tree life
TPD Total period of tree die-off
TPL: 1879-1980
TPD: 1959-1980
KRO1
KRO2b
KRO3
KRO4
KRO7
KRO10
KRU1
UW1
UW2
UW3
UW4
UW5
UW6
Samples from Lake Krummer See (n = 13)
1880
1895
1910
1925
1940
1955
1970
1985
2000
2015
Time (year)

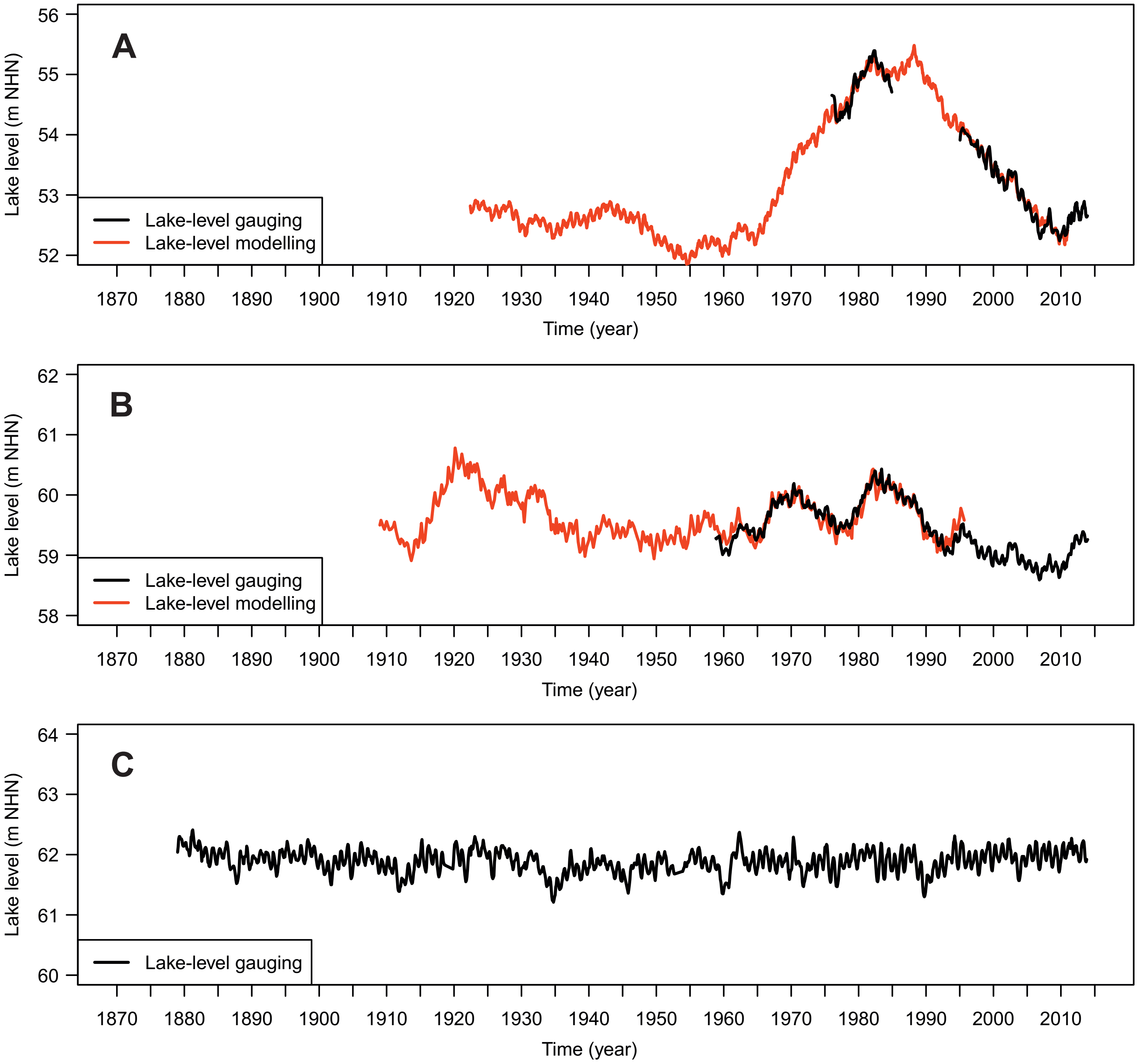

423000
424000
426500
427000
5878500
5878000
5890500
0 250 500 m
2012-05-24
0 125 250 m
2012-05-24
2007-04-14
2007-04-14
2003-09-09
2003-08-09
1987-05-10
1987-03-23
1959-06-01
Bild 180/ 86 /59 / 1
1959-06-19
53,5
Redernswalder See
72,6
37,2
1937-07-00

