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A 7000 yr runoff chronology from varved sediments of Lake Mondsee (Upper Austria)

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Abstract

The potential increase in frequency and magnitude of extreme floods is currently discussed in terms of global warming and the intensification of the hydrological cycle. The profound knowledge of past natural variability of floods is of utmost importance in order to assess flood risk for the future. Since instrumental flood series cover only the last ~150 years, other approaches to reconstruct historical and pre-historical flood events are needed. Annually laminated (varved) lake sediments are meaningful natural geoarchives because they provide continuous records of environmental changes >10000 years down to a seasonal resolution. Since lake basins additionally act as natural sediment traps, the riverine sediment supply, which is preserved as detrital event layers in the lake sediments, can be used as a proxy for extreme discharge events.

Within my thesis I examined a ~8.50 m long sedimentary record from the pre-alpine Lake Mondsee (Northeast European Alps), which covered the last 7000 years. This sediment record consists of calcite varves and intercalated detrital layers, which range in thickness from 0.05 to 32 mm. Detrital layer deposition was analysed by a combined method of microfacies analysis via thin sections, Scanning Electron Microscopy (SEM), µX-ray fluorescence (µXRF) scanning and magnetic susceptibility. This approach allows characterizing individual detrital event layers and assigning a corresponding input mechanism and catchment. Based on varve counting and controlled by ^{14}C age dates, the main goals of this thesis are (i) to identify seasonal runoff processes, which lead to significant sediment supply from the catchment into the lake basin and (ii) to investigate flood frequency under changing climate boundary conditions. This thesis follows a line of different time slices, presenting an integrative approach linking instrumental and historical flood data from Lake Mondsee in order to evaluate the flood record inferred from Lake Mondsee sediments.

The investigation of eleven short cores covering the last 100 years reveals the abundance of 12 detrital layers. Therein, two types of detrital layers are distinguished by grain size, geochemical composition and distribution pattern within the lake basin. Detrital layers, which are enriched in siliciclastic and dolomitic material, reveal sediment supply from the Flysch sediments and Northern Calcareous Alps into the lake basin. These layers are thicker in the northern lake basin (0.1–3.9 mm) and thinner in the southern lake basin (0.05–1.6 mm). Detrital layers, which are enriched in dolomitic components forming graded detrital layers (turbidites), indicate the provenance from the Northern Calcareous Alps. These layers are generally thicker (0.65–32 mm) and are solely recorded within the southern lake basin. In comparison with instrumental data, thicker graded layers result from local debris flow events in summer, whereas thin layers are deposited during regional flood events in spring/summer. Extreme summer floods as reported from flood layer deposition are principally caused by cyclonic activity from the Mediterranean Sea, e.g. July 1954, July 1997 and August 2002.

During the last two millennia, Lake Mondsee sediments reveal two significant flood intervals with decadal-scale flood episodes, during the Dark Ages Cold Period (DACP) and the transition from the Medieval Climate Anomaly (MCA) into the Little Ice Age (LIA) suggesting a linkage of transition to climate cooling and summer flood recurrences in the Northeastern Alps. In contrast, intermediate or decreased flood episodes appeared during the MWP and the LIA. This indicates a non-straightforward relationship between temperature and flood recurrence, suggesting higher cyclonic activity during climate transition in the Northeast Alps.

The 7000-year flood chronology reveals 47 debris flows and 269 floods, with increased flood activity shifting around 3500 and 1500 varve yr BP (varve yr BP = varve years before present, before present = AD 1950). This significant increase in flood activity shows a coincidence with millennial-scale climate cooling that is reported from main Alpine glacier advances and lower tree lines in the European Alps since about 3300 cal. yr BP (calibrated years before present). Despite relatively low flood occurrence prior to 1500 varve yr BP, floods at Lake Mondsee could have also influenced human life in early Neolithic lake dwellings (5750–4750 cal. yr BP). While the first lake dwellings were constructed on wetlands, the later lake dwellings were built on piles in the water suggesting an early flood risk adaptation of humans and/or a general change of the Late Neolithic Culture of lake-dwellers because of socio-economic reasons. However, a direct relationship between the final abandonment of the lake dwellings and higher flood frequencies is not evidenced.

The runoff chronology from Lake Mondsee sediments shows a high climatic sensitivity of spring/summer floods. Despite seasonal and regional peculiarities, European flood activity increased during 2800 and 1500 cal. yr BP that reveals a substantial change of atmospheric circulation patterns, triggering flood prone weather regimes in Europe on millennial times-scales. However, large regional differences in European flood activity appeared on multi-decadal-times scales that necessitate further investigation on peculiar changes in atmospheric circulation pattern. The reconstruction of spring/summer floods from Lake Mondsee demonstrates the potential of varved sediment records to investigate the impact of changing climate boundary conditions on seasonal flood activity for pre-instrumental times.

Zusammenfassung

Ein verstärktes Auftreten von Hochwassern, sowohl in ihrer Häufigkeit als auch in ihrer Frequenz, wird im Zuge der Klimaerwärmung und einer möglichen Intensivierung des hydrologischen Kreislaufs diskutiert. Die Kenntnis über die natürliche Variabilität von Hochwasserereignissen ist dabei eine grundlegende Voraussetzung, um die Hochwassergefahr für die Zukunft abschätzen zu können. Da instrumentelle Hochwasserzeitreihen meist nur die letzten 150 Jahre abbilden sind andere Methoden erforderlich, um das Auftreten von historischen und prä-historischen Hochwassern festzustellen. Jährlich laminierte (warvierte) Seesedimente sind bedeutende natürliche Archive, denn sie liefern kontinuierliche Zeitreihen >10000 Jahre mit einer bis zur saisonalen Auflösung. Seebecken stellen natürliche Sedimentfallen dar, wobei eingetragenes Flusssediment in den Seesedimenten als eine distinkte detritische Lage aufgezeichnet wird, und daher zur Rekonstruktion von extremen Abflussereignissen genutzt werden.

Im Rahmen meiner Doktorarbeit habe ich einen 8.50 m langen Sedimentkern aus dem Mondsee (Nordostalpen) untersucht, welcher die letzten 7000 Jahre abdeckt. Dieser Sedimentkern besteht aus Kalzitwarven und eingeschalteten detritischen Lagen mit einer Mächtigkeit von 0.05–32 mm. Detritische Lagen wurden mit Hilfe einer kombinierten Methode untersucht: Mikrofaziesanalyse, Rasterelektronenmikroskopie, Röntgenfluoreszenzanalyse (µXRF) und magnetische Suszeptibilität. Dieser Ansatz ermöglicht die Charakterisierung der einzelnen detritischen Lagen bezüglich der Eintragsprozesse und die Lokalisierung des Einzugsgebietes. Auf Grundlage der Warvenzählung und ^{14}C Datierungen sind die wichtigsten Ziele dieser Arbeit: (i) die Identifizierung der Eintragsprozesse, welche zu einem Sedimenteintrag vom Einzugsgebiet bis in den See führen und (ii) die Rekonstruktion der Hochwasserfrequenz unter veränderten Klimabedingungen. Diese Arbeit zeigt eine Untersuchung auf verschiedenen Zeitscheiben, wobei instrumentelle und historische Daten genutzt werden, um die Aufzeichnung von pre-historischen Hochwasser in den Mondseesedimenten besser zu verstehen.

Innerhalb der letzten 100 Jahre wurden zwölf Abflussereignisse aufgezeichnet. Zwei Typen von detritschen Lagen können anhand von Korngröße, geochemischer Zusammensetzung und des Verteilungsmusters unterschieden werden. Detritische Lagen, welche aus siliziklastischen und dolomitischen Material bestehen, zeigen eine Sedimentherkunft vom Teileinzugsgebiet des Flysch (nördliches Einzugsgebiet) und der Nördlichen Kalkalpen (südliches Teileinzugsgebiet) auf. Diese Lagen sind im Nördlichen Becken mächtiger (0.1–3.9 mm) als im südlichen Seebecken (0.05–1.6 mm). Detritische Lagen, welche nur aus dolomitischem Material bestehen und Turbititlagen aufzeigen (0.65–32 mm), weisen auf eine Herkunft aus den Nördlichen Kalkalpen hin. Im Vergleich mit instrumentellen Zeitreihen, stammen die mächtigeren Lagen von lokalen Murereignissen im Sommer und feinere Eintragslagen von regionalen Frühjahrs- und Sommerhochwassern. Extreme Som-

merhochwasser am Mondsee werden hauptsächlich durch Zyklonen vom Mittelmeer ausgelöst, z.B. Juli 1954, Juli 1997 und August 2002.

Die Untersuchung des langen Sedimentkerns vom Mondsee zeigt während der letzten 2000 Jahre signifikante Hochwasserintervalle mit dekadischen Hochwasserepisoden während der Völkerwanderungszeit und im Übergang vom Mittelalter in die Kleine Eiszeit. Dies weist auf eine Verknüpfung von Abkühlungsphasen und Sommerhochwassern im Nordostalpenraum hin. Während der Mittelalterlichen Wärmephase und in der Kleinen Eiszeit kam es jedoch zu einer geringeren Hochwasseraktivität. Dies zeigt einen komplexen Zusammenhang von Temperaturentwicklung und Hochwasseraktivität in den Nordostalpen, mit einer erhöhten Zyklonenaktivät in den Übergängen von wärmeren zu kälteren Phasen.

Während der letzten 7000 Jahre wurden 47 Muren und 269 Hochwasser aufgezeichnet, wobei es eine signifikante Änderung mit erhöhter Häufigkeit um 3500 und 1500 Warvenjahre v. h. gab (v.h. = vor heute = AD 1950). Diese signifikante Änderung stimmt mit einem langfristigem Abkühlungstrend überein, welcher durch alpine Gletschervorstöße und das Absinken von Baumgrenzen seit etwa 3300 Warvenjahre v.h. berichtet wird. Trotz relativ geringer Hochwasseraktivität um 1500 Warvenjahre v.h., könnte das Auftreten von Hochwasser auch das Leben Menschen in Neolithischen Pfahlbausiedlungen (5750–4750 cal. yr BP) beeinflusst haben. Während die ersten Pfahlbauten noch als Feuchtbodensiedlungen am Land entstanden, wurden spätere Siedlungen eventuell als Anpassung an stark schwankenden Seewasserspiegeln auf Pfählen im Wasser gebaut und/oder zeigen eine allgemeine Veränderung der Siedlungsaktivitäten der Neolithischen Pfahlbaukultur an, aufgrund sozio-ökonomischer Veränderungen. Ein direkter Zusammenhang zwischen dem Verlassen der Pfahlbausiedlungen und einer erhöhten Hochwasseraktivität konnte jedoch nicht festgestellt werden.

Die Hochwasserchronologie vom Mondsee zeigt eine starke klimatische Sensitivität von Frühjahrs- und Sommerhochwassern. Trotz saisonaler und regionaler Feinheiten zeigt die Hochwasseraktivität in Europa einen zunehmenden Trend von Hochwassern zwischen 2800 und 1500 Jahren, was auf grundlegende Änderungen im Klimasystem und atmosphärischen Zirkulationsmechanismen hindeutet. Dennoch weisen dekadische Hochwasserepisoden räumlich starke Unterschiede auf, was weitere Untersuchungen von Zirkulationsmechanismen erforderlich macht. Die Rekonstruktion von Frühjahrs- und Sommerhochwassern am Mondsee zeigt das große Potential von warvierten Seesedimenten, an denen der Einfluss von Klimaveränderungen auf die saisonale Hochwasseraktivität für prä-instrumentelle Zeiten, studiert werden kann.

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Preface

This thesis was financed by the Helmholtz Centre Potsdam (GFZ German Research Centre for Geosciences) and participated within the Deutsche Forschungsgemeinschaft (DFG) funded Graduate School “Natural Disasters” at the University of Potsdam. Sedimentological investigations were carried out on a long sediment core retrieved within the project DecLakes (Decadal Holocene and Lateglacial variability of the oxygen isotopic composition in precipitation over Europe reconstructed from deep lake sediments), which has been funded by the European Science Foundation (ESF) EuroCLIMATE programme.

My investigation focused on the seasonal 7000 yr runoff history as recorded within the annually laminated (varved) sediments from Lake Mondsee (Upper Austria). In combination with various instrumental and historical datasets on floods and hydrological changes of this region, this sedimentary record of runoff events will help to understand flood variability under changing climate boundary conditions in the NE Alps further back in time complementing instrumental and documentary archives.

This thesis is a “cumulative thesis” and includes four single manuscripts (Chapters 2-5), which are presented after the introduction within the main part (Chapter 1). These manuscripts represent the history of flood variations at various time scales, from modern instrumental time (last 150 years) to (pre-) historic time (ca. 7000 yr BP) by using varve counting with a broad range of limnological, meteorological and geological parameters. The manuscripts have been either published, are submitted or are dedicated for publication. Manuscript no. 1 is published, manuscript no. 2 has been submitted and manuscript no. 3 is in pre-review to be submitted for a special issue. An additional manuscript in the Appendix is in preparation with the co-authors. A summary and conclusion of this thesis is presented in the final chapter (chapter 6).

Manuscript overview:

Instrumental to historical time scale

Manuscript #1 (Chapter 2)

Title: A 1600-year seasonally resolved record of decadal-scale flood variability from the Austrian pre-Alps
Autors: Tina Swierczynski, Achim Brauer, Stefan Lauterbach, Celia Martín-Puertas, Peter Dulski, Ulrich von Grafenstein, Christian Rohr
Published in Geology (doi: 10.1130/G33493.1)

The manuscript #1 presents a spring/summer flood record from Lake Mondsee covering the last 1600 years by applying microfacies analysis and µXRF element scanning at a 263 cm long sediment core from the central part of the southern lake basin (Mo-05P3).

The main goal of this article was to investigate flood activity during prominent climate extremes of the last two millennia (Wanner et al., 2008) that include warm climate conditions of the Medieval Climate Anomaly (MCA), unstable climate conditions of the Dark Ages Cold Period (DACP) and the coldest period of the Little Ice Age (LIA).

Additional information about detrital layer deposition between AD 1900 and 2000 is provided by a Manuscript in prep. (Appendix A)

Title: Distinguishing floods, debris flows and hydrological changes in a 100-year varved sediment record from Lake Mondsee, Upper Austria
Authors: Tina Swierczynski, Stefan Lauterbach, Peter Dulski, Achim Brauer)
In preparation, to be submitted to Natural Hazards

Manuscript in prep. presents a multi-core study (eleven short cores) from Lake Mondsee surface sediments showing the characteristics of the event layer deposition during the last 100 years (e.g. geochemical compositions, proximal to distal patterns). Sedimentary imprints of runoff events and intra-basin correlation of detrital layers have been studied by applying a combination of microfacies analysis and µXRF element scanning. Additionally, daily lake water levels and precipitation data of the last 100 years were utilized to characterize the seasonality of floods triggering sediment deposition in Lake Mondsee.

Pre-historical time scale

Manuscript #2 (Chapter 3)

Title: Late Holocene paleohydrological changes in the NE Alps: A 4000-year flood record from varved sediments of Lake Mondsee, Upper Austria
Authors: Tina Swierczynski, Stefan Lauterbach, J. Delgado, Peter Dulski, Ulrich von Grafenstein, Bruno Merz, Achim Brauer
Submitted to Quaternary Science Reviews

This manuscript discusses the 4000-year flood chronology from Lake Mondsee sediments as obtained from a 575 cm long sediment core from the central part of the southern lake basin. This chapter investigates main flood episodes in the context of pronounced climate change affecting the Alps and Europe on millennial and multi-decadal time scales.

Manuscript #3 (Chapter 4)

Title: The Late Neolithic Mondsee Culture- living on lakes and living with floods
Authors: Tina Swierczynski, Stefan Lauterbach, A. Brauer
In pre-review, to be submitted to Climate of the Past

This manuscript deals with sediments deposited between 4000 and 7000 yr BP, during the time of Neolithic settlements at Lake Mondsee. Scenarios of unfavourable climatic conditions are discussed that may have been responsible for the decline of the Lake Mondsee Culture at about 4700 cal. yr ago. To unravel flood event history during the Late

Neolithic at Lake Mondsee, I reconstructed the flood events from the deposition of detrital layers intercalated within varved Lake Mondsee sediments from the core of the central part of the lake basin.

Author's contribution

I am the first author of all presented articles within this thesis. I led the interpretation of the results as well as the writing of the manuscripts. Helpful discussions and valuable comments on the manuscripts with constructive improvements were given by the co-authors A. Brauer, S. Lauterbach, B. Merz, C. Martin-Puertas and J. Delgado. I conducted the microfacies analyses and the varve counting for the last 4000 years. I established the flood chronology for the last 7000 yr based on my varve chronology (AD 2005 until ca. 4000 varve yr BP) and the varve based chronology by S. Lauterbach (ca. 4000–7000 varve yr BP). My work concerned the combined interpretation of geochemical data with microfacies analysis and detrital layer identification. P. Dulski scanned sediment cores for geochemical composition (microX-ray Fluorescence data) at the German Research Centre for Geosciences (GFZ-Potsdam). J. Delgado helped with implementing the significance band of the kernel regression by using the Matlab® program. S. Lauterbach, furthermore, calculated the ^{14}C Age depth model and the lake dwellings phases in manuscript #3. We took both part in the interpretation of the results and the writing of the manuscript #3.

Chapter 1

Introduction

1.1 Climate change and flood variability

Meteorological events causing river floods are the most common and widespread of all natural hazards worldwide (MunichRE, 2011). Throughout the last decades, an increased focus was set on the emerging evidence of higher frequency and magnitude of severe floods during the 20th century (Allen and Ingram, 2002; Bronstert et al., 2002; Milly et al., 2002). The latest report of the International Panel on Climate Change (IPCC, 2007) underlines the increase of extreme events under global warming. The upcoming 5th IPCC report states that changes in precipitation and temperature imply possible changes in extreme flood events, however, 'there is low confidence in projections of changes in fluvial floods' (IPCC, 2011).

In order to detect such changes, however, long-term monitoring programmes are required. Central Europe, for example, is covered with a dense network of climate stations and relatively long flood series (50 years) that enable the detection of multi-decadal flood trends, as well as determining seasonal and regional characteristics of floods within instrumental time period. For instance, the seasonality of extreme rainfall events in Germany as identified during the time period 1951-2002 reveals different regional patterns (Beurton and Thieken, 2009) corresponding to increasing summer floods in southern Germany (Petrow, 2009b) and increasing winter floods in western Germany (Petrow, 2009b). A trend of increased summer rainfall events is also reported for the Austrian Alps, Bohemia and Saxony (Kaszewski and Filipiuk, 2003; Merz, 2009; Petrow et al., 2007). At multi-decadal timescale, the occurrence of European floods and the principle variations in circulation patterns are mainly obtained from data of the instrumental and historical period (Jacobeit et al., 2006; Kaszewski and Filipiuk, 2003; Kundzewicz et al., 2005; Mudelsee et al., 2004; Petrow, 2009b); however, evaluating the flood response to changes in the climate conditions as the recent global warming is poorly constrained because of short instrumental time series (Blöschl and Merz, 2008; Rohr, 2007). Understanding spatio-temporal patterns of flood variability in Europe and the sensitivity under changing climate conditions is of particular interest for the understanding of future scenarios and risk assessment in this region.

A main problem for risk assessment on a regional scale is the assumption of non-stationary climate within the model output because of covering too short time series. Additionally, global circulation models (GCM) are limited in down-scaling the hydro-climatic processes (Bronstert et al., 2002; Delgado et al., 2010; Katz and Brown, 1992; Zolina et al., 2010) that districts the prediction of flood activity on a regional scale. These large uncertainties in climate projections emphasize the need of other methods to better evaluate the occurrence of floods and heavy precipitation events in the context of climate change.

1.2 Flood reconstruction - State of the art

Classical flood reconstruction is based on instrumental data recording the occurrence and magnitude of floods of the last 50 years on a sub-daily resolution. Future scenarios on flood occurrence are based on these highly-resolved data sets, however, the input data rarely exceed the last 50–100 years that limitates a representative record of the natural flood variability. The occurrences of strong pre-instrumental flood events can be inferred from historical archives, which commonly report extreme floods of the last 500 years (Glaser et al., 2010) and often document floods in combination with social impacts (Rohr, 2006, 2007). Some of these data have been also used within trend modelling to prolong instrumental time series (Mudelsee et al., 2003). However, a main uncertainty using historical data is due to an unknown subjective perception and description of such flood events as documented within historical archives (Börngen and Tetzlaff, 2000–2002; Weikinn, 1958–1963). These data need a very critical and time-consuming evaluation (Rohr 2006, 2007).

The interest in establishing long flood chronologies and investigating paleoflood evolution beyond instrumental datasets is growing in order to elucidate the long-term relationship between floods and climate change on a long time scale. In the following, I will compare two approaches of flood reconstruction based on geoarchives (paleoflood hydrology and the flood reconstruction from lake sediments), and with a special emphasis on varved lake sediments, which I used in this thesis to perform a seasonal flood chronology.

1.2.1 Paleoflood hydrology

The concept of paleoflood hydrology is based on the reconstruction of flood magnitudes using geomorphological indicators, such as alluvial deposits and slackwater deposits, or erosion features of floods. Slackwater deposits (SWD) were firstly described by (Tarr, 1892) and were later recognized as important indicators for paleoflood stages (PSI). SWD's are deposits composed of fine-grained sediments from riverbanks, which were deposited during large floods in areas of reduced flow velocity. The identification of SWD enables to reconstruct highest magnitude floods overtopping ancient floods of lower magnitudes. Accordingly, numerous publications followed in the 1980ies and 90ies (Baker, 2006; Ely et al., 1993; Hirschboeck, 1988; Kochel and Baker, 1982) investigating long flood records covering the Holocene under changing climate boundary conditions in the U.S.A. (Ely et al., 1993; Knox, 1993, 2000). Recently, this approach has been applied to fluvial sedimentary records in European sites to explore significant atmospheric circulation patterns triggering large-scale flood events druing the Holocene (Benito et al., 2003; Macklin et al., 2010, 2012; Starkel, 2002; Shorthouse and Arnell, 1999; Thorndycraft et al., 2005). Despite of methodological advances throughout the last decades, dating uncertainties as revealed by ^{14}C dating may include decadal-scale ranges of flood reconstruction that limitate the estimation of high-frequency flood activity on decadal-scale down to seasonal resolution.

1.2.2 Reconstruction of floods from lake sediments

In contrast to alluvial deposits occurring in highly dynamic river environments, lake sediments record the final deposition of sediment particles, which have been transported from the lake catchment during flood events. These sediment particles are trapped within the lake basin and form distinct "event layers" (detrital layers) on the lake bottom, which commonly contrast from the endogenic background sedimentation throughout the year. Since detrital layers are intercalated within "background" sediments, long and continuous flood records can be obtained from lake sediments that allow investigating their recurrence/frequency through time (Arnaud et al., 2005; Brown et al., 2000; Chapron et al., 2002; Debret et al., 2010; Moreno et al., 2008; Siegenthaler and Sturm, 1991).

However, when reconstructing flood frequency from detrital layer deposition in lakes, it is important to consider the complexity of processes within the catchment and in the lake that might mobilise soil material, because detrital layer deposition can be also triggered by earthquakes (Chapron et al., 1999; Lauterbach et al., 2012; Nomade et al., 2005), debris flows (e.g. Irmler et al., 2006; Osleger et al., 2009; Sletten et al., 2003) and slumps (Girardclos et al., 2007; Irmler et al., 2006; Wirth et al., 2011). An advanced distinction between different runoff processes is gained by evaluating the sedimentological and geochemical characteristics of detrital layers within lake sediments (Mulder and Alexander, 2001; Siegenthaler and Sturm, 1991). According to the concept of turbidity currents in lakes (Sturm and Matter, 1978), the combination of microfacies and geochemical composition enables the discrimination between predominantly higher-concentrated underflow deposits (turbidites) by slumps/debris flows (large sediment volumes) and lower-concentrated inter-and overflows of a flood suspension (Siegenthaler and Sturm, 1991), which are preferably formed within warmer surface lake water in summer (Fig. 1.1). Some studies have reconstructed magnitudes of runoff events from detrital deposits (Irmler et al., 2006; Wilhelm et al., 2012), however, anthropogenic impact possibly modifies the amount of transported sediments that has to be taken into account as well.

The dating of such event layers depends on the temporal resolution of the sediments and the chronological method, which are applied to the sediments. Annually laminated lake sediments present particularly valuable archives because of a sub-annual resolution of runoff deposits (Czymzik et al., 2010; Mangili et al., 2005) providing large potentials for flood reconstruction from millennial- to seasonal resolution. The deposition time of detrital layers can be directly inferred from the seasonal position of the detrital layers within the lake sediments. Additionally, detrital layers incorporate information about the specific runoff process (Mangili et al., 2005). To better understand the flood process, instrumental data can be directly linked to detrital sediment supply (Cockburn and Lamoureux, 2007; Czymzik et al., 2010; Foster et al., 2003; Leemann and Niessen, 1994).

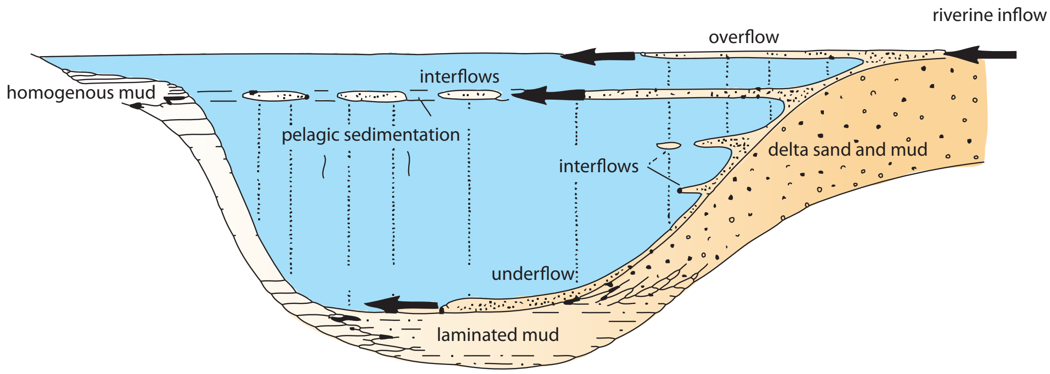

Figure 1.1. Scheme of turbidity currents modified from Sturm and Matter (1978).

There is large and unexploited potential to improve chronologies from varved lake sediments and to develop proxies to reconstruct long time series of flood events in context of climatic changesz throughout the Holocene. Within my thesis, I applied the novel approach of complementary sedimentological (microfacies) and geochemical (µ-XRF) data at ultra-high resolution on varved sediments of the pre-Alpine Lake Mondsee. This method been developed at the GFZ in order to facilitate the reliable detection of even microscopic deposits (Brauer et al., 2009). Following this procedure, I investigated the sedimentary imprints of runoff events within varved sediments of Lake Mondsee.

1.3 Lake Mondsee- Study area

The pre-Alpine Lake Mondsee is located in the NE European Alps (47°49'N, 13°24'E) at an altitude of 481 m above sea level (Fig. 1.2, Table 1.1). Three main tributaries (Griesler Ache/Fuschler Ache, Wangauer Ache and Zeller Ache) drain the northern catchment, whereas several smaller streams, such as the Kienbach, drain the southern catchment. The lake has one outlet and is connected with the Danubian river catchment. According to its geology, the lake is subdivided into a deeper southern lake basin (max water depth: 68 m) and a shallower northern lake basin (max water depth: 50 m). The oligo-mesotrophic hardwater lake is meromictic with at least one mixing period in winter (Jagsch and Megay, 1982; Schultze and Niederreiter, 1990).

The lake has been shaped by tectonic activity during the Pleistocene evolution of the Alps. Later, the lake morphology was reformed by the Traun glacier during the Würmian glaciation (van Husen, 1989; van Husen, 2004). Nowadays, the lake is situated within a chain of lakes in the Salzkammergut Lake district of Upper Austria. The lake catchment has a size of 247 km^2. Two geological units are separated by a thrust fault along the southern lake shoreline. The southern sub-catchment (ca. 25% of the catchment), which is drained by the main rivers, is composed of Triassic dolomite and Mesozoic limestones marking the steep slopes of the Northern Calcareous Alps up to 1782 m a.s.l. The northern catchment (ca. 75%) that is drained by smaller streams, is composed of cretaceous marls, shales and sandstones of the Rhenodanubic Flysch and local Quaternary deposits and characterizes mainly gently formed hills (ca. 1000 m a.s.l.). The area is forested by a total of 50% (Beiwl, 2008; Klug et al., 2010).

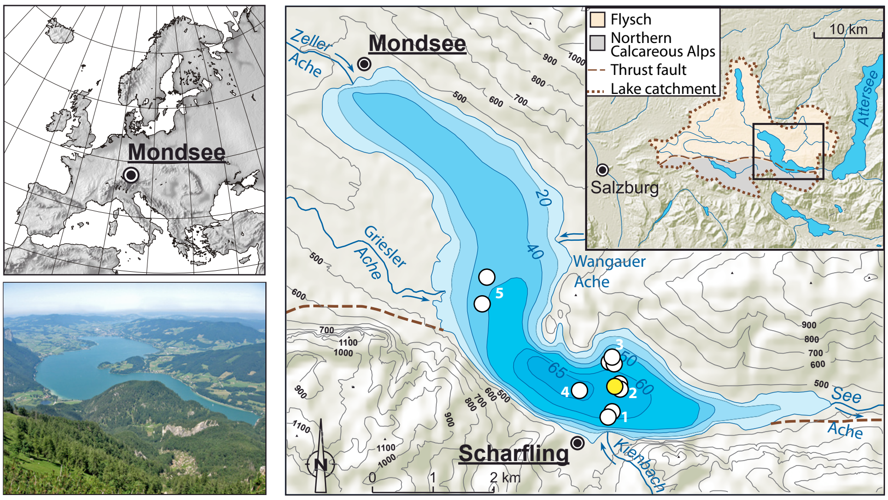

Figure 1.2. Location, simplified geological map of Lake Mondsee and coring locations of short cores (white circles) and one 15 m long sediment core (yellow circle). Coring position 1: Mo-07SC1, Mo-07SC2, Mo-07SC3; Coring position 2: Mo-07SC4, Mo-05P3, Mo-05P5; Coring position 3: Mo-07SC5, Mo-07SC6; Coring position 4: Mo-07SC7; Coring position 5: Mo-07SC8, Mo-07SC9.

Table 1.1: Morphometric, hydrological and limnological parameters from Lake Mondsee (Jagsch and Megay, 1982) and Hydrographic Service of Upper Austria).

Lake Mondsee	
Coordinates	47°48'N, 13°23'E
Altitude (m above sea level)	481
Length (km)	9.2
Width (km)	2.3
Catchment area (km^2)	247
Surface area (km^2)	14.21
Ratio catchment/surface area	1:17
Volume (10^6 m^3)	510
Depth, maximal (m)	68.3
Depth, average (m)	36
Seeache, outlet of the lake (m^3/s)	9.2
Griesler Ache, inflowing river (m^3/s)*	4.9
Renewal time (year)	1.7

Lake Mondsee exhibits exceptionally warm water temperatures caused by warm katabatic airmasses deriving from the Alps. These predominant dry air masses in the Northern Alps ("Fön") derive from air masses of the Mediterranean Sea flowing northwards over the Alps. After prolonged rainfall in the Southern Alps these air masses form dry katabatic winds in the northern Alps. This meteorological constellation breaks down during enhanced cyclonic disturbances. Lake Mondsee is located at the Northern Alps presenting a barrier for Atlantic Westerlies. Annual precipitation is around 1550 mm as averaged for the time period 1971–1999 (Zentralanstalt für Meteorologie und Geowissenschaften/ZAMG, Vienna), with highest rainfall from June-August. Floods occur in spring and summer after rainfall during snowmelt events (spring) and convective rainfall (summer).

Mountainous systems such as the European Alps are particularly sensitive to climate change showing particular regional disparities since temperature and precipitation increased non-linearly (Haeberli et al., 2007; Keiler et al., 2010). This effects the occurrence of natural hazards such as landslides, debris flows and floods (Beniston, 2003) thus potentially rendering the alpine regions particularly sensitive to climatic changes. The European Alps are located in a transitional position between the Mediterranean, the Atlantic Ocean and European continent (Sodemann and Zubler, 2010; Wanner et al., 1997) encompassing 39.6% of moisture transport from the North Atlantic, 23.3% from the Mediterranean, 16.6% from the Baltic Sea and 20.8% from the European land surface (Sodemann and Zubler, 2010). Because of its west to east extent at the climate divide between polar and sub-tropical air masses (Fig. 1.3), the Alpine climate is characterized by warm and dry summers in the Southern Alps and wetter summers commonly appearing in the Northern Alps (Auer et al., 2007; Böhm and Wetzel, 2006; Casty et al., 2005; Pauling and Paeth, 2007; Wanner et al., 1997). A climate gradient from wetter climate conditions in the Western Alps towards drier and more continental climate conditions in the Eastern Alps are furthermore distinguished by homogenised and regionalised data series (Auer et al., 2007).

According to the seasonal position of the polar jet as a main climatic influence, the European winter is predominantly characterized by the variability of the North Atlantic Ocean (NAO) (Casty et al., 2005; Hurrell, 1995). The modes of NAO are strongly depended on Atlantic Sea Surface Temperature, which typically influences the strength of the Westerlies and moisture inflow towards Europe. The positive NAO is coupled with strong pressure gradients between the Icelandic low and Azores High and is characterized by strong Westerlies influencing climate over northern and central Europe. In contrast, negative NAO modes are linked to less pressure gradients and a more southward component of moisture inflow. During winter, the polar jet is localised further to the South, thus diminishing the constant Atlantic moisture inflow. In summer, extreme floods are predominantly generated by convective rainfall events because of orographic effects. Besides the Atlantic inflow of air masses, cyclonic activity over the Gulf of Genoa is an important climatic aspect affecting large-scale floods in Central Europe (Kundzewicz et al., 2005; Mudelsee et al., 2004). In order to understand the variability of alpine precipitation and the linkage to extreme hydro-meteorological events in the alpine region (Frei et al., 2000) it is important to understand the predominant atmospheric circulation patterns, seasonal cycles governing water transport to the Alps (Sodemann and Zubler, 2010) and variable influences causing extreme flood events. Investigating the seasonality and the influence of the NAO on flood generation processes as suggested by Kingston (2006) is of utmost importance for further investigations in the context of climate change.

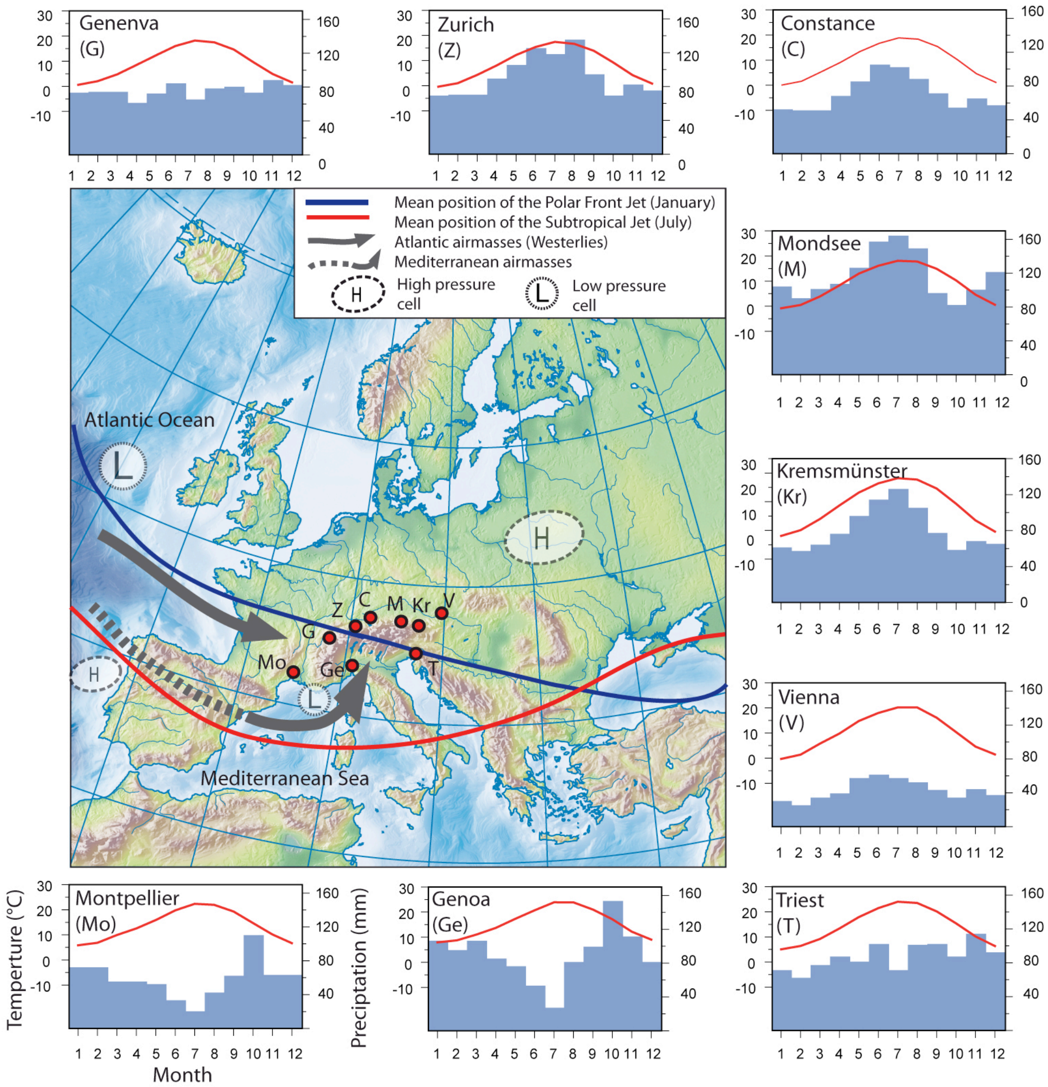

Figure 1.3. Climate data of selected cities in the Alpine realm (Deutscher Wetterdienst, Offenbach/Main (2007)/http://stadionwetter.info). Moisture transport from the Atlantic Ocean and the Mediterranean Sea (arrows) and the mean position of polar jet in winter (blue line) and subtropical polar jet in summer (red line) that characterizes the climate system in Europe (Wigley, 1982). Climate diagrams show peaking precipitation in winter for the southern Alps and maximum in precipitation in summer for the northern Alps. Auer et al. (2007) propose a further distinction into four alpine regions of the northwestern region (e.g. Geneva, Zurich, Constance), northeastern region (e.g. Mondsee, Kremsmünster, Vienna), northeastern region (e.g. Triest) and southwestern region (e.g. Montpellier, Genoa).

1.4 Lake Mondsee sediments

A long sediment core of 15 m was recovered from the central part of the southern lake basin in 2005 using a Piston corer (UWITEC). Additionally, eleven short cores (Fig. 1.2) were retrieved in 2005 and 2007 using a gravity coring system (UWITEC). The sediment cores present finely laminated sediments of rhythmic light and dark sublayers (Fig. 1.4). Independent ^{137}Cs dating and historical evidence of a debris flow deposit in 1986 proved that the sediments are annually laminated (varved). The sediments are composed of well-preserved couplets of light spring-summer layers (euhedral calcite crystals) and dark autumn-winter clay-sized detrital matter (Lauterbach et al., 2011). Abundantly, brownish clastic or organic detrital layers of cm- to sub-mm thickness are intercalated within the varves.

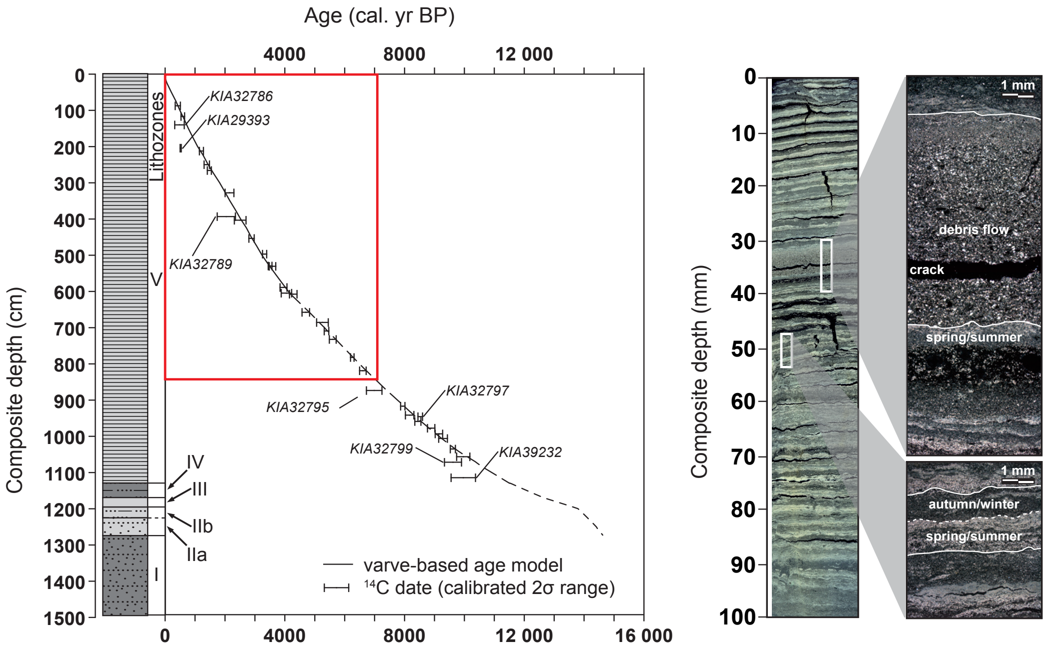

Figure 1.4. Left panel: Lithology with age-depth model of Lake Mondsee sediments as recovered from a long composite profile. The red box indicates the time interval of my thesis. Right panel: Thin section from the uppermost sediments (both panels modified from Lauterbach et al., 2011).

Previous work on Lake Mondsee sediments focused predominantly on recent limno-ecological aspects concerning lake eutrophication by human activity (Dokulil, 1984; Dokulil et al., 2006; Irlweck and Danielopol, 1985; Klee and Schmidt, 1987). Paleolimnological investigation considered the Late Glacial/Holocene transition (Lauterbach et al., 2011; Schultze and Niederreiter, 1990) and the Neolithic time (Ruttkay et al., 2004; Schmidt, 1986). The very recent study within the DecLakes project (Lauterbach et al., 2011) presented the varved sediment record of Lake Mondsee with particular focus on sedimentological and vegetation responses in terms of climatic changes of the Late Glacial and Holocene transition (Fig. 1.4). Based on this well-dated sediment core, using ^{14}C chronology and varve counting (Lauterbach et al., 2011), Lake Mondsee sediments reveal an ideal geoarchive to investigate detrital layer deposition in a sub-annual resolution.

1.5 Objectives

The principal objective of this thesis is addressed to the reconstruction of a continuous and seasonally resolved flood chronology from varved sediments from the pre-Alpine Lake Mondsee that covers the last 7000 years. Since climate change plays a role on various times scales, the sensitivity of hydrological changes and extreme events is analysed on millennial down to seasonal time scales. In order to reconstruct a coherent picture of the regional flood activity in the past, the comparison of adequate hydro-meteorological datasets and natural archives is one of the greatest challenges of this thesis. Main questions within this thesis deal with:

1. Sedimentary imprints of different runoff events within Lake Mondsee: Which principle runoff processes can be inferred from sedimentary features within Lake Mondsee sediments?

2. Flood occurance during the last 7000 years: Which relationship exists between climate change and flood variability as reconstructed from Lake Mondsee sediments? Is there a consistent temporal and spatial change in the Alps and in Europe?

3. Flood activity during the Neolithic: Was the Neolithic Lake Mondsee culture affected by enhanced fluvial activity? Is there a hydro-climatic evidence for the abandonment of Neolithic lake dwellings at Lake Mondsee?

Methods applied in this thesis

The flood chronology obtained from Lake Mondsee sediments is based on a robust varve counting, which is controlled by various AMS ^{14}C dates (Lauterbach et al., 2011). The sediment record from Lake Mondsee sediments is subjected to various sedimentological methods (µXRF, XRD, microfacies analysis, magnetic susceptibility) in order to characterize the sediment supply and event layers (detrital layers) by different runoff processes. I refer to the single manuscripts for further information on the methods used for the analysis. Additionally, instrumental and historical datasets are used to compare flood events with the detrital layer record in the lake sediments. For statistical significance and to distinguish in-lake and runoff processes, Pearson's correlation and Principle Component Analysis (PCA) have been applied for geochemical composition (µXRF). Furthermore, a Kernel-regression and corresponding significance bands were calculated for the entire flood series.

Chapter 2

A 1600-year seasonally resolved record of decadal-scale flood variability from the Austrian pre-Alps

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Abstract We present a record of extreme spring/summer runoff events for the past 1600 years preserved in the varved sediments of Lake Mondsee, Austrian pre-Alps. Combined sediment microfacies analyses and high-resolution µXRF element scanning allow to identify 157 detrital event layers deposited in spring/summer and to discriminate between regional flood and local debris flow deposits. Higher spring/summer flood activity with a mean event recurrence of 3–5 years occurred in several well-confined multi-decadal episodes during the Dark Ages Cold Period (DACP) and Medieval Times (A.D. 450–480, A.D. 590–640, A.D. 700–750 and A.D. 1140–1170) as well as during the early Little Ice Age (LIA; A.D. 1300–1330 and A.D. 1480–1520). In contrast, lowest spring/summer flood activity with an event recurrence of only 30–100 years is observed during the Medieval Climate Anomaly (MCA; A.D. 1180–1300) and the coldest interval of the LIA (A.D. 1600–1700). These findings indicate a complex relationship between temperature conditions and extreme hydro-meteorological events and suggest that enhanced summer Mediterranean cyclogenesis triggers large-scale floods in the NE Alps during climatic transitions. The

Lake Mondsee data demonstrate the climatic sensitivity of spring/summer floods and prove the potential of varved sediment records to investigate the impact of changing climate boundary conditions on seasonal flood activity for pre-instrumental times.

2.1 Introduction

During the last two millennia, Central Europe experienced several pronounced climate fluctuations (Büntgen et al., 2011; Mangini et al., 2005) during the Dark Ages Cold Period (DACP), the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). In contrast to the general development of temperature and precipitation conditions, only little is known about the occurrence of extreme hydrological events during the MCA-LIA transition because the time span covered by historical archives rarely exceeds the past 500 years. Extending time series of extreme events and investigating their natural frequencies and seasonal and regional peculiarities is a key issue for assessing the effects of global warming on flood recurrence (IPCC, 2007).