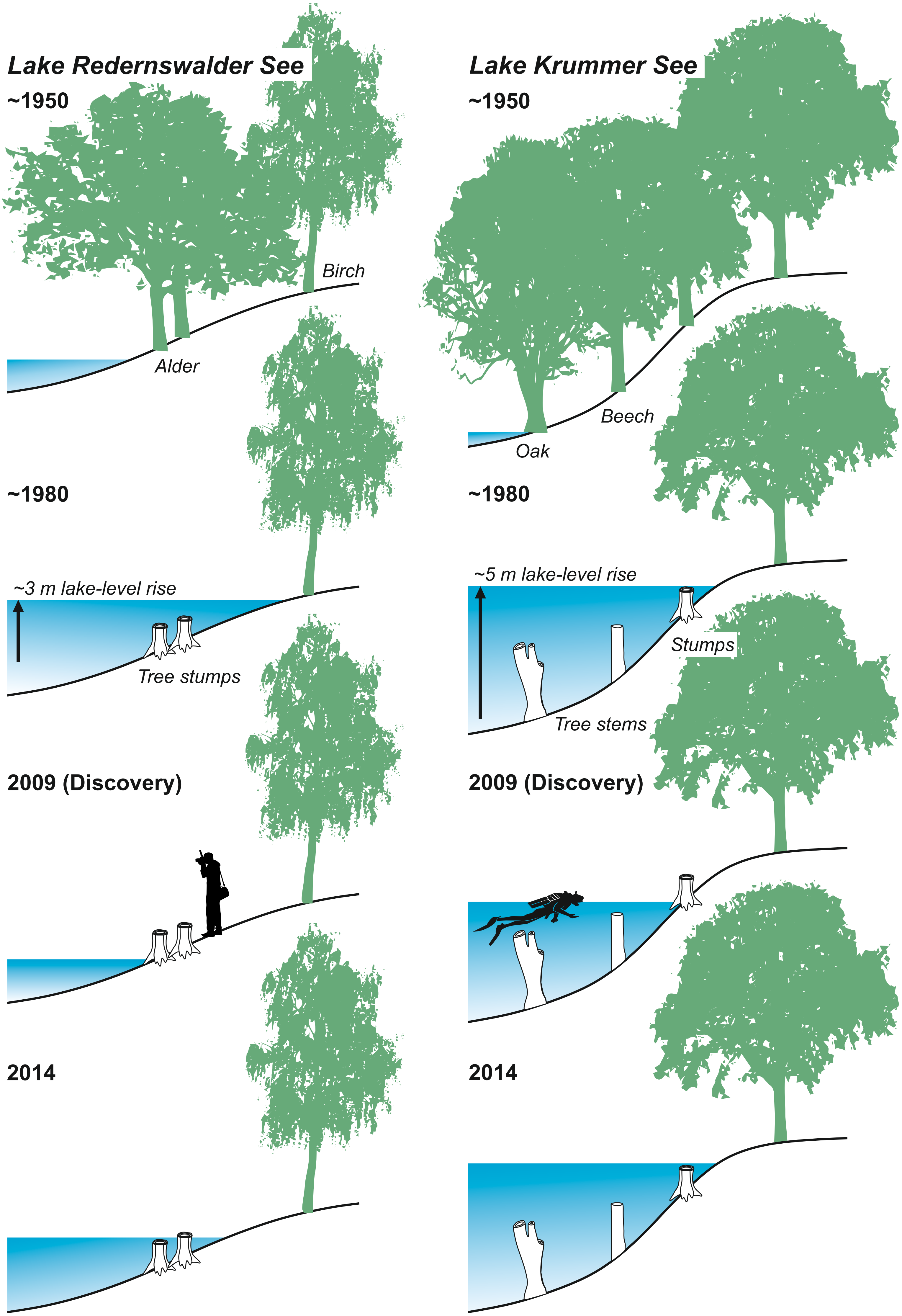

423000
424000
5878500
5878000
0 250 500 m
Lake level (2012-05-24)
54.10 m
50.26 m
426500
427000
5890500
0 125 250 m
Lake level (2014-01-14)
85.94 m
82.15 m
Mean: 53.07
Frequency
0
100
200
300
400
500
600
51.0
52.0
53.0
54.0
Lake level (m NHN)
Mean: 86.54
Frequency
0
100
200
300
400
500
86.0
87.0
88.0
Lake level (m NHN)


Lake level (m NHN)
60
55
50
45
1937–07
1959–06–01
1969–09–08
1973–05–30
1978–05–04
1987–05–10
1993–04–27
2003–08–09
2007–04–14
2009–04–24
2012–05–24
Time (date)


Lake level (m NHN)
90
85
80
75
1959–06–19
1970–06–09
1973–05–30
1978–05–04
1981–05–13
1987–03–23
1993–04–27
2003–08–09
2007–04–14
2009–04–12
2012–05–24
2014–01–14
Time (date)


A
Water balance (mm)
500
250
0
-250
-500
1900
1908
1916
1924
1932
1940
1948
1956
1964
1972
1980
1988
1996
2004
2014
Time (year)
Catchment water balance (P-ET$_{real}$)
Climatic water balance (P-ET$_0$)
5 year average catchment water balance
5 year average climatic water balance
B
Lake level (m NHN)
57
56
55
54
53
52
51
Red4-9
Red1-3
Time (year)
Lake level observed (1976-2014)
Lake level modelled (own approach)
Lake level modelled (approach after Richter 1997)
Lake level derived from aerial photo
Altitude of dendro samples Red1-3 and Red4-6 (Alder)
C
Lake level (m NHN)
87
86
85
84
83
82
81
KRU1
UW3
Time (year)
Lake level derived from aerial photo (2014-01-14 from GPS)
Altitude of dendro samples KRU1 (oak) and UW3 (beech)


A
Lake level (m NHN)
56
55
54
53
52
Lake-level gauging
Lake-level modelling
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Time (year)
B
Lake level (m NHN)
62
61
60
59
58
Lake-level gauging
Lake-level modelling
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Time (year)
C
Lake level (m NHN)
64
63
62
61
60
Lake-level gauging
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Time (year)


Lake Redernswalder See
~1950
Birch
Alder
~1980
~3 m lake-level rise
Tree stumps
2009 (Discovery)
2014
Lake Krummer See
~1950
Beech
Oak
~1980
~5 m lake-level rise
Stumps
Tree stems
2009 (Discovery)
2014