Annually laminated (varved) lake sediments with intercalated detrital layers provide ideal geoarchives for reconstructing environmental and hydrological events beyond the range of instrumental and historical data at high temporal resolution. First attempts to utilize lake sediments as paleoflood archives have been made by relating detrital layers in non-varved sediments to individual historical floods (e.g., Chapron et al., 2005). Due to the specific methodological requirements, only few varved sediment records have been investigated in this respect so far (Mangili, et al., 2005; Czymzik et al., 2010).

This study utilizes the varved sediments of Lake Mondsee, Austrian pre-Alps to examine detrital flux to the lake and particularly the recurrence of discrete detrital layers, which originate from extreme depositional events triggered by heavy rainfall. This allows establishing a record of extreme hydro-meteorological events in the past and comparing flood activity in Central Europe with climatic changes on multi-decadal to millennial scales.

2.2 Study Site

Lake Mondsee is located in the Salzkammergut lake district of Upper Austria (47°49°N, 13°24°E, 481 m a.s.l.) at the NE fringe of the European Alps. The lake has a surface area of ~14.2 km^2 and a maximum water depth of 68 m (Fig. 2.1). The lake catchment (247 km^2) extends over two major geological units, divided by a main Alpine thrust fault (van Husen, 1989). The northern part of the catchment is characterized by Cretaceous Flysch sediments, partly covered by Quaternary deposits (<1000 m asl); the southern part (1782 m asl) is dominated by Mesozoic limestones and dolomites of the Northern Calcareous Alps. The main tributary Griesler Ache flows through both parts of the catchment, whereas several small streams drain only the southern catchment amongst which the Kienbach is closest to the coring location (Fig. 1). The average annual precipitation in the Lake Mondsee region is ~1550 mm with a maximum in spring/summer. The flood regime in the NE Alps is predominantly driven by rainfall events in summer (long-rain floods) and enhanced snowmelt events (rain-on-snow floods) in spring.

Precipitation in the European Alps is largely influenced by North Atlantic and Mediterranean cyclonic activity (Sodemann and Zubler, 2010). During the past 100 years, extreme summer floods mainly occurred in summer, caused by the Mediterranean (Genoa) cyclones (Mudelsee et al., 2004). In winter, temperature and rainfall variability in the Alps are influenced by mid-latitude westerlies and associated storm tracks, which are modulated by the North Atlantic Oscillation (NAO) (Luterbacher et al., 2002).

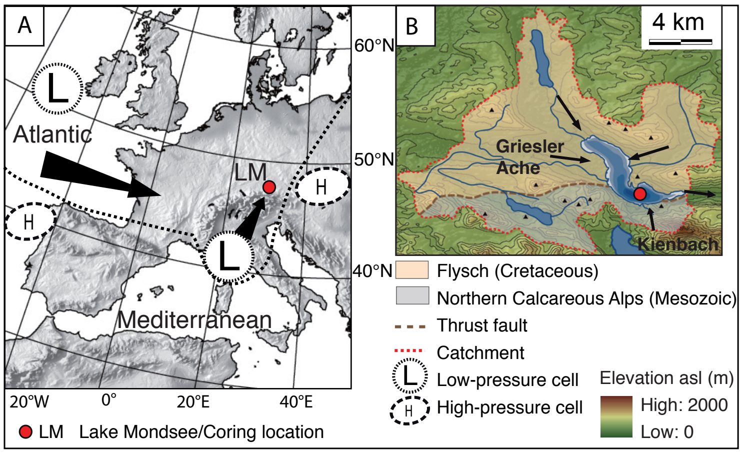

Figure 2.1 (A) Location of Lake Mondsee and pathways of low-pressure cells from the Atlantic and Mediterranean (arrows). Mediterranean moisture transport is controlled by Genoa cyclones and the trough over Central Europe (broken line). (B) Catchment of Lake Mondsee with the two main geological units and major tributaries draining the northern (Flysch Zone) and southern catchment (Northern Calcareous Alps).

A continuous sediment core of ~15 m length, comprising the Late Glacial and Holocene, was retrieved from Lake Mondsee. The Holocene age-depth model is based on microscopic varve counting, supported by 28 AMS ^{14}C dates and ^{137}Cs dating (Lauterbach et al., 2011). Here, we focus on the uppermost 263 cm of varved sediments, spanning the last ca. 1600 years. Varve counting and microfacies analyses were carried out by polarization microscopy of large-scale petrographic thin sections according to Brauer and Casanova (2001). Major element variations were measured by micro X-ray fluorescence (µXRF) scanning of impregnated sediment blocks using an EAGLE III XL µXRF spectrometer with a low-power Rh X-ray tube at 40 kV and 300 µA (250 µm spot size, 60 s counting time). Measurement results are given as counts per second (cps). Since µXRF scanning has been carried out on those impregnated sediment blocks used for thin section preparation, it was possible to directly combine optical data and element scans (cf. Brauer et al., 2009). This allows the precise transfer of the varve chronology derived from microscopic layer counting to the major element data.

2.3 Results

2.3.1 Sediment Microfacies and Geochemistry

The late Holocene part of the Lake Mondsee record (Fig. 2.2) is characterized by well-preserved couplets of light spring/summer layers (euhedral calcite crystals) and dark autumn/winter layers (diatom frustules, amorphous organic material and clay-sized detrital matter), which represent biogeochemical calcite varves. Calcite layers are clearly depicted by maxima in Ca counts (Fig. 2.2), while increased Ti and Mg counts reflect higher allochthonous flux from both the northern (Ti-enriched siliciclastic rocks of the Flysch Zone) and southern catchment (Mg-enriched dolomite of the Northern Calcareous Alps).

Within the varved sediments, 157 discrete detrital layers are identified, which are classified into two types based on sediment microfacies, thickness, composition and grain size. Detrital layers of type 1 (134 layers) consist of coarse silt- to fine sand-sized detrital material (50–100 µm) and commonly have a thickness of <1mm. These layers are composed of quartz, feldspar, calcite and dolomite as inferred from microscopic inspection. Corresponding peaks in Ti and Mg (Fig. 2.2) reveal that catchment material originates from both the northern and southern parts of the catchment. Detrital layers of type 2 (23 layers) are composed of a mixture of fine to medium sand-sized angular clastic material (100–200 µm) and organic debris (e.g., leaves, small twigs). These layers are commonly graded and range in thickness between 0.65 and 26 mm. More pronounced peaks in Mg and lower Ti counts indicate that dolomite is the main constituent of these detrital layers, suggesting a Northern Calcareous Alps source (southern catchment).

2.3.2 Age Model and Event Chronology

The age model of the studied interval (Fig. 2.2) is based on two independent microscopic varve counts with a cumulative error of <20 years (1.25%). The varve counts are supported by four AMS ^{14}C dates (Lauterbach et al., 2011).

The relative position of the detrital layers within the calcite layer implies that event deposition exclusively occurred in spring and summer. The mean event recurrence over the studied interval is ~10 years. Detrital layers of type 1 show highest recurrence rates (3–5 years) during six intervals of 30–50 year duration (Fig. 2.3): A.D. 1480–1520 (FE1), A.D. 1300–1330 (FE2), A.D. 1140–1170 (FE3), A.D. 700–750 (FE4), A.D. 590–640 (FE5) and A.D. 450–480 (FE6). Intermediate event recurrence (5–10 years) characterizes the Middle Ages (A.D. 750–1130) and the past 470 years, whereas lowest recurrence rates (>30 years) are observed during two episodes of ~100 years duration: A.D. 1170–1300 and A.D. 1600–1700. Detrital layers of type 2 show no significant recurrence pattern over the entire study period.

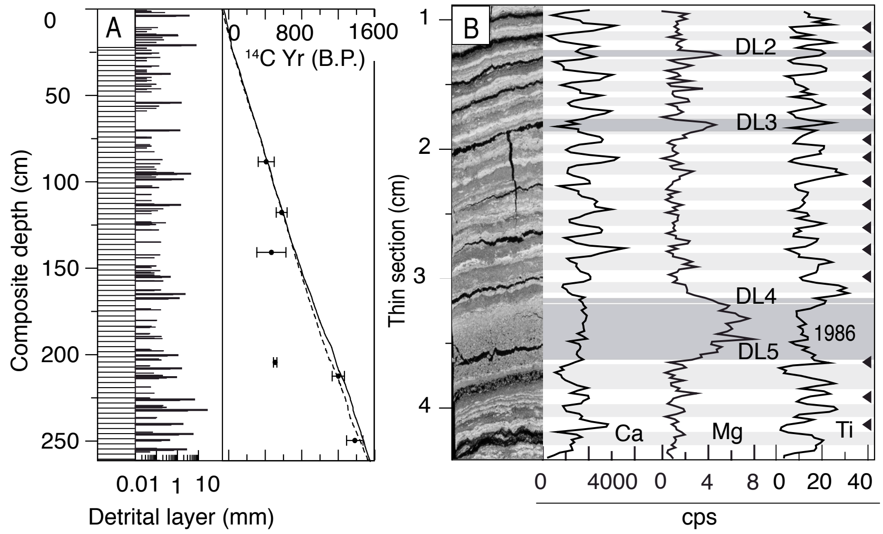

Figure 2.2 (A) Lithostratigraphy of the studied sediment section and detrital layer record (thickness in mm log-scale). The age-depth model is based on two microscopic varve counting supported by AMS 14C dating (circles with error bars). Bar length of the calibrated ^{14}C ages indicates the 95% confidence interval. (B) Thin section image (cross-polarized light) of sub-recent Lake Mondsee varves with light spring/summer calcite layers (triangles), greyish autumn/winter layers and occasional thicker coarse grained detrital layers (DL2–DL5). μXRF element scans at 200 μm resolution (cps- counts per second) reflect endogenic calcite (Ca) and different lithic components (Ti – siliciclastics, Mg – dolomite).

2.4 Discussion

2.4.1 Reconstruction of Hydro-Meteorological Events

Detrital layers of facies types 1 and 2 exhibit distinct sedimentological and geochemical characteristics, allowing discrimination of different source areas and triggering processes. As type 1 layers contain both siliciclastics from the northern and dolomite from the southern catchment, they represent catchment-scale flood deposits of the main tributary Griesler Ache. This is confirmed by a lattice of short cores, proving the basin-wide occurrence of type 1 layers, as well as by comparison with instrumental flood data (Swierczynski et al., 2009). In contrast, type 2 layers are only deposited in the southern lake basin and composed of southern catchment material thus excluding the Griesler Ache as source area. A southern catchment origin of type 2 layers is further confirmed by grading, coarser grain sizes and abundant plant debris found in these layers indicating short-range transport and turbidite deposition triggered by local debris flows (Mulder and Alexander, 2001). This is proven for modern times by a type 2 detrital layer triggered by a well-documented debris flow in the steep Kienbach valley after a local thunderstorm in July 1986 (Swierczynski et al., 2009). In result, the Lake Mondsee record includes time series of both regional floods and local debris flows. As the occurrence of debris flows is controlled by local processes they are not interpreted in relation to climatic change.

A critical issue in interpreting detrital layer deposition in lake records is a possible bias through deforestation and increased agricultural land-use. As human-induced catchment erosion mainly affects the amount of suspended sediment flux during flood events (Dearing and Jones, 2003) rather than the occurrence of the flood event itself, we consider a bias of our flood frequency record through human impact as unlikely. This is proven for the calibration period by the coincidence of all detected type 1 detrital layers with instrumentally documented floods. The long-term relationship between type 1 detrital layers and flood events is further supported by the agreement of the detrital layer record with detailed historical flood reconstructions in the neighboring Traun River catchment for the 15th and 16th century (Rohr, 2006; 2007). Even periods of increased human activity documented in a nearby pollen record (Draxler, 1977) do not coincide with peaks in flood layer frequencies except for FE3. Moreover, at Lake Mondsee even the total suspended sediment flux is apparently not strongly affected by human impact as indicated by rather constant values of detrital matter proxies and the good correlation of annual precipitation and Ti counts (r = 0.34, Figure 2.2). The supplementary file contains additional information on depositional processes of detrital layers with a special focus on potential human impact effects (Data Repository 1). Possible reasons for the absence of a clear human impact on sediment flux into Lake Mondsee are sediment storage in the floodplains (Dearing et al., 2001; Richards, 2002) or diligent land-use.

2.4.2 Flood Variability and Paleoclimate

The Lake Mondsee sediment record reveals multiple decadal-scale episodes of increased spring/summer flood activity during two main intervals between A.D. 1140–1520 (FE1 – FE3) and A.D. 450–750 (FE4 – FE6) (Fig. 2.3), coinciding with the DACP (A.D. 250–600), the transition from the MCA to the LIA (ca AD 1200–1300) and the first half of the LIA (ca A.D. 1350–1550) (Büntgen et al. 2011). These two intervals of distinctly increased flood activity are interrupted by longer intervals of lower flood recurrence between ca AD 850–1140 and ca AD 1170–1300.

The first main flood interval lasted ca 300 years and comprises three decadal-scale flood episodes (FE4 – FE6) (Fig. 2.3). Whereas episodes FE5 and FE6 occurred during a period of relatively low summer temperatures and precipitation in Central Europe (Büntgen et al., 2011), FE4 (A.D. 700–750) appears at the transition to the MCA with increasing summer temperatures and precipitation (Büntgen et al., 2011, Fig. 2.3).

The second flood interval occurred during the MCA-LIA transition (FE3) and during the early LIA (A.D. 1300–1520) (FE1 and FE2). These flood episodes correspond to decadal-scale flooding in the adjacent Traun River (Rohr, 2006; 2007) and are also reported from other documentary and sedimentary archives from Central Europe (e.g., Glaser et al., 2010; Mudelsee et al., 2003; Schmocker-Fackel and Naef, 2010). Interestingly, the two most recent episodes of increased summer flood frequencies (FE1 and FE2) occurred during a period of gradual reduction in surface runoff (Ti counts, Fig. 2.3), commencing at ca A.D. 1350 and implying drier conditions in the NE Alps. Apparently, the occurrence of extreme precipitation events (floods) in spring and summer is not strictly linked to annual precipitation. This might be either due to seasonal effects or to the interaction of various atmospheric circulation modes. The hydro-climatological conditions in the NE Alps are controlled by the interplay of westerly winds, Mediterranean cyclones and the strength of the Siberian high-pressure cell (Glaser et al., 2010; Sodemann and Zubler, 2010). The change in winter climate conditions from the MCA to the LIA in Central Europe is commonly explained by a transition from a predominantly positive to a negative NAO index (Trouet et al., 2009), accompanied by a southward displacement of the mid-latitude westerlies and associated storm tracks (Jacobeit et al., 2003). On the other hand, the influence of the Central Mediterranean climate on summer flood generation in Central Europe including the Lake Mondsee region is confirmed for several historical and present-day floods (Mudelsee et al., 2004; Jacobeit et al., 2006). Thus an augmented formation of strong Genoa cyclones and meridional inflow of Mediterranean air masses in the summer season during the early LIA could cause extreme rainfall events in eastern Central Europe. The importance of Mediterranean cyclones for flood generation might have been further amplified by continental high-pressure cells over Eastern Europe, which should have blocked the northward moving cyclones, leading to quasi-stationary cyclones in the NE Alps.

The later stage of the LIA is characterized by low flood layer recurrence in the Mondsee region particularly during the Maunder Minimum (A.D. 1645–1715), the coldest phase of the LIA (Büntgen et al., 2011). In a larger spatial context, this time interval is marked by contrasting hydro-meteorological conditions in different regions of Europe. Records from eastern Central Europe also show lower flood activity (Glaser et al., 2010), while from Western Europe wetter conditions (Magny, 2004) and increased flood activity (Czymzik et al., 2010; Glaser et al., 2010) are reported. This diverge distribution of flood events in eastern and western Central Europe can be reconciled by an extension of the high-pressure cells over Eastern Europe (Glaser et al., 2010; Jacobeit et al., 2006), leading to cold and dry climate conditions and rare floods in the NE Alps, while Atlantic cyclones should still have reached more western locations, resulting in wetter conditions (Magny, 2004) and higher flood frequencies (Czymzik et al., 2010) there.

The variability of flood occurrence during the past 1600 years emphasizes the complex mechanisms triggering extreme rainfall in the NE European Alps rather than a simple relation between flood frequency and climate change. The influence of combined zonal (Atlantic) and meridional (Mediterranean) circulation modes upon regional hydrological conditions in Central Europe is likely the reason for the observed spatial differences in flood frequencies, which itself are not stationary but appear to vary in time with highest contrasts between western and eastern Central Europe during the coldest part of the LIA.

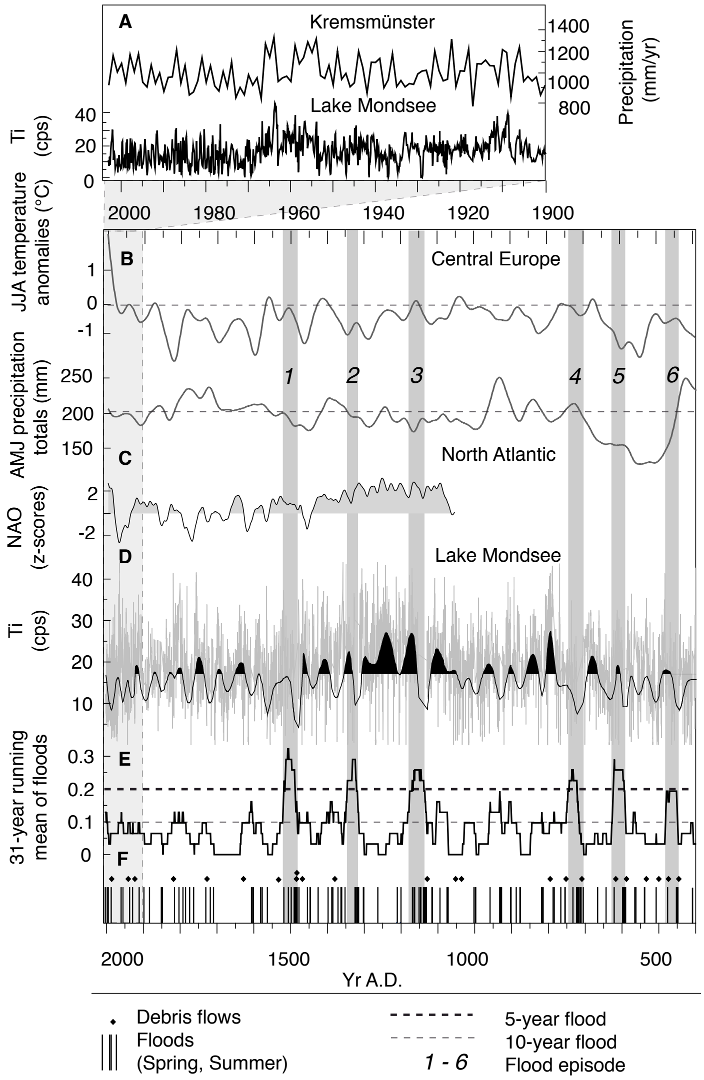

Figure 2.3. Hydro-climatic reconstructions (A.D. 400–2005) for Lake Mondsee in an European context. (A) 100-year record of Ti (cps-counts per second, detrital input) and regional annual precipitation (r = 0.34). (B) European temperature anomalies for June-August (JJA) and summer precipitation for April-June (AMJ) inferred from Central European tree-rings (Büntgen et al., 2011). (C) North Atlantic Oscillation (NAO)-reconstruction for Central Europe using normalized data (z-scores) (Trouet et al., 2009). (D) μXRF Ti counts (black line: 30-year lowpass filtered series). (E) 31-year running mean of detrital spring/summer flood layers. (F) Facies type 1 detrital layers (bars) and type 2 detrital layers (diamonds). Grey bars indicate main flood episodes (FE1-FE6).

In addition to the long-term trends in flood variability on centennial time scales with two main flood intervals during early Medieval times and at the onset of the LIA, the maxima in flood frequency of 30–50 years duration at Lake Mondsee exhibit a pronounced decadal-scale pattern. The mechanisms behind this quasi-cyclic behavior remain unexplained and emphasize the need for a better understanding of flood activity including seasonal effects and the role of re-organizations of atmospheric circulation at regional scales and their consequences on extreme rainfall events.

Acknowledgements

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2.5 Data Repository (DR)

DR 2.5.1 Intra-basin correlation of detrital layers covering the last 100 years

Investigating the spatial distribution of detrital layers within the lake basin based on detailed intra-basin correlation by using microscopic analyses allows tracing back the different types of detrital layers to their source regions. In turn, this provides information on sediment transport mechanisms and depositional processes.

Twelve short gravity cores (42–103 cm length) along two transects were obtained from Lake Mondsee (Fig. DR 2.5.1): a North-South transect across the southern lake basin (A-B) and a Northwest-Southeast transect from the northern to the southern part of the lake basin (C–D). Both transects meet at the location of the long piston core (Mo-05P3). Within the annually laminated lake sediments found in each of these gravity cores, nine detrital layers of facies type 1 and three of facies type 2 can be distinguished and used for correlation along the transects (Swierczynski et al., 2009). The two facies types exhibit distinctly different proximal-distal distribution patterns allowing to distinguish between two sediment transport pathways: (1) facies type 1 layers originate from the Griesler Ache River (C–D) and (2) facies type 2 layers originate from the Kienbach Creek (A–B) discharging into the lake from the south.

Transect A-B: All cores from the southern lake basin exhibit both types of detrital layers. However, only facies type 2 layers exhibit a clear pattern in thickness distribution. Close to the mouth of the Kienbach Creek (ca 400 m north), type 2 detrital layers are between 0.4 and 30 mm thick and contain coarse-grained (100–200 µm) clastic material and plant fragments (e.g. leaves). In cores further north including the master core (800 m north of the mouth of the Kienbach Creek), the correlating layers are thinner (0.2–6 mm) and consist of finer clastic material (50–100 µm), clearly indicating the Kienbach Creek as

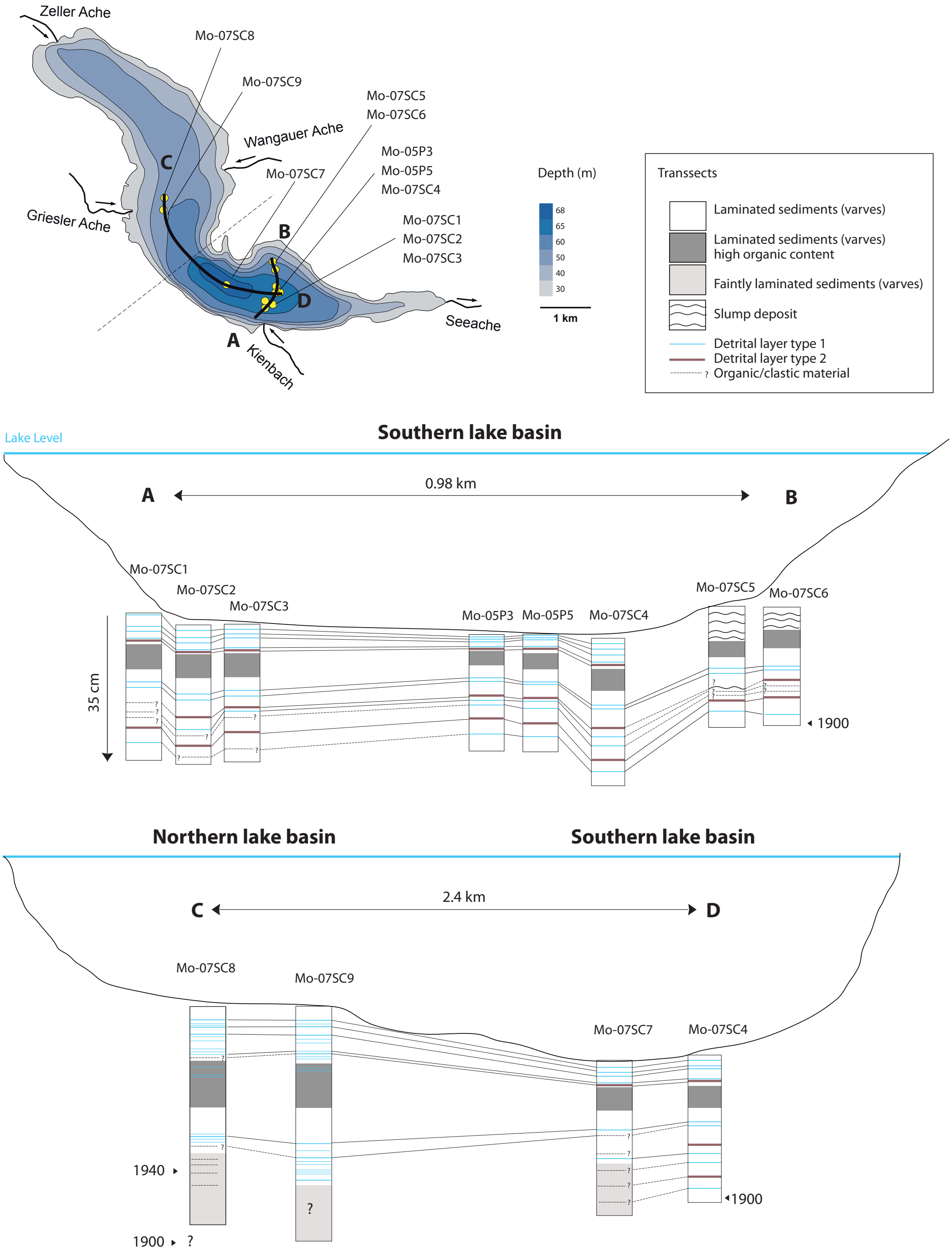

Figure DR 2.5.1. Intra-basin correlation of detrital layers along two transects across the southern (A-B) and from the northern to the southern lake basin (C-D) based on microscopic inspection of each core (modified after Swierczynski et al., 2009). Note: Due to the higher sedimentation rate in the near-delta locations, cores Mo-07SC8 and Mo-07SC9 comprise shorter time interval spans.

source region. This interpretation is confirmed by the predominantly dolomitic composition of these layers reflecting the Kienbach catchment geology.
In contrast, type 1 detrital layers are generally thinner and do not show a clear thickness pattern along the A–B transect. This points to a more distant source and excludes the Kienbach as source for these detrital layers. This is further supported by their mixed siliciclastic-dolomitic composition, which distinctly differs from the largely dolomitic type 2 detrital layers.

Transect C–D: Cores from the northern lake basin close to the delta of River Griesler Ache (ca 500 m east of the mouth of the river) are correlated with cores in the transition to the southern lake basin located ca 1.7 km and 2.4 km further southeast. In the near-delta cores 31 coarse-grained (100–200 µm) detrital layers (up to 8 mm thick) have been identified in the time interval A.D. 1940–2005. Only six of these layers correspond to layers in the more distal coring sites in the southern lake basin indicating the Griesler Ache as source. This is further supported by the mixed siliciclastic-dolomitic composition reflecting the mineralogy of the Griesler Ache catchment. In none of the near delta cores in the northern basin type 2 detrital layers occur. This excludes reworking of sediments from the Griesler Ache delta of the northern lake basin as triggering process for these layers.

DR 2.5.2 Comparison of detrital layer occurrence with historical floods events

All independently dated type 1 detrital layers during the last 100 years correspond either to high-magnitude summer floods (A.D. 1936, 1954, 1959, 1997 and 2002) or snow melt events in spring (A.D. 1910, 1928 and 1994).

For some time intervals before instrumental monitoring, i.e. the 15th and 16th centuries, we can compare our detrital layer record with available historical flood data for the adjacent Traun River (Rohr, 2006; Rohr, 2007) (Fig. DR 2.5.2). Detailed reconstructions based on historical documents reveal that high magnitude summer floods occurred in two phases at the end of the 15th century (e.g. A.D. 1478, 1492, 1499 and 1501) and during the later 16th century (e.g. AD. 1567, 1569 and 1572). The older interval coincides with the higher detrital layer frequency in episode FE1 (A.D. 1480–1520) suggesting intensified regional-scale flooding at the beginning of the LIA. The younger River Traun flood period likely correlates with the increase in detrital layer frequency commencing in the late 16th century. However, the increase in flood layers at that time appears not as strong in the sediment record and thus has not been classified as distinct flood episode. Unfortunately, there are no historical flood data available for the period after A.D. 1600 until the beginning of instrumental measurements.

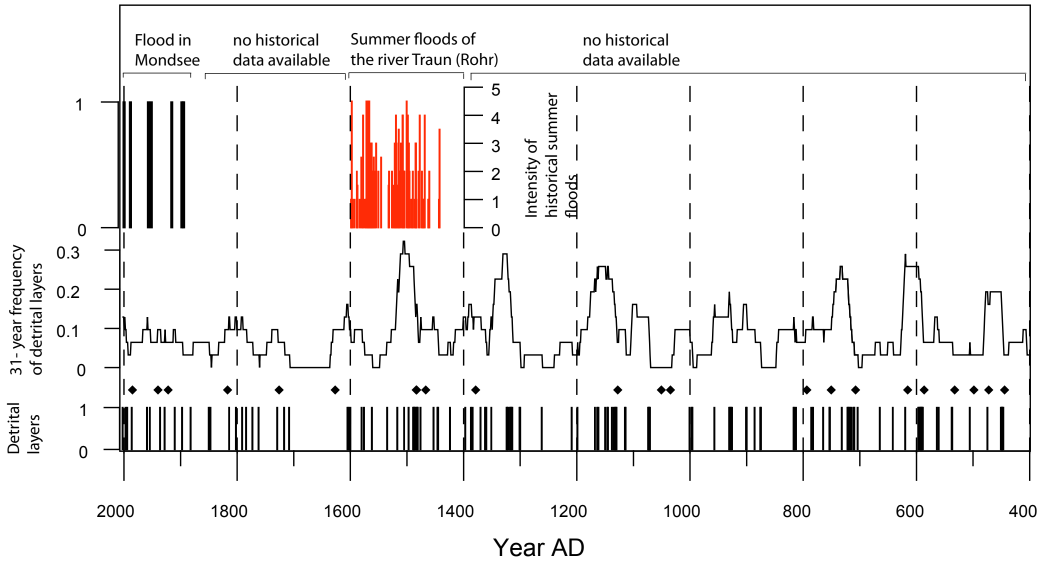

Fig. DR 2.5.2. Comparison of detrital layers in the Lake Mondsee record (bars: flood layers, diamonds: debris flow layers, 31-year running mean frequency of detrital flood layers) with available information about historical floods in the Traun River during the 15th and 16th century and with lake level-highstands from Lake Mondsee indicating floods during the 20th century (Hydrographic Service from Upper Austria).

DR 2.5.3 Human activity as recorded by pollen data and historical chronicles

Human impact in the Lake Mondsee region is well reflected in a pollen profile (Fig. DR 2.5.3) from the Moosalm peat bog located ca 5 km southeast of Lake Mondsee (Draxler, 1977). The Moosalm pollen record exhibits generally low non-arboreal pollen (NAP) not exceeding 5% until ca A.D. 1600 indicating that human impact in the Mondsee region remained low to moderate until that time. Nevertheless, in the period between 2800 cal. years B.P. (base of pollen zone IX) and A.D. 1600 four intervals of slightly increased NAP values appear. Since even in these intervals NAP values stayed below 5%, human impact in the catchment must be considered as low. The first two of these intervals are related to pre-Roman and Roman settlements between 500 B.C. and A.D. 200 (Kunze, 1986). These intervals are followed by a period of again very low NAP values corresponding to the migration period and the associated recovery of natural forests *(Fagus, Picea)* in the Lake Mondsee region (Draxler, 1977) and central Austria (Nicolussi et al., 2005). The third interval of slightly higher NAP values appears around A.D. 750 and coincides with peaks in herbs and the first appearance of *cereals* and *Rumex*. This interval corresponds to the time when the Mondsee monastery was built (A.D. 748). Despite the first appearance of *cereals* and *Rumex*, the abundance of tree pollen was still high indicating a still predominantly forested landscape. These data are in good agreement with historical chronicles, reporting that the monastery declared forest protection (Kunze, 1986). A low to moderate human impact on forests at that time is further confirmed by an unchanged composition of tree species in the pollen record. Therefore, we rule out human impact as a cause for the observed higher flood layer frequency between A.D. 700 and A.D. 750 (FE4). This is

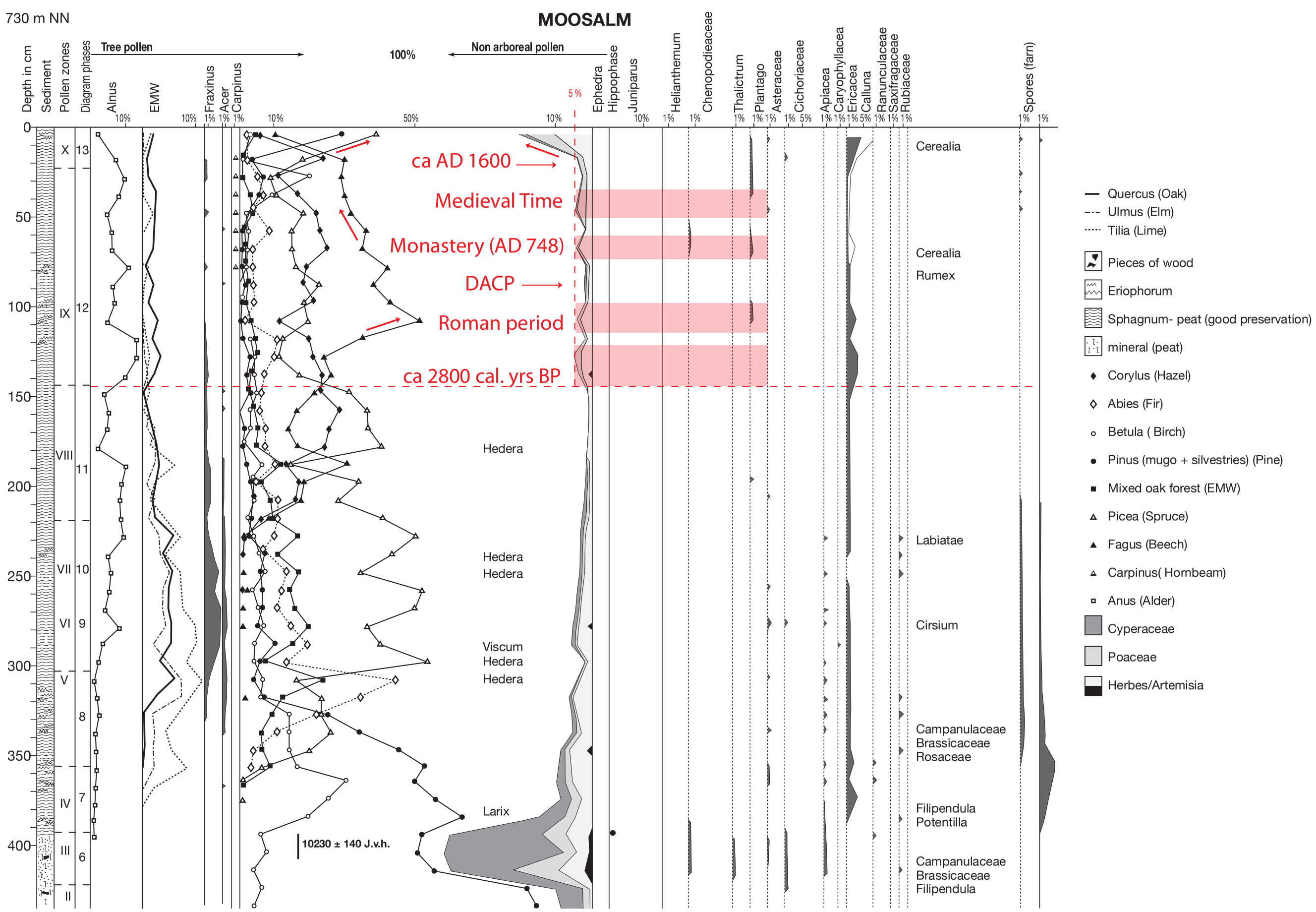

Figure DR 2.5.3. Pollen profile from the Moosalm peat bog (modified after Draxler, 1977), showing generally low values of non-arboreal pollen (< 5%) and indicator plants (e.g. Plantago) human for human impact until about A.D. 1600. The intervals of minor increases of human-induced vegetation changes from 2800 cal. years B.P. until A.D. 1600 are indicated by red rectangles. Low non-arboreal pollen contents prevail during the Dark Ages Cold Period (DACP).

further corroborated by the earlier increase in flood layer frequency which commenced a few decades before the foundation of the monastery at A.D. 748. The fourth interval of increased NAP values at around A.D. 1300 coincides with a known phase of forest clearing in the Alpine realm (Brosch, 2000; Kaplan et al., 2009). However, since NAP still did not exceed 5% we assume that human impact remained low to moderate in the catchment of Lake Mondsee region during this period. Only around A.D. 1600 (pollen zone X in Fig. DR 2.5.3) the Mondsee region experienced for the first time a pronounced increase in NAP exceeding 10%. Since that time increasing abundances of *Picea* pollen further indicate a principle change in forest management. The onset of an intense use of forests and the cultivation of Picea for salt production date during the late 16th century has also been reported also in historical chronicles (Kunze, 1986). Interestingly, the frequency of flood layers did not increase during times of most intense human impact on the vegetation in the catchment (all six flood episodes FE1–FE6 occurred before A.D. 1600). This is a clear indication that human impact on flood layer generation and frequency in the Lake Mondsee sediment record is negligible.

DR 2.5.4 The Holocene magnetic susceptibility record

Magnetic susceptibility data for the entire Holocene measured at 1 mm resolution reveals generally low values and exhibits no significant variations and trends (Fig. DR 2.5.4). This indicates both, relatively low detrital matter deposition at the coring site and the absence of major fluctuations and trends in detrital matter flux during the Holocene. This is in contrast to other pre-Alpine lakes like, for example, Lake Bourget (Debret et al., 2010). A possible explanation for the specific behaviour of the Lake Mondsee record might be the comparably small size of the influent river Griesler Ache. In comparison with the Rhone River feeding Lake Bourget the Griesler Ache has a much smaller transport capacity for suspended detrital matter. The absence of a significant increase in the amount of detrital matter in the Lake Mondsee record even during times of human settlements in the catchment makes us confident that human induced erosion can be largely excluded as a major bias of detrital matter supply and that it is thus even more unlikely that human impact had an influence on the frequency of flood layer occurrence.

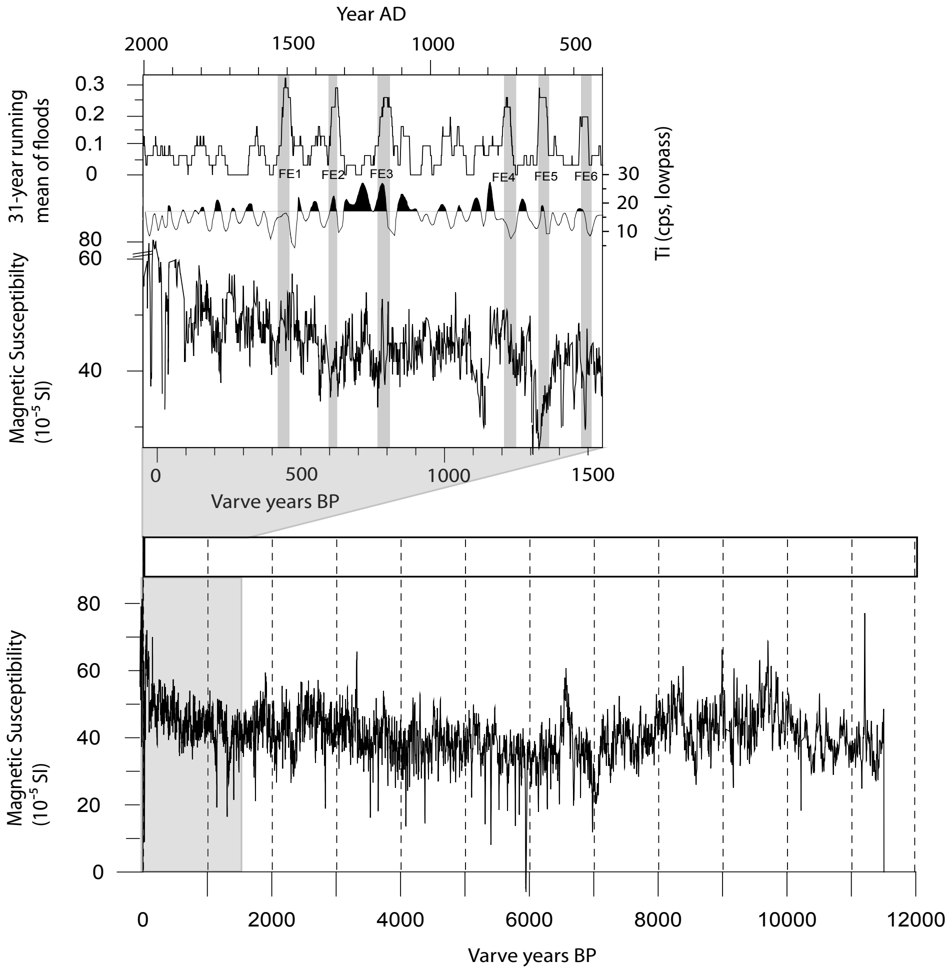

Figure DR 2.5.4. Magnetic susceptibility of the entire Holocene sediment record indicates generally low and rather constant contents of detrital material without any pronounced fluctuations. There is no correspondence to the described flood episodes FE1-FE6 as indicated by grey bars in the upper graph (zoom-in).

DR 2.5.5 µXRF Ti counts versus annual precipitation of the last 100 years

In order to identify the relation between detrital input and precipitation, we correlated the µXRF Ti record with a 100-year instrumental precipitation data available from the climate station Kremsmünster, located ca 70 km NE of Lake Mondsee (Fig. DR 2.5.5.1). We consider this station as representative for the Lake Mondsee region based on the good correlation ($r=0.81$, $p < 0.0001$) of precipitation data from Kremsmünster station with those from Thalgauberg station in the Lake Mondsee catchment for the period 1976–2003.

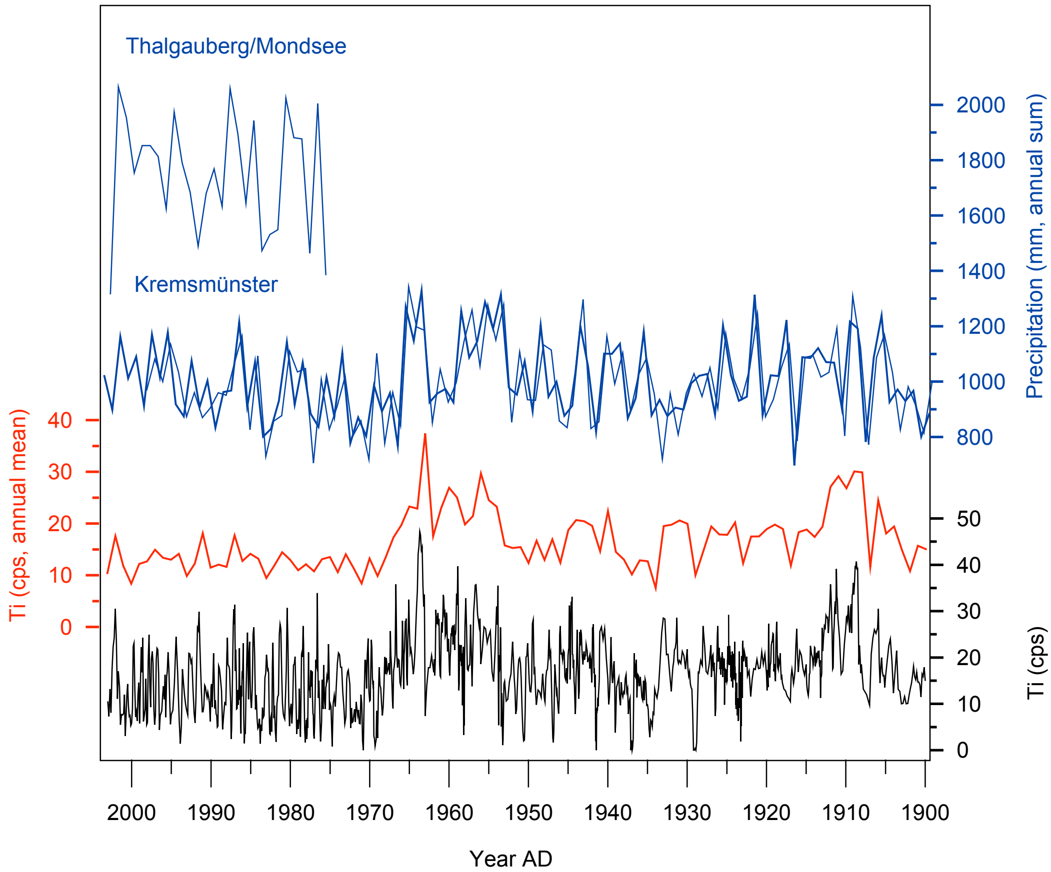

Figure DR 2.5.5.1. Comparison between the Lake Mondsee µXRF Ti record as a proxy for detrital material supply and annual precipitation data from the climate stations Kremsmünster and Thalgauberg (Mondsee). Thick blue line: annual precipitation May-April, thin blue line: annual precipitation January-December.

The µXRF Ti data have been anchored to the varve time scale by aligning the rise in calcium counts measured together with titanium to the calcite sub-layer as observed in the thin sections. Since both the sediment slabs for µXRF scanning and thin sections have been prepared from the same sediment sample a precise link of the data is ensured (Fig. DR 2.5.5.2). Regular peaks in Ca counts reflect biochemical precipitation of calcite in the lake water column. Since the onset of calcite precipitation occurs in spring (April/May), we calculate the annual mean of Ti counts for each varve cycle starting with the rise in Ca counts. Given the 200-µm resolution of the element scans and the mean varve thickness of

2 mm the average number of µXRF data points per varve is about ten. The resulting annual averages of Ti counts are correlated with the annual precipitation data calculated from May to April of the following year (Fig. DR 2.5.5.2). This division has been chosen to obtain best comparability of the climate and sediment-derived data. The Pearson's correlation coefficient of r=0.34 reveals a significant correlation at a 99% level between the annual mean of Ti counts and the annual precipitation sum suggesting a strong influence of rainfall on the average background detrital matter flux.

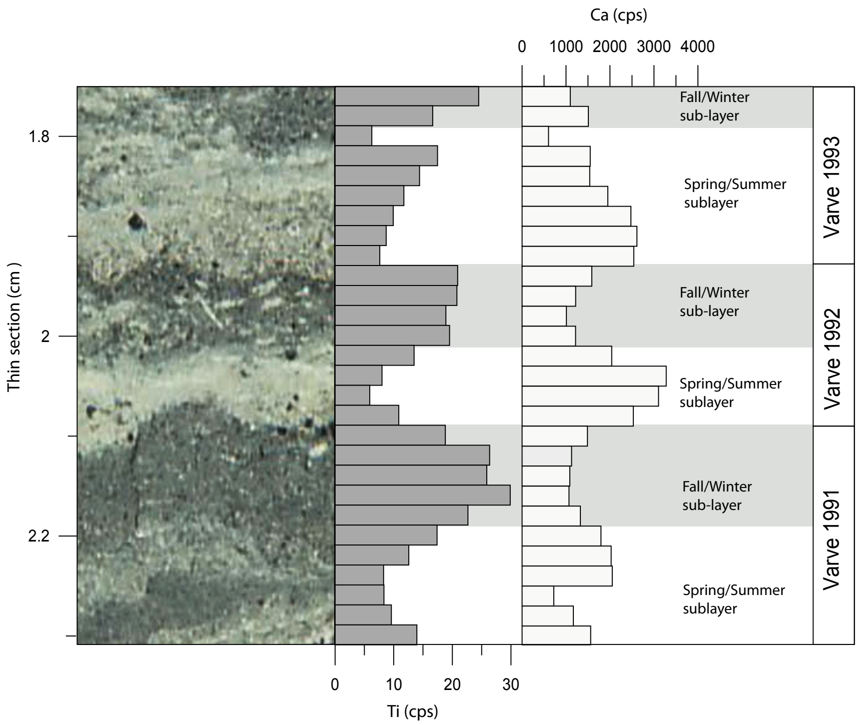

Figure DR 2.5.5.2. Anchoring of µXRF element counts at sub-seasonal resolution to the varve time scale demonstrated for varve years 1991, 1992, and 1993. Each varve cycle starts with an increase in Ca counts reflecting biochemical spring/summer calcite precipitation, whereas highest Ti counts occur in the fall/winter sub-layer. Mean annual Ti counts have been averaged over one varve cycle. Note: each bar represents an individual µXRF data point of a continuous line scan at 200 µm resolution.

For more infomation on detrital layer deposition in Lake Mondsee during the last 100 years see Appendix A:

Distinguishing floods, debris flows and hydrological changes in a 100-year varved sediment record from Lake Mondsee (in prep.)

Chapter 3

Late Holocene flood frequency changes in the northeastern Alps as recorded in varved sediments of Lake Mondsee (Upper Austria)

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submitted to Quaternary Science Reviews

Abstract Annually laminated (varved) lake sediments with intercalated detrital layers from extreme runoff events are ideal archives to establish precisely dated records of past extreme runoff events. The late Holocene varved sediments of Lake Mondsee (Upper Austria) were analyzed by combining sedimentological, geophysical and geochemical methods. This approach allows to distinguish two types of detrital layers related to different types of extreme runoff events (floods and debris flows) and to detect changes in flood activity during the last 4000 years. In total, 207 flood and 34 debris flow layers, deposited during spring and summer, were identified, which cluster in nine main flood episodes (FE 1-9) with durations of 30–50 years each. These main flood periods occurred during the Little Ice Age (450–750 varve yr BP) and throughout the Dark Ages Cold Period (1200–1500 varve yr BP), the late Iron Age (2000–2050 varve yr BP) and the transition from the Bronze Age to the early Iron Age (2700–2800 varve yr BP and 3250–3350 varve yr BP).

Summer flood episodes in Lake Mondsee are generally more abundant during the last 1500 years, often coinciding with multi-centennial advances of alpine glaciers. Prior to

1500 varve yr BP, spring/summer floods and debris flows are generally less frequent coinciding with fewer alpine glaciers advances. Lake Mondsee flood episodes occurred during climate cooling periods and mostly coincide with flood intervals in other European regions. Major exceptions appear, however, during the coldest and warmest climate conditions for which a higher spatio-temporal variability in European flood activity is observed. Lake Mondsee presents a precisely dated and several millennia long summer flood record for the NE Alps at the climate device between Atlantic, Mediterranean and East-European air masses. This helps to the understanding of regional and seasonal flood frequencies under changing climate conditions.

3.1 Introduction

Modelling studies predict increased flood risk in Europe under global warming conditions, related to an intensification of the water cycle and hence more frequent extreme precipitation events in summer (Arnell, 1999; Christensen and Christensen, 2003; Kundzewicz et al., 2006; 2005; Milly et al., 2002; Svensson et al., 2006). However, investigation of instrumentally recorded flood activity in Germany during the last 50 years exhibits a more complex spatial and seasonal pattern with increased summer floods in southern Germany and increased winter flood occurrence in western Germany (Petrow and Merz, 2009), showing that the response of flood patterns to climatic changes is variable on temporal and spatial scales (Beurton and Thieken, 2009; Merz and Blöschl, 2003). To decipher the mechanisms triggering flood recurrence and the resulting regional flood patterns, mainly instrumental data have been analyzed so far (Delgado et al., 2010; Glaser et al., 2010; Mudelsee et al., 2006; Pfister et al., 2004; Pinter et al., 2006). Locally, also historical flood event chronologies from documentary archives have been utilized to prolong instrumental time series (Brázdil et al., 2006; Glaser et al., 2010; Mudelsee et al., 2003; Schmocker-Fackel and Naef, 2010). However, the natural variability of flood recurrence on centennial or millennial time scales and the regional peculiarities of flood patterns cannot be clearly distinguished from these data because high-resolution instrumental and historical records do not extend beyond the last 150 to 1000 years.

To improve the knowledge about the natural frequency and seasonality of severe floods, long and reliable records of extreme events such as those preserved in geoarchives are required. First attempts to establish long flood time series have been made by palaeoflood hydrology, using riverine deposits in the United States (Baker, 1987; Baker, 2008; Ely et al., 1993; Enzel and Wells, 1997; Hirschboeck, 1988; Knox, 2000) and Europe (Benito, 2002; Chiverrell et al., 2008; Dearing, 1991; Macklin et al., 2009; Sheffer et al., 2003; Starkel, 2002; Thorndycraft et al., 2005). Despite the identification of significant flood occurrence patterns (Knox, 2000; Rumsby and Macklin, 1996), this approach is limited by poorly resolved chronologies and only allows, due to the erosional power of rivers, the reconstruction of those flood events, which overtop the preceding ones. In contrast to riverine deposits, lake sediment records provide more continuous records of detrital material deposition during high magnitude floods. For instance, investigations on non-varved lake sediments revealed increased flood occurrence during episodes of colder climate conditions (Arnaud et al., 2005; Bøe et al., 2006; Brown et al., 2000; Chapron et al., 2005; Chapron et al., 2002; Corella et al., 2010; Moreno et al., 2008; Nesje et al., 2001; Thorndycraft et al., 1998). However, due to chronological uncertainties from ^{14}C dating, these records do not allow to draw conclusions about the precise occurrence of floods on decadal time-scale. Additionally the seasonality of floods remains unknown by age models established by ^{14}C dating. In contrast, annually laminated (varved) lake sediments with intercalated detrital flood event layers are more suitable to establish continuous and precisely dated event chronologies with sub-annual resolution (Mangili et al., 2005). For example, varved sediments of Lake Ammersee in southern Germany (Czymzik et al., 2010) have provided a spring/summer flood record for the last 450 years, suggesting a relation between flood occurrence and changes in solar activity. A link between reduced solar irradiation and a cool and moist climate (Mangini et al., 2005; Mayewski et al., 2004; Wanner et al., 2008) due to changes in atmospheric circulation leading to an increased generation of flood-prone weather regimes in Europe (Benito et al., 2004; Jacobeit et al., 2003; Jacobeit et al., 2006; Luterbacher et al., 2001; Trouet et al., 2009) is widely discussed. However, suitable lake sediment records to address this issue by the reliable reconstruction of Holocene flood recurrence are still scarce.

The European Alps are a climatically sensitive region, which encompasses the influence of Mediterranean and Atlantic air masses (Auer et al., 2007), both triggering extreme flood events. Most paleohydrological and flood reconstructions so far cover the western Alps (Arnaud et al., 2005; Magny, 2004). The Lake Mondsee sediment record in the NE Alps has been previously demonstrated a valuable climatic and environmental archive (Lauterbach et al. 2011). More recently, detailed micro-facies analyses of detrital layers intercalated in the Mondsee record of the last 1600 years has shown the high potential of this sediment record as seasonal paleoflood record (Swierczynski et al., 2012). Here, we present an extended seasonally resolved flood reconstruction for the last 4000 years from the varved lake sediment record of pre-Alpine Lake Mondsee (Upper Austria). The recurrence pattern of intercalated detrital layers within the varved Lake Mondsee sediments was investigated with respect to the relation between flood occurrence and regional changes in climatic boundary conditions as reflected by Alpine glacier advances (Holzhauser et al., 2005; Ivy-Ochs et al., 2009b; Joerin et al., 2006), lake-level fluctuations (Magny, 2004), wet phases reconstructed from peat deposits (Haas et al., 1998) as well as speleothem-derived temperature oscillations (Mangini et al., 2005; Vollweiler et al., 2006).

3.2 Study area

Lake Mondsee (surface area 14.2 km², lake volume 5.1 km³) is located in the northeastern Alps (47°49'N, 13°24'E) in Upper Austria at an altitude of 481 m above sea level (Fig. 3.1). The lake basin, which has been substantially altered by the Pleistocene glaciations (Kohl, 1998; van Husen, 1989; van Husen, 2004), comprises a shallower northern sub-basin (up to 40 m deep) and a deeper southern sub-basin with a maximum water depth of 68 m. The catchment area (241 km²) can be sub-divided into two major geological units, separated by a main Alpine thrust fault along the southern shoreline of the lake (van Husen, 1989). The gently sloped northern part of the catchment (ca. 75 %) is characterized by siliciclastic sediments of the Rhenodanubic Flysch and local Quaternary deposits. The southern catchment (ca. 25%) reveals a steeper relief and is dominated by the Triassic Main Dolomite and Mesozoic limestones of the Northern Calcareous Alps. Three main rivers drain the northern part of the catchment, whereas only smaller creeks (e.g. Kienbach, Klausbach) discharge into the southern lake basin.

The regional climate is temperate, characterized by a mean annual temperature of 8.7 °C and an average annual precipitation of ~1500 mm (ZAMG, 1971-2000). The climatic effects of the North Atlantic Oscillation (NAO) are predominantly apparent during winter (Beniston and Jungo, 2002; Casty et al., 2005; Wanner et al., 2001). The precipitation regime of the northeastern Alps is mainly controlled by Atlantic and Mediterranean cyclonic activity (Sodemann and Zubler, 2010). Because of orographic effects, enhanced convective rainfall during July and August is the main cause for extreme floods as confirmed by the exceptional summer rainfall events of 1954, 1959, 1997 and 2002. However, extreme runoff also occurs after rain-on-snow events in winter and early spring.

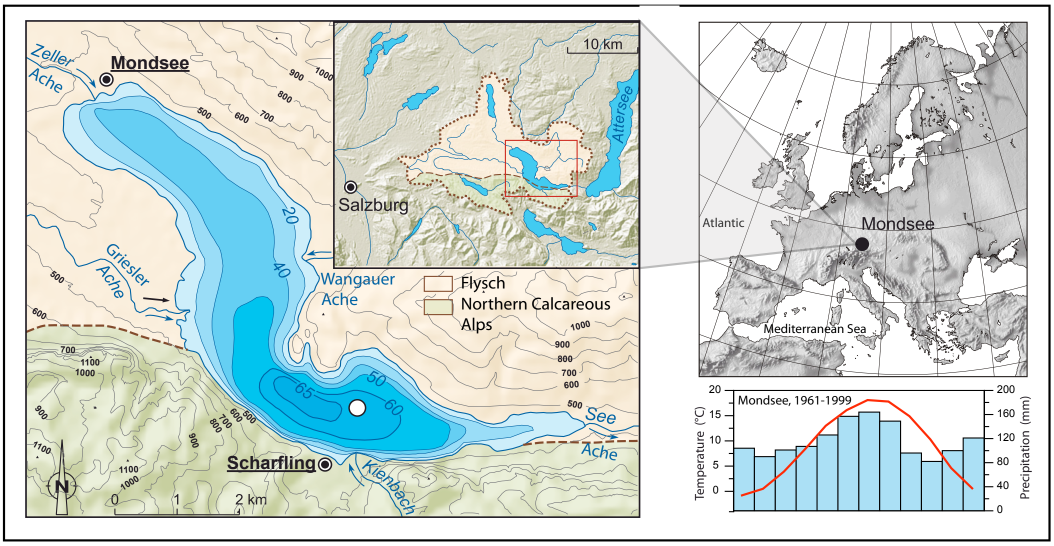

Figure 3.1. Simplified geographical and geological map of Lake Mondsee and climate diagram for the 1971-2000 observation period (ZAMG, Vienna). The northern sub-basin is located within Flysch sediments, which are drained by the three main tributaries Griesler Ache (synonymous: Fuschler Ache), Wangauer Ache and Zeller Ache. The southern sub-basin is fed by several smaller creeks, coming from the Northern Calcareous Alps. The investigated piston core has been retrieved from the southern sub-basin (white circle).

3.3 Methods

3.3.1 Coring and microfacies analysis

A continuous sediment profile of about 15 m length, covering the Holocene and Late Glacial, has been recovered from the southern sub-basin of Lake Mondsee in June 2005 by using a 90-mm-diameter UWITEC piston corer (Lauterbach et al., 2011). This study focuses on the uppermost 575 cm of the sediment record, covering approximately the last 4000 years. The Holocene chronology of the Lake Mondsee sediment record is based on microscopic varve counting, confirmed by additional AMS ^{14}C dating (Lauterbach et al., 2011). In addition to varve counting, detailed sediment micro-facies analysis was carried out on a continuous set of overlapping large-scale petrographic thin sections (100 x 20 x 10 mm), prepared according to Brauer et al. (1999). Micro-facies analysis and varve and detrital layer thickness measurements were undertaken under a ZEISS Axiophot polarization microscope at 25–400 x magnification.

3.3.2 Geophysical and geochemical properties

Magnetic susceptibility as a proxy for the content of magnetic minerals and grain size variations was measured with a Bartington MS2E point sensor at continuous steps of 1 mm. Semi-quantitative major element scanning was carried out at 200 µm resolution on the impregnated sediment blocks from thin section preparation by using a vacuum-operating EAGLE III XL micro X-ray fluorescence (µXRF) spectrometer with a low power Rh X-ray tube at 40 kV and 300 µA (250 µm spot size, 60 s counting time, single scan line). Element intensities for Mg, Ti and Ca are expressed as counts s^{-1} (cps), representing relative changes in element composition. The approach of combining parallel microfacies and µXRF element analyses on the same sediment blocks (Brauer et al., 2009) enables the characterization and reliable detection of even microscopic detrital layers. Selected sediment samples were additionally investigated by scanning electron microscopy (SEM), including EDS analysis.

3.3.3 Statistical treatment of detrital layer time series

Statistical treatment of the detrital layer record was carried out using Matlab. Extreme floods are rare events by nature and their recurrence rate has to be modelled accordingly. Due to the length of the investigated dataset, inhomogeneities in flood occurrence are likely to be present at different scales and with unknown patterns. To better estimate the occurrence of floods and to improve the comparison with other proxy records, we applied a Gaussian kernel regression on the reconstructed flood counts. According to Nadaraya (1964) and Watson (1964):

$l(t) = SiY*K((t-T(i))/h)/SiK((t-T(i))/h)$

(l = regression estimator, K = Gaussian kernel function, T(i) = observed events, t = time, Y = flood cluster, h = bandwidth).

The applied Gaussian kernel regression is a non-parametric method, representing a meaningful predictor for the occurrence of rare events. It is based on the assumption that flood occurrence follows an inhomogeneous Poisson process, i.e. flood events are unrelated to each other. A modified kernel regression (Diggle, 1985) was previously used to quantify trends in flood occurrence in German rivers during the last 1000 years (Mudelsee, 2010; Mudelsee et al., 2003). We used the original Nadaraya-Watson estimator and selected a bandwidth of 30 years, which is regarded as period of climatic significance. To estimate the significance of the flood pattern and to reduce probable errors in the reconstructed time series, confidence intervals were calculated by bootstrapping. From this envelope of simulated flood series, individual Kernel regressions were calculated. The 5% confidence intervals around the flood series were confined from the multiple kernel regressions of the simulated flood series by applying the t-percentile technique, which is especially used for non-stationary Poisson processes (Cowling et al., 1996).

3.4 Results

3.4.1 Sediment microfacies and geochemistry

The Holocene sediments from Lake Mondsee are composed of endogenic calcite varves with frequently intercalated sub-mm to cm thick brownish detrital layers. The investigated uppermost 575 cm of the sediment record (Lithozone V in Lauterbach et al. (2011) can be subdivided into four lithological sub-units based on varve quality and the abundance of detrital layers: (Va) 450–575 cm – faintly laminated calcite mud with frequent detrital layers; (Vb) 300–450 cm – faintly to well-laminated calcite mud with one distinct interval of detrital layers; (Vc) 170–300 cm – faintly to well-laminated calcite mud with frequent detrital layers; (Vd) 0–170 cm – well-laminated calcite mud with frequent detrital layers (Fig. 3.2).

Well-laminated sediments are characterized by distinct light-dark couplets. The light layers are composed of biochemically precipitated calcite, reflected by elevated Ca and low Ti and Mg µXRF counts, and represent spring/summer sedimentation. The dark layers, representing autumn/winter sedimentation, are composed of clay-sized minerogenic detritus, reflected by elevated Mg and Ti counts. Calcite layers reveal sharp basal boundaries and consist of two or three sub-layers with well defined rhombohedral calcite crystals (5–10 µm) at the base, followed by a layer of smaller crystals (2–5 µm) and intermediate crystals (ca. 5 µm) on top. This sub-lamination is caused by several pulses of calcite precipitation

(Kelts and Hsü, 1978; Koschel et al., 1983; Lotter, 1989; Ohlendorf and Sturm, 2001). Abundant pelagic diatoms *(Stephanodiscus sp., Aulacoseira sp.*), organic detritus (e.g. leaves), ostracods and clastic detrital material occur within the basal calcite sub-layer. The sharp basal boundary of the calcite layers and the good preservation of endogenic calcite and pelagic diatoms are indicative for anoxic conditions at the water-sediment interface, related to a stratified water column in spring/summer (Koschel et al., 1983). The occurrence of reworked littoral material in the spring layer suggests increased fluvial activity or wave activity that causes reworking of littoral sediments. Within faintly laminated intervals, the annual couplets show only indistinct layer boundaries and the internal variability of Ca, Ti and Mg counts is lower compared to well-laminated intervals. Calcite layers are mainly composed of small calcite crystals with traces of dissolution marks but diatom frustules has been deposited as well. Faint laminae, small grain sizes and the dissolution of calcite crystals may indicate disturbed calcite precipitation due to intensified calcite precipitation due to higher water temperatures and/or high biological productivity (Bluszcz et al., 2008).

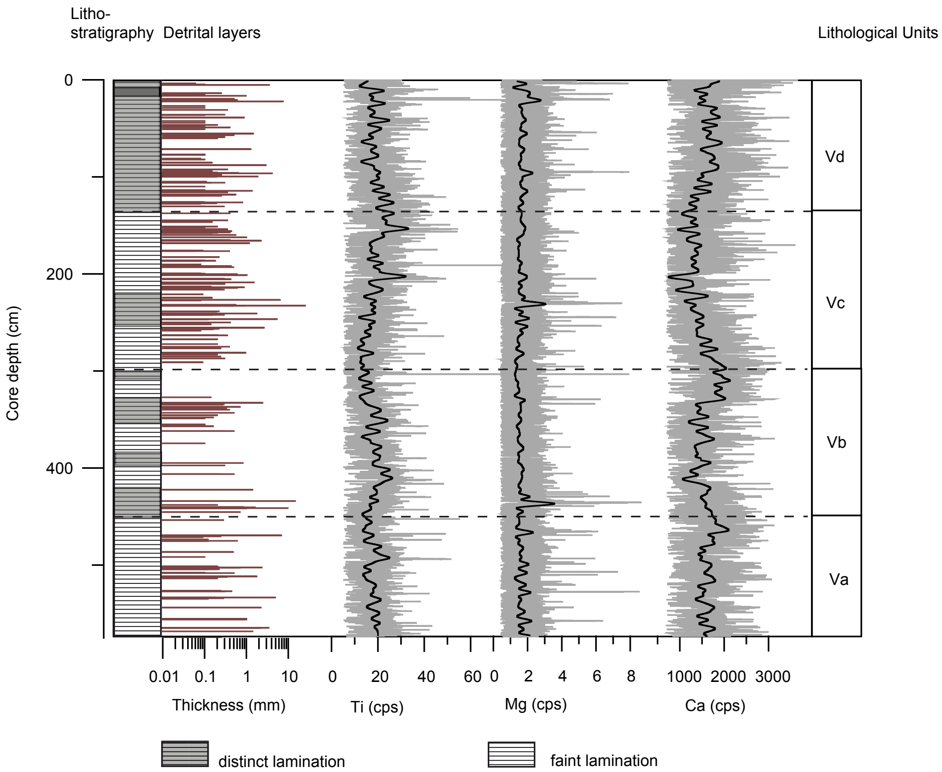

Figure 3.2. Lithostratigraphy of the investigated sediment sequence from Lake Mondsee (Lithozone V in Lauterbach et al. (2011)). The abundance of detrital layers, sediment microfacies, μXRF measurements for Ti, Mg and Ca (grey line: raw data in counts s-1 (cps), black line: 300pt-lowpass filtered data) are used to define four lithostratigraphical sub-units (Va to Vd).

Two types of detrital layers, intercalated within the summer/spring calcite layers, can be distinguished. Thin detrital layers (0.05–2.2 mm) are composed of silt- to sand-sized (<50–100 µm) angular shaped quartz, feldspars, dolomite and calcite, which can be easily distinguished from the endogenic calcite (<10 µm). Increased Ti and Mg counts suggest a

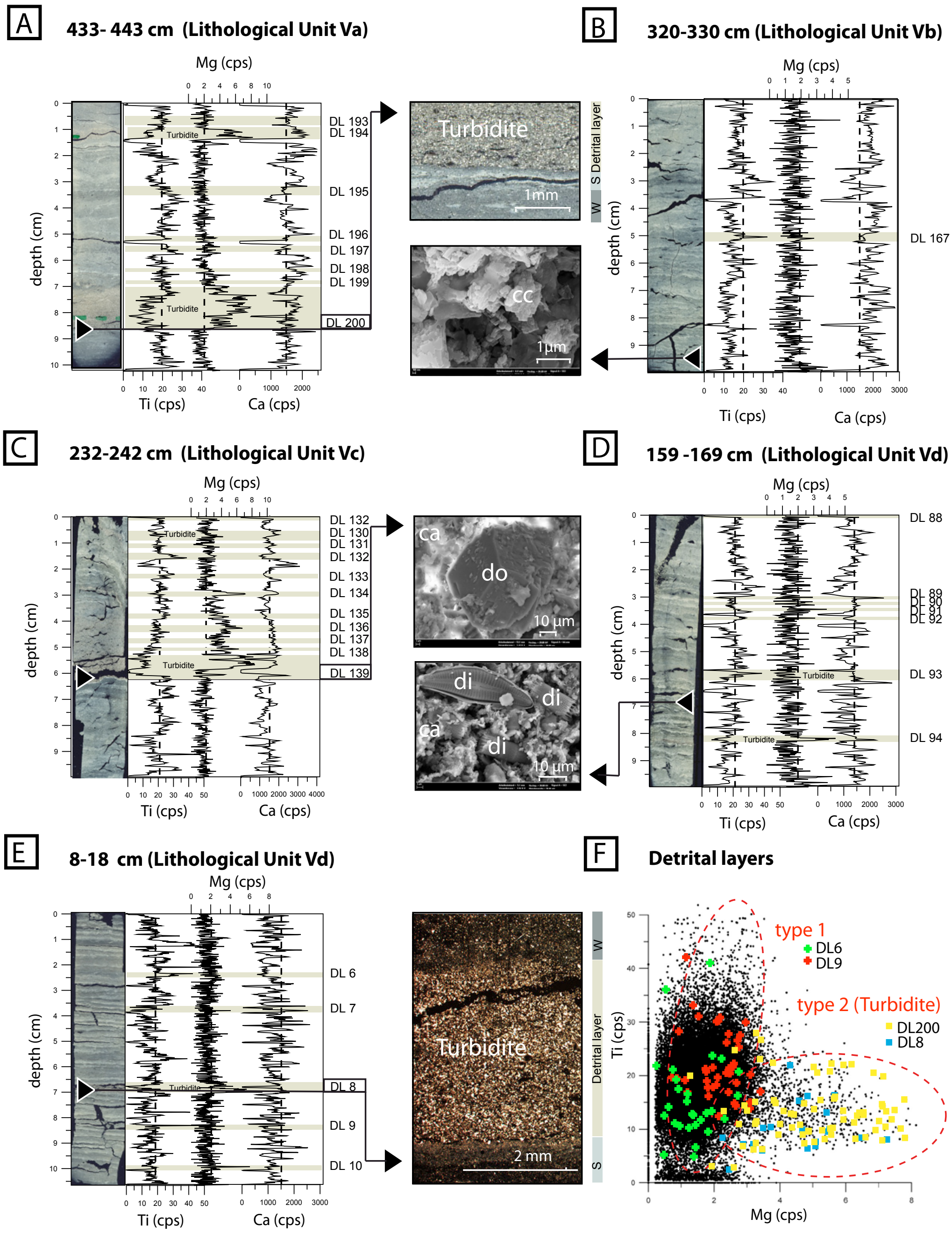

Figure 3.3. Thin section images and geochemical characterization of lithological sub-units Va (A), Vb (B), Vc (C) to Vd (D and E). Va (A) and Vd (E) with a typical detrital layer (DL) intercalated within summer sublayer (S) and winter sublayer (W) and detrital layer (turbidite). SEM images (B, C and D) show Dolomite (do) within DL 139, varve composition of diatoms (di), Calcite (ca) and autochthonous calcite carbonate (cc). (F) High Ti and low Mg counts characterize thin detrital layers (<1mm), whereas high Mg and low Ti counts characterize thick detrital layers (>1mm).

provenance from both, the siliciclastic (Flysch Zone) and the dolomitic (Northern Calcareous Alps) part of the catchment, respectively. Thin detrital layers within Lake Mondsee sediments reflect spring and summer flood deposits (Swierczynski et al., 2012) originating from the main tributary Griesler Ache (syn.: Fuschler Ache), which flows through both catchment geologies, the mainly siliciclastic Flysch deposits and the carbonatic Northern

Calcareous Alps. The Griesler Ache enters the northern part of the lake basin from the western shore in ca 3 km from the coring location (Fig. 3.1). The good sorting of the detrital material indicates inter- and overflows as the main transport mechanism (Mulder and Alexander, 2001; Sturm and Matter, 1978), which spread in a well-stratified water body along the thermocline before the particles settle down to the lake bottom. Several short gravity cores from different locations in Lake Mondsee show a basin-wide occurrence of these detrital layers, confirming their relation to regional-scale flood events.

In contrast, thick detrital layers (0.65–26 mm) are composed of organic fragments and predominantly sand-sized (100–200 µm) angular shaped mineral grains (Swierczynski et al., 2012). Microscopic inspection reveals dolomite and calcite as the main clastic components. Thick detrital layers are graded and show a sharp basal contact to the underlying endogenic calcite layer. Mg and Ca counts are high, whereas siliciclastic components (Ti) remain low. Thick detrital layers are interpreted as deposits of highly concentrated turbidity currents / underflows (Mulder and Alexander, 2001), representing the subaqueous propagation of debris flows from the catchment (Gomi et al., 2004). The sharp erosional basal contacts to the underlying calcite layers and the continuation of calcite precipitation above the event layer indicate instantaneous deposition in summer. Mg enrichment as well as the spatial distribution of these detrital layers within the southern sub-basin reveal sediment supply from the Northern Calcareous Alps, induced by local debris flow events through the Kienbach creek close to the coring site (Swierczynski et al., 2012).

3.4.2 Chronology

The chronology for the investigated part of the Lake Mondsee sediment record is based on microscopic varve counting (Fig. 3.4A). The annual character of the calcite laminae is confirmed by sediment microfacies analysis and ^{137}Cs dating (Lauterbach et al., 2011) as well as a detrital event layer related to a documented debris flow in summer 1986 (Swierczynski et al., 2009) intercalated within the 1986 calcite layer. The varve-based age-depth model is further supported by 14 AMS ^{14}C dates in the interval under investigation (Lauterbach et al., 2011). As deduced from two independent varve counts by different examiners, the varve chronology has a total error of less than 25 years for most parts of the investigated sequence (Fig. 3.4B). This is smaller than the uncertainty range of the ^{14}C dates and thus provides a robust chronology for the event layer record. Differences in the two varve countings are on the one hand due to seasonal calcite sublayers, which could be mistaken as individual years, thus leading to an overestimation of the number of varves. On the other hand, occasional massive calcite layers or calcite mud with only weak layering might lead to an underestimation of the time included. Varve thickness during the late Holocene varies between 1.0 and 2.5 mm (Fig. 3.4A) with a mean sedimentation rate of about 1.5 mm/a.

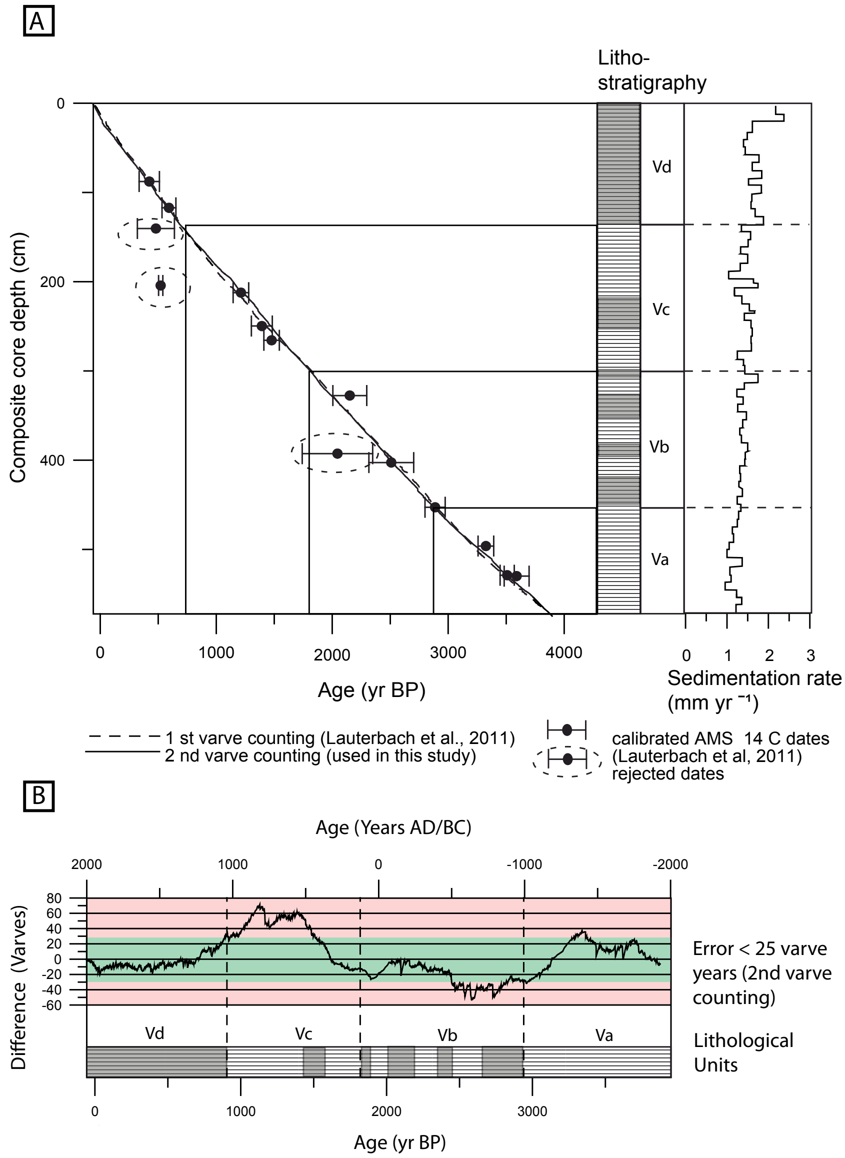

Figure 3.4. (A) Age depth model for the investigated sequence of the Lake Mondsee sediment record, based on two varve countings and additionally confirmed by AMS ^{14}C dates (for details on radiocarbon dating see Lauterbach et al. (2011)). Sedimentation rates are given as 10 cm averages. (B) Low differences of mainly less than 25 years between the two independent varve counts indicate the reliability of the varve chronology. Highest differences between the two varve counts occur within faintly laminated intervals.

3.4.3 Detrital layer record and reconstruction of flood episodes

The sediment record of the last 4000 years comprises 207 flood and 34 debris flow layers. The distinct annual layering in the uppermost 2000 years of the record allows allocating >95% of the detrital layers to the spring/summer season based on their micro-stratigraphic position within the varve succession. Based on these data we suggest a similar seasonal pattern also for the lower part of the record although less clear varve preservation prevented to prove this assumption. Both types of event deposits reveal a pronounced hydrological variability on decadal, centennial and millennial time scales. Floods are generally less frequent prior to ca 1500 cal. yr BP (1–10 events per 100 years) than during the last 1500 years (2–15 events per 100 years). Interestingly, on shorter time scales enhanced flood layer deposition occurred in nine characteristic periods of 30–50 years duration (Fig. 3.5), hereafter labelled as flood episodes (FE). These flood episodes are dated at 430–470 (FE1), 620–650 (FE2), 780–810 (FE3), 1200–1250 (E4), 1310–1360 (FE5), 1470–1500 (FE6), 1950–2100 (FE7), 2700–2800 (FE8) and 3250–3350 varve yr BP (FE9). The 30-year running mean of flood events reveals flood recurrences of 3–7 years within these main flood episodes, whereas the Kernel regression indicates slightly lower flood recurrences of 6–12 year. Relatively narrow bands for the t-percentiles of the bootstrapping results confirm that these occurrence rates are robust and representative (Fig. 3.5). Main flood episodes do not

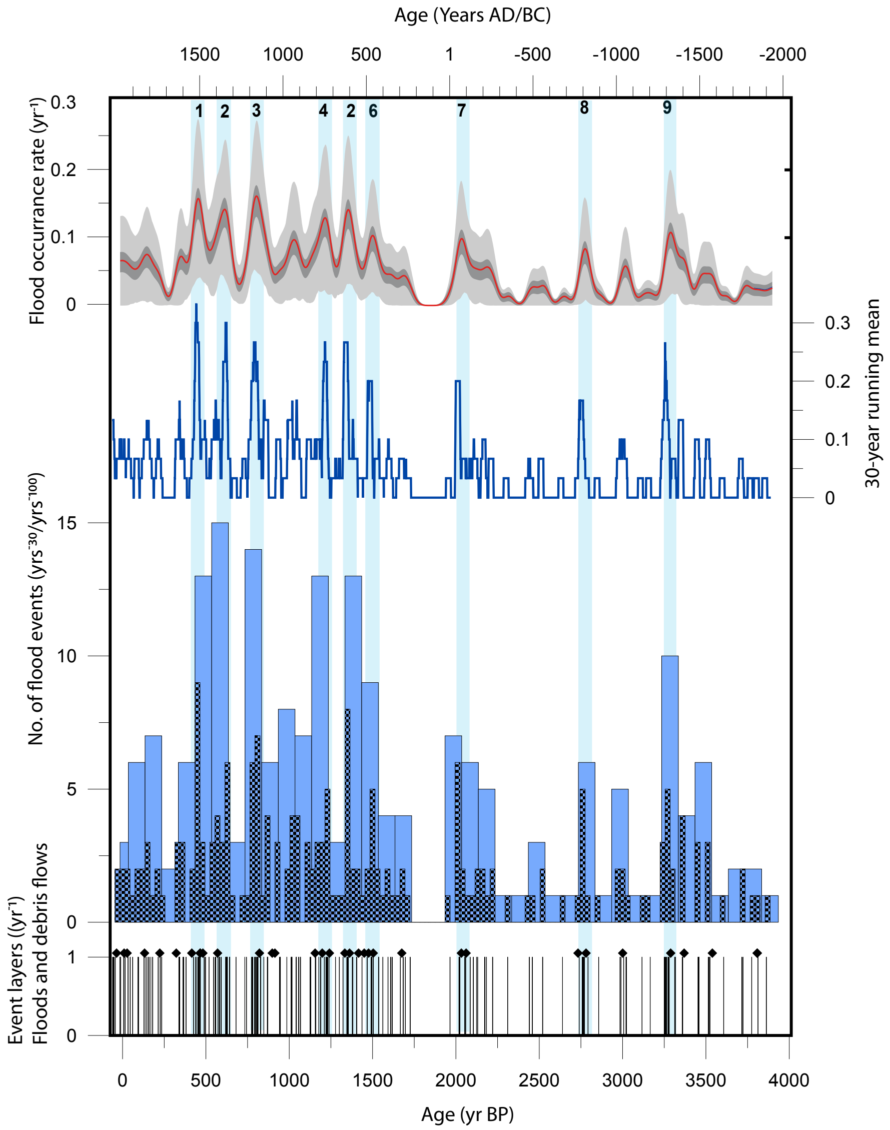

Figure 3.5. Reconstruction of flood and debris flow events from the Lake Mondsee sediments: Number of flood events per 30 years, 30- year running mean of flood events and estimation of the flood occurrence rate by Gaussian kernel regression (30 years band width, light gey shading: 90% significance level of 2000 bootstrapping results of the original dataset, dark grey shading: significance level based on a student's t distribution). Light blue columns indicate main flood episodes with 8–15 flood events (0–1500 cal. yr BP) and 6–10 flood events per 100 years (1500–4000 cal. yr BP) derived from kernel regression.

generally coincide with higher background input of detrital material. Debris flows as recorded in Lake Mondsee are rare events originating from the Kienbach valley after heavy but very localized thunderstorms, which do not cause a major flood as observed, for example, for the AD 1986 event. On the millennial time-scale, local debris flows appear to be more frequent during periods of higher flood abundance in the last 1500 years.

3.5. Discussion

3.5.1 Human impact on the Lake Mondsee sedimentary record

It has been demonstrated that the deposition of generally rather low amounts of detrital material in Lake Mondsee is triggered by extreme rainfall events (Swierczynski et al., 2012) and related surface runoff. In addition to climatic triggers, catchment erosion and detrital matter supply to the lake might be influenced by human activity, thereby amplifying detrital sediment transport processes (Brown et al., 2009; Hoffmann et al., 2010; Houben et al., 2009; Zolitschka et al., 2003; Lauterbach et al., 2012b). However, several arguments indicate that detrital layer deposition in Lake Mondsee is mainly driven by climate variability (Swierczynski et al., 2012). Pollen records derived from peat bogs in the vicinity of Lake Mondsee 5 km (Draxler, 1977) and 0.2 km apart (Schmidt, 1981) indicate intense human impact in the catchment only after AD 1600 (Draxler, 1977) and moderate impact after 1000 cal. yr BP (Schmidt, 1981). The presence of *Rumex* and *Cerealia* indicates human land-use during the early Medieval Time when a monastery has been constructed (Draxler, 1977, AD 748). Intense deforestation only occurred since ca. 350 cal. yr BP (Draxler, 1977; Kunze, 1986). Prior to Medieval times, only slightly increased human impact with 1-5% non-arboreal pollen is reported for the Iron Age (ca 2800–2000 cal. yr BP) and the Roman periods (ca 2000–1800 cal. yr BP). Except for one case none of the flood periods coincided with periods of either weaker or stronger human impact thus suggesting a decoupling of human activity and flood layer deposition in Lake Mondsee. The only exception appears for flood episode FE3 which coincides with mill constructions along the of Griesler Ache in the late Medieval (Kunze, 1986) that might have enhanced erosion in the catchment.

3.5.2 Paleoflood activity and hydrological changes in European context

Millennial-scale variability

The observed late Holocene increase in flooding apparently did not synchronously occur in different parts of Europe. On the western margin of the continent enhanced flooding has been reported either at around 2800 cal. yr BP from England and Spain (Macklin et al., 2006; Macklin et al., 2010; Thorndycraft and Benito, 2006) and the NW Alps (Debret et al., 2010) or slightly later at 2500 cal. yr BP from Norway (Støren et al., 2010). In more continental regions like Poland the onset of increased flooding has been found to later at

2000 cal. yr BP in Poland (Starkel et al., 2006) or even around 1500 varve yr BP at Lake Mondsee (this study). However, even if the main shift in the Mondsee flood record occurred later, there is evidence for an enhanced flood activity also at around 2800 cal yr BP in FE 8, but this was rather a short-term fluctuation than a longer lasting change.

Despite the differences in timing the late Holocene increase in hydro-climatic extreme events coincides with the northern hemisphere climate cooling of the so-called Neoglacial (Wanner et al., 2008), which is explained by reduced solar insolation during boreal summer. This trend towards cooler conditions in the Alps is clearly expressed by expanding glaciers (Ivy-Ochs et al., 2009) and lowering of the tree-lines (Nicolussi et al., 2005).

Although it is tempting to interpret the apparent differences in timing of the onset of the hydrological shift in different regions of Europe in terms of regional climate change one has to consider several other factors that might influence the flood reconstructions derived from different sediment archives. The factors influencing paleoflood records are complex and include (1) different flood recording processes in lake and alluvial systems and (2) local catchment processes and hydrological conditions.

(1) Alluvial deposits record floods in a very different way than lake systems. While lake sediments continuously record the frequency of events, alluvial deposits mainly record floods, which overtop older events in magnitude (intensity of floods). In consequence, lakes provide proxy records for flood frequencies, whereas alluvial deposits provide information on the intensity of the strongest floods. Additionally, strong floods may possibly erode previous flood deposits (Gilli et al., 2013).

(2) Hydrological and morphological characteristics of the lake and its catchment might influence the flood record derived from the sediment profiles. This can be nicely demonstrated by comparing the Mondsee flood record with that of Lake Ammersee (48°00’N, 11°07’E), another pre-Alpine lake located only 165 km northwest of Lake Mondsee. Due to differences in catchment morphology and daily river discharge the number of flood-triggered detrital layers in both lakes during the last 450 years is distinctly different: 28 event layers in Lake Mondsee (ca. 5% of these layers are thicker than 1 mm) versus 97 event layers in Lake Ammersee (Czymzik et al., 2010) of which 35 % are thicker than 1 mm. The different thresholds in terms of flood layer formation of these two lakes can be explained by a larger (990 km^2) catchment and higher relief energy (1652 m) as well as a stronger river runoff (mean daily discharge: 16 m^3/s, max. daily discharge: 650 m^3/s) at Lake Ammersee compared to Lake Mondsee (catchment size: 247 km^2; relief: ca. 1300 m; mean daily discharge: 4 m^3/s; max. daily discharge: 82 m^3/s). In addition the specific locations of the coring sites with respect to the inflowing river might play an important role. At Lake Ammersee the river mouth is directly directed towards the coring site while in Lake Mondsee the core has been taken in a more distal position to the main river inflow due to the specific basin morphometry with two sub-basins (Fig. 3.1). In result, detrital sediment supply is generally lower in Lake Mondsee, which in turn might have affected the

thresholds for floods that resulted in deposition of a detrital layer.

In addition to these local factors of the recording flood archive, the type and seasonality of floods might influence the formation of flood layers. For instance, high-Alpine lake sediments preferably record snowmelt and rain-on snow events in winter and spring (Debret et al., 2010a) and flash floods (Wilhelm et al., 2012a), whereas the larger pre-Alpine lakes at lower elevation in Northern Alps preferably reflect long-rain floods (Czymzik et al., 2010) or convective short-rain floods in spring and summer (Swierczynski et al., 2012). The seasonality of the main flood season also differs between regions (Merz and Blöschl, 2003) so that, for example, in western Europe mainly winter floods might be recorded (e.g. (Støren et al., 2010; Bøe et al., 2006; Debret et al., 2010), whereas the Mondsee sediments represent spring and summer floods.

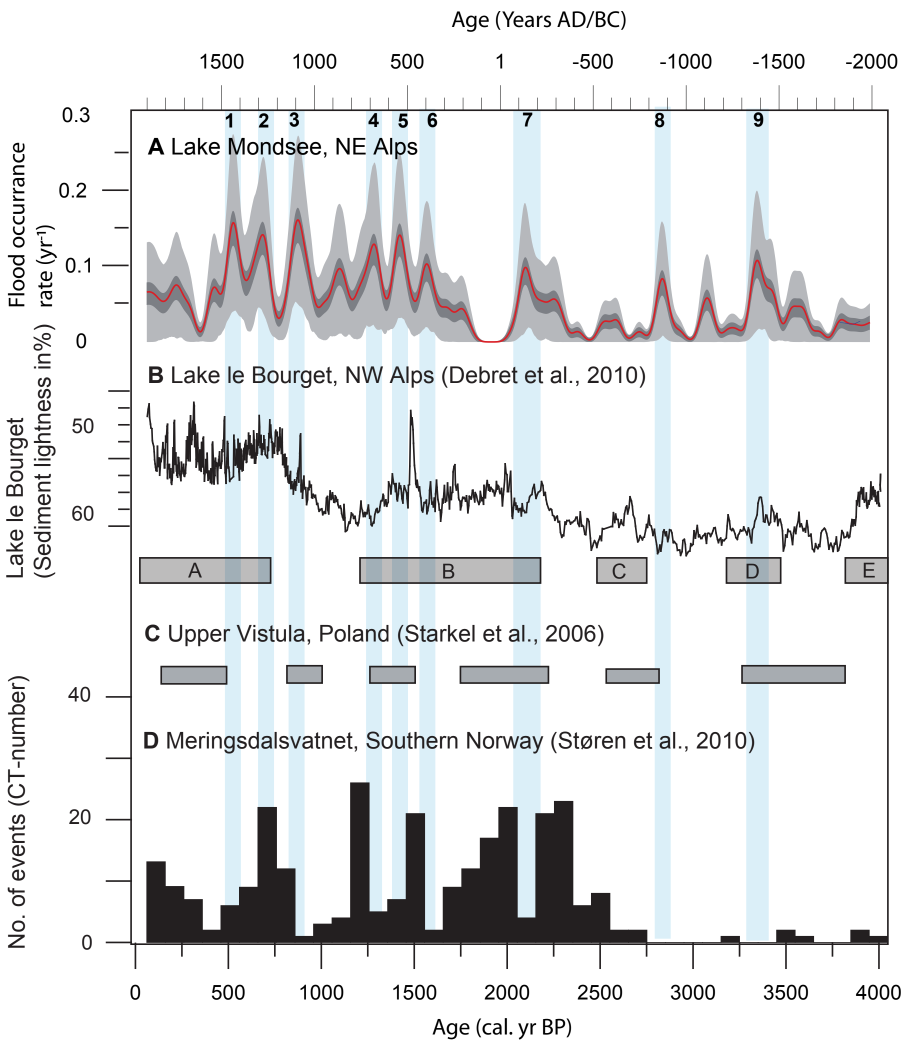

Figure 3.6. Comparison of proxy-based European flood reconstructions for the last 4000 years. (A) Kernel regression of the Lake Mondsee flood record with nine main flood episodes (E1 to E9, light blue columns). (B) Flood reconstruction from Lake Le Bourget sediments (northwestern Alps) with five clastic phases (A to E, Debret et al., 2010b). (C) Flood phases reconstructed from deposits of Upper Vistula River, Poland (Starkel et al., 2006). (D) Flood reconstruction from lake sediments of Lake Meringsdalsvatnet, southern Norway (Støren et al., 2012).

Although it is difficult to disentangle and quantify the affects of each of these local factors on the flood time series, it is likely that the different regional timing of the onset of late Holocene hydrological changes in Europe also reflects variations in changing atmospheric circulation patterns because the occurrence of special weather regimes is crucial for flood generation. While the influence of moisture transport from the North Atlantic is predominant for northern (Støren et al., 2010; Støren et al., 2011) and western Europe (Debret et al., 2010; Thorndycraft and Benito, 2006), east-central Europe is additionally influenced by drier continental air masses from Siberia (Starkel et al., 2006) and/or the Mediterranean moisture regime in summer (Swierczynski et al., 2012) or autumn (Wilhelm et al., 2012b).

Centennial to multi-deacadal time scale variability

In addition to the observed millennial-scale change, flood activity in the Mondsee region exhibits a pronounced variability on centennial to decadal timescales. In addition to six previously reported flood episodes (FE 1–6) during the last 1600 years (Swierczynski et al., 2012) three pronounced flood episodes with flood recurrence times of 3–7 years that lasted between 30 and 50 years (FE 6–9) have been identified between 1600 and 4000 varve yr BP. Flood episodes FE 1–2 and FE 4–9 at Lake Mondsee correlate with multi-centennial flooding phases at Lac de Bourget in NW Alps (Debret et al., 2010) thus reflecting a coincidence of winter flood occurrence in NW Alps and spring/summer floods in NE Alps. However, flood phases at Lake le Bourget lasted for several centuries compared to the multi-decadal periods at Lake Mondsee. This might be due to the different time resolution of the records with the Mondsee time series established at annual resolution. For other flood episodes recorded at Lake Mondsee, like FE 3 (AD 1140–1170) no corresponding signal has been found in other regions (Debret et al., 2010; Støren et al., 2010; Thorndycraft and Benito, 2006). This might partly be related to a bias in the Mondsee record by mill constructions in the catchment (Kunze, 1986).

The decadal-scale flood episodes in the Lake Mondsee sediments occur during periods of main glacier advances in the Central Alps during the Löbben glacier advance between 3800 and 3400 cal. yr BP, Göschen I cold phase between 3000–2300 cal. yr BP and the Göschen II cold phase between AD 500–900 and during the LIA after 750 cal. yr BP (Holzhauser, 2007; Ivy-Ochs et al., 2009). Two flood episodes, FE1 (430–470 cal. yr BP) and FE7 (1950–2100 cal. yr BP), are not correlated to main glacier advances in the Central Alps. During this time, a possible reduction in winter precipitation might explain alpine glacier retreats. However, since FE 1 and FE7 coincide with a time of lower tree lines in the Austrian Alps, revealing persisting cold climate conditions during summer in the NE Alps, enhanced flood frequencies during these intervals might reflect inflowing of Atlantic and Mediterranean moisture to Lake Mondsee during summer (Swierczynski et al., 2012). The coincidence of centennial scale cold phases and multi-decadal-scale flood episodes at Lake Mondsee reveal that flood activity at Lake Mondsee, and thus changes in atmosphe-

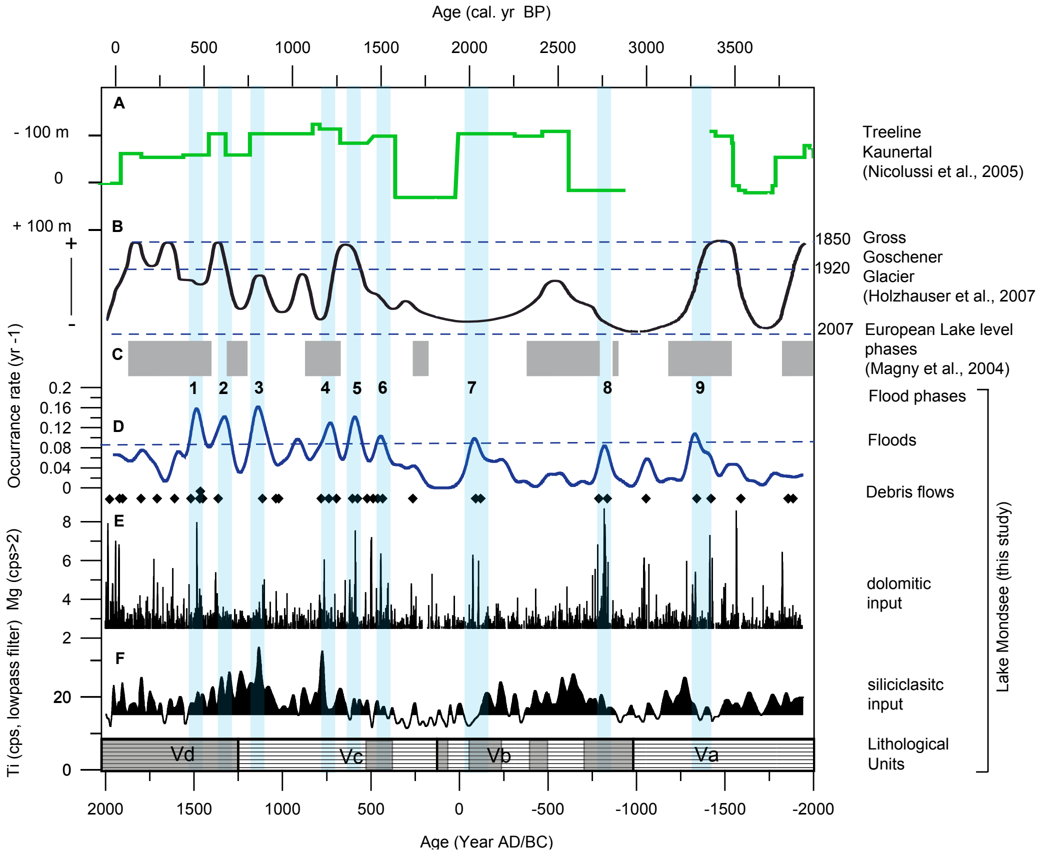

Figure 3.7. Comparison of the Lake Mondsee flood record (d-f) with other palaeoclimate records for the last 4000 years (A-C). (A) Reconstruction of Austria treeline (Nicolussi et al., 2005). (B) Cold events in the Alps a revealed by glacier advances (Holzhauser et al., 2005). (C) Lake-level highstands in the southwestern Alps (Magny, 2004). (D) Flood occurrence rate reconstruction from the Lake Mondsee sediments (see Fig. 5). Diamonds indicate debris flows. (E) μXRF Mg counts as a proxy for dolomitic detrital input from the Northern Calcareous Alps by extreme floods and debris flows. (F) μXRF Ti counts as a proxy for siliciclastic detrital input from the Flysch Zone.

ric circulation patterns in spring/summer, is sensitively responding to a change of climate cooling during the last 4000 years, on different time scales.

3.6 Conclusion

The varve-dated sediments of Lake Mondsee comprise a record of 241 detrital layers deposited during the last 4000 years providing a high-resolution record of extreme spring/ summer runoff events for the northeastern Alps. An increase in flood activity occurred since about 1500 varve yrs BP likely as a consequence of a millennial scale Late Holocene climate cooling. Nine multi-decadal episodes of increased spring/summer flood activity (430–470 (FE1), 620–650 (FE2), 780–810 (FE3), 1200–1250 (E4), 1310–1360 (FE5), 1470–1500 (FE6), 1950–2100 (FE7), 2700–2800 (FE8) and 3250–3350 varve yr BP (FE9) are superimposed on this long-term change. Periods of higher flood activity occurred at the onset of the Little Ice Age (AD 1200–1500, 450–750 cal. yr BP), during the Migration Period (AD 450–750, 1500–1200 cal. yr BP) as well as during the Roman times (ca 2000 varve yr BP) and the pre-Roman Iron Age (ca 2800 varve yr BP) and the late Bronze Age (ca 3300 varve yr BP). Debris flows are rare events caused by high intensity runoff of a short duration and local extent, which occur more often during periods of increased flood activity. The long-term increase in flood activity in the late Holocene has also been reported from other European paleoflood records. The asynchronous onset of increased flood activity in different sediment archives in different regions might be partly due to differences in the sensitivity of the individual flood reconstruction, but may also reveal real seasonal hydrological contrasts within Europe. Despite still existing limitations in understanding regional hydrological activity in Europe, future modelling should implement changes in atmospheric circulation patterns as well as seasonal effects of climate change, in order to better assess regional hydrological response to climate change.

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Chapter 4

Late Neolithic Mondsee Culture in Austria: Living on lakes and living with flood risk?

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Abstract Neolithic and Bronze Age lake-dwellings in the European Alps became recently protected under the UNESCO World Heritage. However, only little is known about the cultural history of the related pre-historic communities, their adaptation strategies to environmental changes and particularly about the almost synchronous decline of many of these settlements around the transition from the Late Neolithic to the Early Bronze Age. For example, there is an ongoing debate whether the abandonment of Late Neolithic lake-dwellings at Lake Mondsee (Upper Austria) was caused by unfavourable climate conditions or a single catastrophic event. Within the varved sediments of Lake Mondsee we investigated the occurrence of intercalated detrital layers from major floods and debris flows to unravel extreme surface runoff recurrence during the Neolithic settlement phase. A combination of detailed sediment microfacies analysis and µXRF element scanning allows distinguishing debris flow and flood deposits. A total of 60 flood and 12 debris flow event layers was detected between 4000 and 7000 varve years BP. Compared to the centennial- to millennial-scale average, a period of increased runoff event frequency can be identified between 4450 and 5900 varve yr BP. Enhanced flood frequency is accompanied by predominantly siliciclastic sediment supply between 5000 and 5500 varve years BP and enhanced dolomitic sediment supply between 4500 and 5000 varve years BP, revealing a change from regional floods to more local runoff events. Interestingly, during the interval of highest flood frequency a change in the location and the construction technique of the Neolithic lake-dwellings at Lake Mondsee can be observed. While lake-dwellings of the first settlement phase (ca. 5750–5200 cal. yr BP) were constructed on wetlands, later constructions (ca. 5400–4650 cal. yr BP) were built on piles upon the water, possibly indicating

an adaptation to either increased flood risk or a general increase of the lake-level. However, also other than climatic factors (e.g. socio-economic changes) must have influenced the decline of the Mondsee Culture because flood activity generally decreased since 4450 varve yr BP, but no new lake-dwellings have been established thereafter.

4.1 Introduction

The catastrophic impact of past climatic changes on pre-historic societies has been the topic of several studies during the last decade (e.g. deMenocal, 2001; Haug et al., 2003; Staubwasser et al., 2003; Webster et al., 2007; Yancheva et al., 2007). However, the demise of ancient civilizations might be more likely driven by a complex interplay of changing environmental conditions and several other factors such as socio-economic changes or natural disasters (e.g. Fedele et al., 2008; Magny, 2004) with distinguishing between these not always being straightforward. In particular, unfavourable climate conditions have also been proposed to be the main cause for the large-scale and broadly synchronous abandonment of lake-dwellings in the Alpine region at the transition between the Neolithic and the Bronze Age (Magny, 1993; Magny, 2004). For example, there is indication that climatic changes might be responsible for the decline of the Late Neolithic Mondsee Culture of Upper Austria (Offenberger, 1986; Schmidt, 1986). However, also a catastrophic landslide event has been proposed to have caused the disappearance of lake-dwellings at this site (Janik, 1969; Schulz, 2008). Hence, further studies are necessary to unravel the local factors leading to the abandonment of Neolithic settlements at Lake Mondsee. This might also provide valuable information about the impact of climate variability on Neolithic lake-shore settlements on a larger spatial scale. In the particular case of the Alpine lake-dwellings, a cold reversal, reflected by rising lake-levels (Magny, 2004; Magny and Haas, 2004) and glacier advances (Ivy-Ochs et al., 2009), between 5600 and 5300 cal. yr BP has been identified, which probably affected Neolithic cultures in the circum-Alpine region. This indicates a significant and overall influence of climate change on pre-historic settlements. However, limitations in the temporal resolution and chronological precision of different geoarchives still represent a major obstacle in investigating the influence of climate change and short-term hydro-meteorological events on early human societies and their settlements. Within this context, annually laminated lake sediments, which are characterized by a robust age control and record climatic changes directly in the habitat of the pre-historic lake-dwellers, can provide valuable information about past environmental conditions (e.g. hydrological changes) and their influence on the settlements.

The varved sediments of Lake Mondsee (Upper Austria) represent an ideal archive of past climate history and changing environmental conditions (e.g. Klee and Schmidt, 1987; Lauterbach et al., 2011; Schmidt, 1991; Schultze and Niederreiter, 1990), but also historical flood events (Swierczynski et al., 2012). The present study of Lake Mondsee sediments focuses on flood and debris flow event layer deposition between 7000 and 4000 varve years

BP, providing information about hydrological changes within this interval at high temporal resolution. The established unique event chronology enables, in comparison with ^{14}C dates from three Neolithic lake-dwelling sites around the lake (Felber, 1970, 1974, 1975, 1985; Felber and Pak, 1973; Schmidt, 1986), the evaluation of possible impacts of changes in runoff activity on the decline of Neolithic lake-dwellings at Lake Mondsee and the hypothesis of increased lake-levels at the end of Neolithic.

4.2 Study Site

Lake Mondsee is located at the northeastern fringe of the European Alps (Upper Austria, 47°49'N, 13°24'E, 481 m above sea level), about 40 km east of Salzburg (Fig. 4.1). The lake has a surface area of about 14 km^2 and a maximum depth of 68 m. The lake basin can be divided into a shallower northern and a deeper southern part. Three main rivers (Griesler Ache/syn.: Fuschler Ache, Zeller Ache and Wangauer Ache) feed the northern lake basin, whereas only several smaller streams discharge into the southern basin. The only outlet (Seeache) is located at the southern end of Lake Mondsee and drains into Lake Attersee. A Tertiary thrust fault, tracking along the southern lake shoreline, divides the catchment (~247 km^2) into a southern and a northern part with two different, clearly distinguishable geological units (Fig. 4.1). Rhenodanubic Flysch sediments and Last Glacial moraines characterize the gentle hills around the northern lake basin, whereas the southern shoreline of the lake is defined by the steep-sloping mountains of the Northern Calcareous Alps, composed of the Triassic Main Dolomite and Mesozoic limestones.

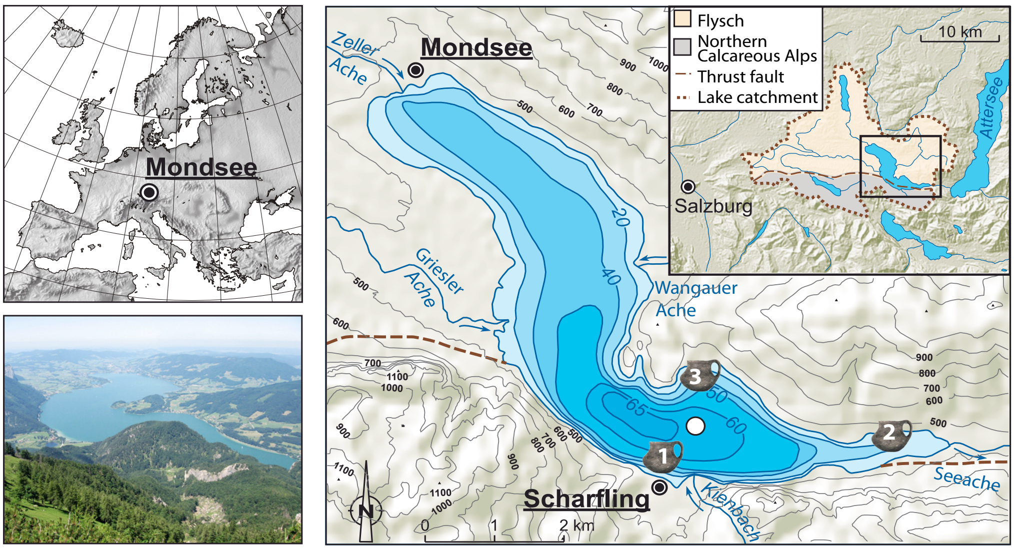

Figure 4.1. Bathymetry of Lake Mondsee (depth below lake level), relief with isobaths and simplified geological map of the lake catchment. Three main rivers (Griesler Ache, Wangauer Ache and Zeller Ache) and the small creek Kienbach are the main sources of detrital input. Pottery symbols indicate the three Neolithic sites (1 - Scharfling, 2 - See, 3 - Mooswinkl).

The climate of the Lake Mondsee region, being influenced by Atlantic and Mediterranean air masses (Sodemann and Zubler, 2010), is characterized by warm summers and frequent precipitation (annual average ~1550 mm for the period 1971–2000, Central Institute for Meteorology and Geodynamics (ZAMG), Vienna, Austria). As typical for the NE Alps, the precipitation maximum and in consequence extreme floods occur in July and August (Parajka et al., 2010). As indicated by historical records of daily lake water level for the last 100 years, only very few flood events occur in winter (e.g. 1974) and autumn (e.g. 1899, 1920, Swierczynski et al., 2009).

4.3 Neolithic lake-dwellings at Lake Mondsee

First research on Alpine lake-dwellings, since 2011 protected under the UNESCO World Heritage, was already published in the mid-19th century (Keller, 1854), reporting the finding of a submerged Bronze Age settlement in Lake Zurich. Within the following decades, several other Neolithic and Bronze Age settlements along Alpine lakes were discovered, accompanied by a lively debate about construction techniques and the socio-cultural and environmental conditions during the settlement phase (see Menotti (2001, 2004, 2009) for a review).

Three lake-dwelling sites have so far been discovered along the shorelines of the southern basin of Lake Mondsee in the Salzkammergut lake district (Fig. 4.1). Radiocarbon dates obtained from several wooden artefacts from these lake-dwellings clearly indicate a Young to Final Neolithic age (Felber, 1970, 1974, 1975, 1985; Felber and Pak, 1973; Ruttkay et al., 2004). The site “See”, which has already been described in the second half of the 19th century (Much, 1872, 1874, 1876) and after whose artefacts the Neolithic Mondsee Culture has been named, is located close to the lake outlet Seeache. Sedimentological and pollen analyses of a sediment core from the lake outlet (Schmidt, 1986) indicate the presence of landuse indicators in a cultural horizon, which is palynologically dated to the Younger Atlantic. This cultural horizon, which has been interpreted as reworked/washed-away material from prehistoric houses, is underlain by clastic material, which is thought to reflect a transgressive phase with increased lake-levels and has been dated to 4720 ± 100 ^{14}C yr BP (5661–5055 cal. yr BP, Schmidt, 1986). This age is in good agreement with conventional radiocarbon dates obtained from wooden artefacts from the Neolithic lake-dwellings at site “See”, dating between 4660 ± 80 and 4910 ± 130 ^{14}C yr BP (5062–5589 and 5325–5920 cal. yr BP, Table 1, Felber, 1970, 1985). The two other lake-dwelling sites “Scharfling” and “Mooswinkel” are located at the southern and northern shoreline of the lake, respectively. While remnants from the site “Scharfling”, which is located ca. 3.5 km west of the site “See”, are dated to the almost similar time interval as those from site “See”, namely between 4660 ± 90 and 4940 ± 120 ^{14}C yr BP (5054–5590 and 5331–5931 cal. yr BP, Table 4.1, Felber, 1974), the site “Mooswinkel” on the northern shore is apparently slightly younger, dating between 4260 ± 90 and 4560 ± 100 ^{14}C yr BP (4525–5213 and

4883-5576 cal. yr BP, Table 1, Felber, 1975; Felber and Pak, 1973).

Table 4.1. Radiocarbon dates obtained from remnants of Neolithic lake-dwellings in Lake Mondsee. Conventional ^{14}C ages (Felber, 1970, 1974, 1975, 1985; Felber and Pak, 1973) were calibrated using OxCal 4.1 (Ramsey, 1995, 2001, 2009) with the IntCal09 calibration dataset (Reimer et al., 2009).

Sample	**Location**	**Dated material**	**Conventional ^{14}C age (^{14}C a BP ± σ)**	**Calibrated age (cal. a BP, 2σ range)**
VRI-250	Mooswinkel	pile from lake-dwelling (probably *Populus*)	4560 ± 100	4883–5576
VRI-331	Mooswinkel	pile from lake-dwelling (*Picea abies*)	4350 ± 90	4657–5294
VRI-332	Mooswinkel	pile from lake-dwelling (*Picea abies*)	4260 ± 90	4525–5213
VRI-333	Mooswinkel	pile from lake-dwelling (*Picea abies*)	4430 ± 110	4826–5445
VRI-311	Scharfling	pile from lake-dwelling (*Picea abies*)	4940 ± 120	5331–5931
VRI-312	Scharfling	pile from lake-dwelling (*Acer pseudoplatanus*)	4870 ± 100	5326–5891
VRI-313	Scharfling	pile from lake-dwelling (*Fagus sylvatica*)	4660 ± 90	5054–5590
VRI-314	Scharfling	pile from lake-dwelling (*Picea abies*)	4780 ± 90	5312–5707
VRI-823	See	pile from lake-dwelling (undetermined)	4660 ± 80	5062–5589
VRI-37	See	pile from lake-dwelling (undetermined)	4910 ± 130	5325–5920
VRI-68	See	pile from lake-dwelling (undetermined)	4750 ± 90	5306–5653
VRI-119	See	pile from lake-dwelling (undetermined)	4800 ± 90	5319–5714

Interestingly, while archaeological and palaeobotanical studies have proven the existence of lake-dwellings until the Early and Middle Bronze Age at other lakes in the European Alps (e.g. Billaud and Marguet, 2005; de Marinis et al., 2005; Magny, 1993; Magny et al., 2009; Menotti, 2004; Pétrequin et al., 2005), no lake-dwellings younger than the Neolithic have been discovered at Lake Mondsee so far (Ruttkay et al., 2004). This observation is in general agreement with the widely observed Late Neolithic decline of lake-dwellings in the Alpine region, for which a climate deterioration towards wetter conditions, probably aggravated by socio-economic changes has been proposed to be the cause (Magny, 2004; Menotti, 2009). However, an attention-grabbing article in a popular magazine recently suggested a single catastrophic rock fall event and a subsequent tsunami as a likely cause for the abrupt abandonment of the lake-dwellings at Lake Mondsee (Schulz, 2008). Although this hypothesis can be clearly rejected from an archaeological perspective (Breitwieser, 2010; Offenberger, 2012), previous investigations on the morphology of the lake and the catchment close to the outlet provided indeed evidence for landslide deposits in the riverbed connecting Lake Mondsee and Lake Attersee (Janik, 1969). Nevertheless, the exact timing of these deposits and particularly the proposed connection to the abandonment of the Neolithic lake-dwellings are highly questionable. Hence, further investigations are necessary to unravel the possible influences of climate conditions but also other factors on the decline of the Neolithic Mondsee Culture.

4.4 *Methods*

Fieldwork

Two overlapping piston cores and three short gravity cores were retrieved from the southern basin of Lake Mondsee (coring site at 47°48’41’’N, 13°24’09’’E, 62 m water depth; Fig. 4.1) in June 2005 by using UWITEC coring devices. All cores were subsequently opened, photographed and lithostratigraphically described on-site in a specially installed field lab. The 2-m-long segments of the two piston cores and the gravity cores were then visually correlated by using distinct lithological marker layers, resulting in a ca. 15 m long continuous composite profile, which covers the complete Holocene and Lateglacial sedimentation history of Lake Mondsee (for further details see Lauterbach et al. (2011)).

Sediment microfacies analysis and microscopic varve counting

A continuous set of large-scale petrographic thin sections was prepared from a series of overlapping sediment blocks (100×20×10 mm) taken from the sediment cores of the composite profile, following the method described by Brauer et al. (1999). Thin sections were examined for detailed sediment microfacies analysis under a ZEISS Axiophot polarisation microscope at 25–200× magnification. In addition, aiming at establishing a varve chronology for the Lake Mondsee sediments, continuous microscopic varve counting and thickness measurements were carried out in the distinctly laminated uppermost part of the Holocene sediment record (0–610 cm), whereas for the lowermost part (610–1129 cm) a varve-based sedimentation rate chronology was established. A detailed description of the microfacies of the Lake Mondsee sediments and the development of the Holocene varve chronology is given by Lauterbach et al. (2011). The present study focuses on the interval between 585 and 840 cm composite depth of the Lake Mondsee sediment record. Within this interval, intercalated detrital layers were counted and their thickness was measured. For testing statistical significances of detrital layer occurrence and a better visual comparison with other proxy records a Kernel regression with bandwidths of 30 and 500 years (Mudelsee et al., 2003; Swierczynski et al., subm.) was applied to the data set.

Radiocarbon dating and calibration

The varve counting-based chronology for the Holocene part of the Lake Mondsee sediment record was additionally controlled by ^{14}C dates. Therefore, terrestrial plant macrofossils (leaf fragments, seeds, bark) found in the sediments (Table 4.2) were dated by accelerator mass spectrometry (AMS) ^{14}C dating at the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research in Kiel. All conventional radiocarbon ages were calibrated using OxCal 4.1 (Ramsey, 1995, 2001, 2009) with the IntCal09 calibration data set (Reimer et al., 2009). In order to ensure comparability and to evaluate possible relationships between Neolithic settlement activities along the shores of Lake Mondsee and climatic events recorded in the sediment core, previously published conventional radiocarbon dates from archaeological findings from the three local lake-dwelling sites (Table 1, Felber, 1970, 1974, 1975, 1985; Felber and Pak, 1973) were carefully reviewed and also calibrated with OxCal 4.1 (Ramsey, 1995, 2001, 2009) using IntCal09 (Reimer et al., 2009). All calibrated ages are reported as 2σ probability ranges.

Table 4.2. Selected AMS 14C dates obtained from terrestrial macrofossils from the Lake Mondsee sediment core. All conventional ^{14}C ages were calibrated using the OxCal 4.1 program (Ramsey, 1995, 2001, 2009) with the IntCal09 calibration data set (Reimer et al., 2009). Sample KIA32795 was rejected from age modelling with OxCal (for further explanations see the text). For a full account on radiocarbon dates from the Lake Mondsee sediment record and the primary varve-based age model see (Lauterbach et al., 2011).

Sample	Composite depth (cm)	Dated material	Carbon content (mg) / $\delta^{13}C \pm \sigma$ (‰)	AMS ^{14}C age (a BP ± σ)	Calibrated age (cal. a BP, 2σ range)
KIA36610	589.00	plant remains[b]	2.22 / -27.03 ± 0.25	3618 ± 33	3839–4070
KIA36611	604.50	plant remains[b]	0.41 / -29.03 ± 0.36	3697 ± 56	3880–4228
KIA29395	607.50	plant remains[b]	4.06 / -29.21 ± 0.04	3848 ± 26	4155–4407
KIA39229	657.00	leaves[a]	1.61 / -28.99 ± 0.09	4142 ± 31	4570–4824
KIA39230	685.00	leaves[a] & needle	2.28 / -28.77 ± 0.12	4581 ± 34	5058–5447
KIA32793	708.75	twig & bark	4.89 / -28.60 ± 0.05	4668 ± 28	5316–5566
KIA36612	732.25	wood & leaves	0.97 / -27.69 ± 0.13	4883 ± 41	5488–5715
KIA32794	782.25	leaves[a]	1.04 / -30.09 ± 0.15	5462 ± 36	6194–6310
KIA36619	818.75	plant remains[b]	1.65 / -26.55 ± 0.13	5809 ± 36	6498–6717
KIA32795	873.00	plant remains[b]	0.28 / -32.70 ± 0.23	6088 ± 104	6727–7246
KIA32796	916.50	leaves[a]	3.29 / -29.61 ± 0.09	7129 ± 36	7869–8014
KIA39231	941.00	twig	0.95 / -29.41 ± 0.12	7349 ± 48	8026–8311

Geochemical analyses

Semi-quantitative µXRF major element scanning was carried out at 200 µm resolution on impregnated sediment slabs from thin section preparation between 585 and 840 cm, using a vacuum-operating Eagle III XL micro X-ray fluorescence (µXRF) spectrometer with a low-power Rh X-ray tube at 40 kV and 300 mA (250 mm spot size, 60 s counting time, single scan line). Element intensities for Mg, Al and Ca are expressed as counts s^{-1} (cps), representing relative changes in element composition. The scanned sediment surfaces are identical to those prepared for thin sections, thus enabling a detailed comparison of high-resolution µXRF and microfacies data (Brauer et al., 2009).

4.5 Results

Chronology of the sediment record and dating of the Neolithic lake-dwellings

The chronology for the Holocene part of the Lake Mondsee sediment sequence and thus also the detrital layer record was established by combining microscopic varve counting (0–610 cm composite depth) and a varve counting-based sedimentation rate chronology (610–1129 cm composite depth; for details see Lauterbach et al. (2011)). Estimating the accuracy of the varve chronology is possible by comparing independent varve counts for the sediments encompassing ca. the last 4000 years carried out by two different examiners, which yields a maximum difference of ca. 50 years, equivalent to a counting error of less than 3% (Swierczynski et al., 2012; Swierczynski et al., subm). Hence, an uncertainty range of ±50 years (indicated in Fig. 4.2 by dashed lines) can also be considered as a reasonable error estimate for the varve chronology around the Neolithic settlement period. To further assess the reliability of the varve chronology, a supplementary age model based on AMS ^{14}C dates has been constructed. For this purpose, 12 radiocarbon dates obtained from terrestrial plant macrofossils from the interval between 550 and 950 cm composite depth were used (Table 4.2). The calibrated radiocarbon dates agree well with the varve chronology (Fig. 4.2), except one date (KIA32795), which was rejected for subsequent ^{14}C age modelling as the calibrated age is considerably younger than expected from the varve chronology. This is most probably owed to the very small sample size (Table 4.2), favouring contamination with modern carbon (Wohlfarth et al., 1998). In the following, the other 11 calibrated dates were used as input parameters for Bayesian age modelling with a P_Sequence deposition model (the model parameter k was set to 1) implemented in OxCal 4.1 (Ramsey, 2008). To avoid model inconsistencies such as unrealistically high uncertainty ranges at the upper and lower boundaries of the modelled interval, which usually occur when there are no radiocarbon dates, we chose a larger interval for ^{14}C-based age modelling (ca. 550–950 cm) than that actually under investigation (ca. 585–840 cm, ca. 4000–7000 varve yr BP). The agreement index Amodel of 69.1% for the resulting age-depth-model is fairly above the critical threshold of 60%, proving the robustness of the model (Ramsey, 1995, 2001). The comparison of the varve- and radiocarbon-based age model reveals that both models are statistically indistinguishable within their uncertainty ranges in the interval under investigation, supporting the robustness of the original varve chronology, which is hence used as the chronological framework for the sediment-derived proxy data.

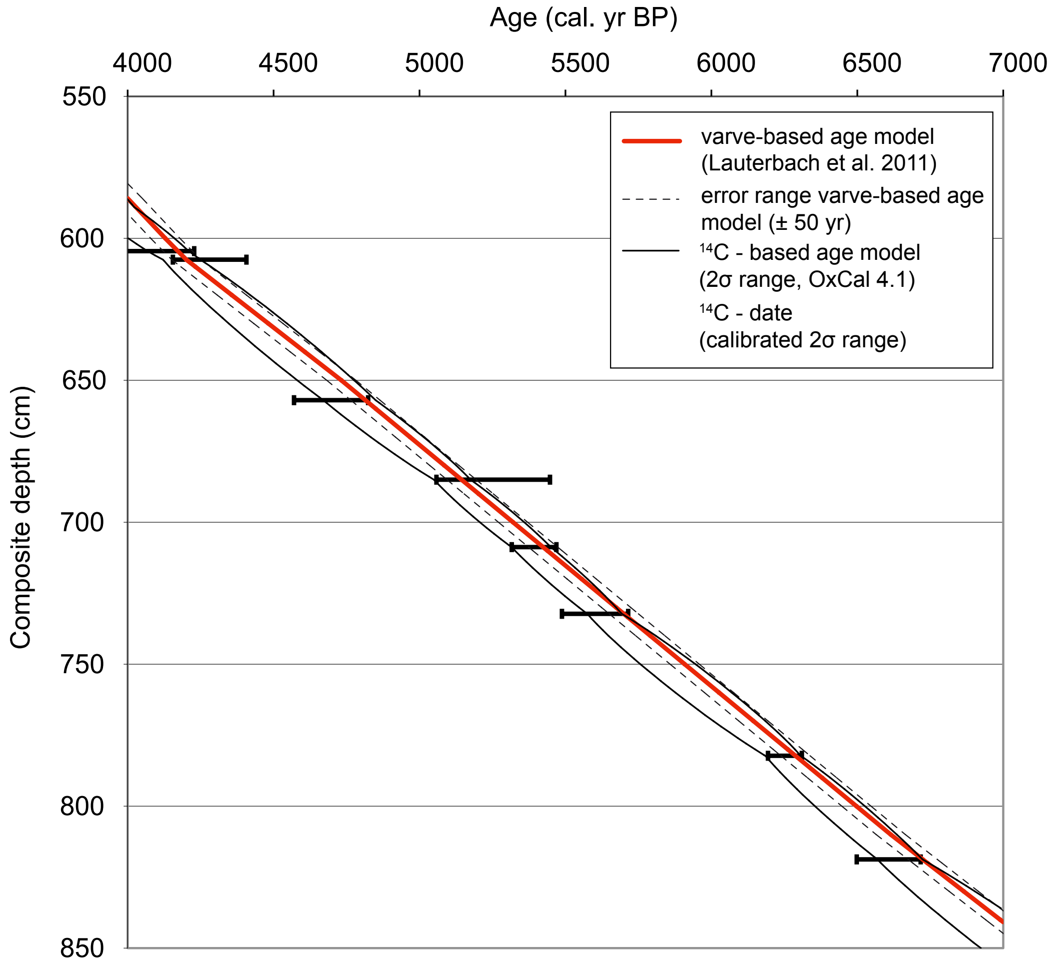

Figure 4.2. Comparison of the primary varve-based age model (given with a counting uncertainty of ±50 years as dashed lines) of the Lake Mondsee record (Lauterbach et al., 2011) and a secondary radiocarbon-based age model (2σ probability range in grey), which has been established using OxCal 4.1 (Ramsey, 1995, 2001, 2008) to evaluate the reliability of the varve chronology. Individual AMS ^{14}C dates from terrestrial plant macrofossils, which are included in the radiocarbon-based age model are given with their 2σ probability ranges.

In order to evaluate the chronology of the Neolithic settlements at Lake Mondsee, we used 12 published conventional radiocarbon dates (Table 4.1, Felber, 1970, 1974, 1975, 1985; Felber and Pak, 1973), which were obtained from wooden artefacts from the three subaquatic lake-dwelling sites during previous archaeological surveys. In order to model the settlement phases of the three individual sites, the calibrated dates were used as input parameters for a Phase model implemented in OxCal 4.1 (Ramsey, 2009). As a result, the two settlements "Scharfling" and "See" on the southeastern and southern lake shore apparently existed almost contemporaneously (Fig. 4.3) from 5594 ± 167 to 5505 ± 111 cal. yr BP and from 5448 ± 134 to 5369 ± 147 cal. yr BP, respectively. In contrast, the site "Mooswinkel" appears to have been established slightly later (ca. 5167 ± 244 cal. yr BP) than the two other sites. The upper age boundary of the “Mooswinkel” settlement phase is dated to 5003 ± 351 cal. yr BP, a time when the two other sites apparently were already abandoned. Concerning the assessment of the reliability of the dating of the settlement phases, it should be mentioned that the wooden lake-dwellings from whose remnants the dated samples have been obtained likely existed not longer than a few decades after their construction (and the cutting of the trees, which is given by the radiocarbon age) and then were repaired or replaced by new buildings (Schlichtherle, 2004). Hence the radiocarbon dates are expected to reflect approximately also the time of the abandonment of a wooden construction within the dating uncertainty.

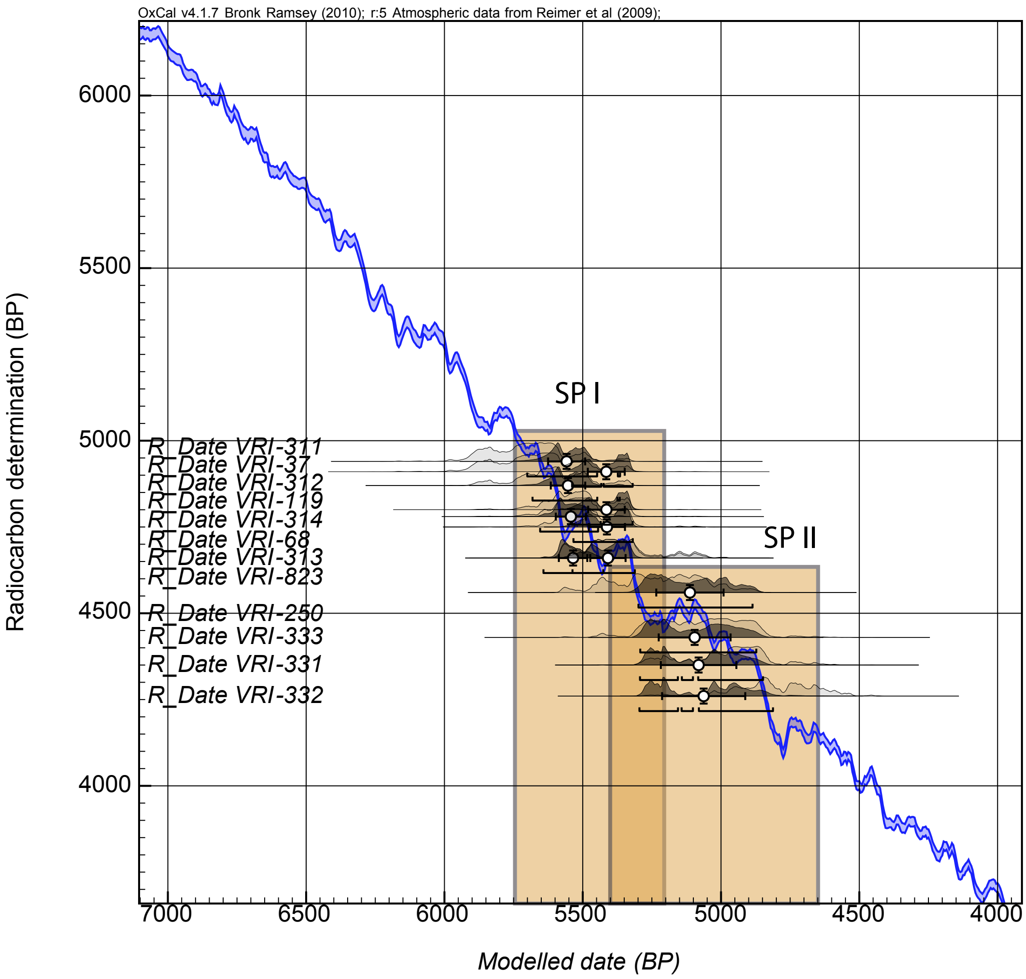

Figure 4.3. Chronology of settling phases at Lake Mondsee. Twelve published AMS radiocarbon dates from three Neolithic lake-dwelling sites (”See”, “Scharfling” and “Mooswinkel”) were calibrated and used as input parameters for phase modelling with OxCal 4.1 (Ramsey, 2009). Two different settling phases can be distinguished: SP I from ca. 5750 to 5200 cal. yr BP and SP II from ca. 5400 to 4650 cal. yr BP.

Sediment microfacies and geochemical properties

The Holocene sediments of Lake Mondsee are composed of varved calcite mud (Lauterbach et al., 2011; Schmidt, 1991) with frequently intercalated detrital layers. As revealed from µXRF data, the light sub-layers are enriched in Ca (Fig. 4.4B), resulting from endogenic calcite precipitation after spring/summer algae bloom. In contrast, the dark sub-layers are enriched in siliciclastic elements (e.g. Ti), reflecting clastic sediment deposition during autumn/winter. Two types of detrital layers can be distinguished within the Lake Mondsee sediments (Swierczynski et al., 2012). Thick (0.9–32.0 mm) and mainly graded detrital layers reflect local debris flow events. The enrichment of Mg, indicative for dolomitic rocks, and low contents of siliciclastic elements (e.g. Ti) reveal the Northern Calcareous Alps as the source region. In contrast, thin detrital layers (0.05-1.7 mm) are non-graded and composed of both, siliciclastic and dolomitic components, thus revealing sediment delivery from both the northern and southern part of the catchment by regional-scale flood events. Thick detrital layers from flood events reveal a higher abundance and also increased thicknesses between 665 and 800 cm, whereas for debris flow-related layers no clear clustering can be observed. Increased Ti counts characterize the interval between 670 and 715 cm (4968-5497 varve yr BP), whereas Mg is enriched between 630 and 665 cm (4909-4482 varve yr BP) (Fig. 4.4A).

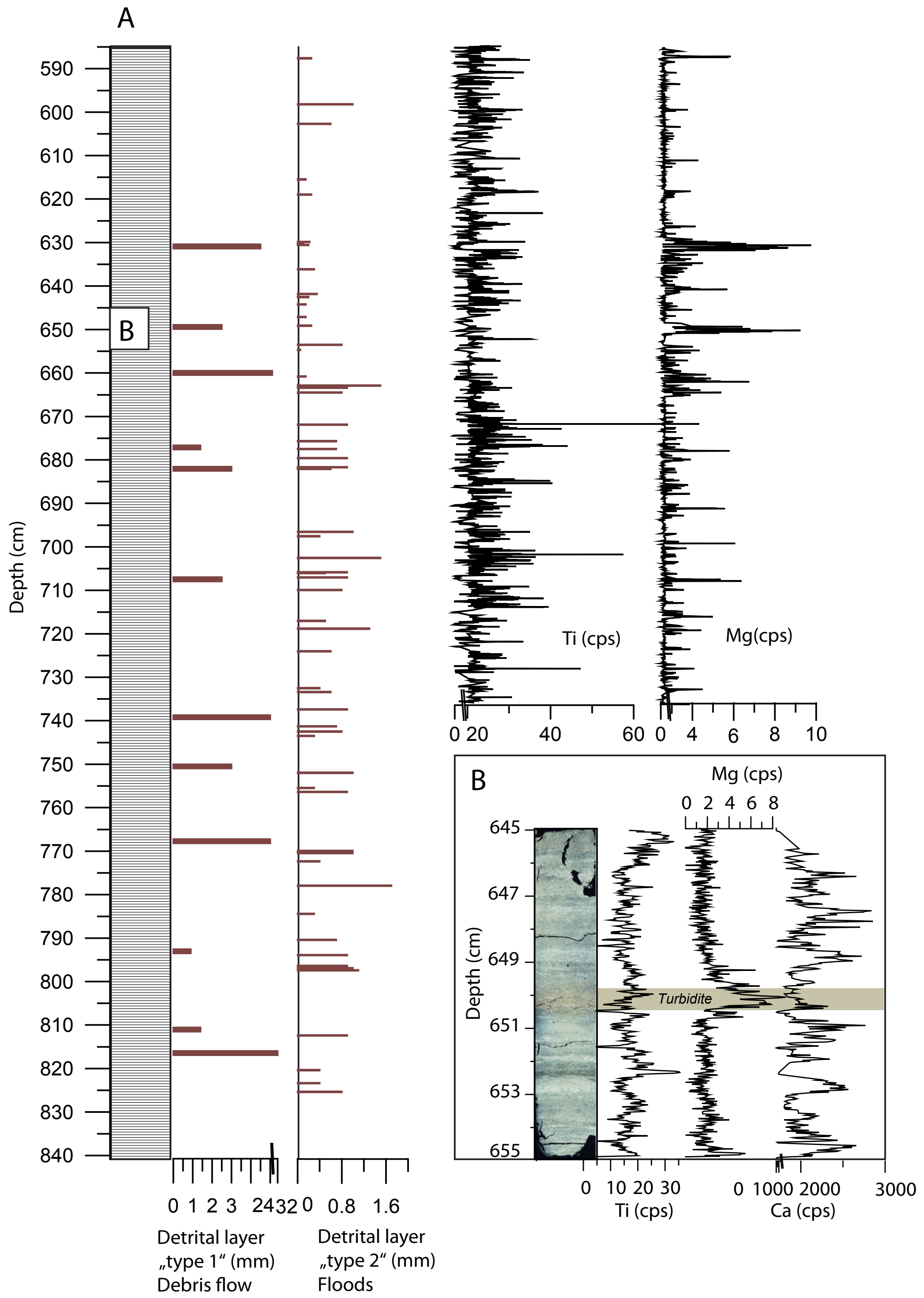

Figure 4.4. Sediment data. (A) Lithology of the sediment core covering the interval between 585 and 840 cm with complementing detrital layer record (for further explanations see the main text) and µXRF element scanning data for titanium (Ti) and magnesium (Mg) for the interval between 585 and 736 cm. (B) Sediment microfacies as revealed from a thin section (645–655 cm) with a turbidite (detrital layer type 1) and corresponding µXRF data for Ti, Mg and Ca.

Flood and debris flow deposition

By combining sediment microfacies and geochemical analyses, a total of 60 flood and 12 debris flow layers could be detected within the investigated interval between 585 and 840 cm composite depth (ca. 4000–7000 varve yr BP; Fig. 4.5). The mean recurrence of floods during this 3000-year interval is ca. 67 years, while debris flows have a mean recurrence interval of ca. 333 years. Although anthropogenic land use is commonly regarded to influence erosion processes in the catchment, detrital layer deposition in Lake Mondsee has been shown to be mainly climate-controlled, even during recent times when human impact in the catchment was likely much more intense than during the Neolithic (Swierczynski et al., 2012).

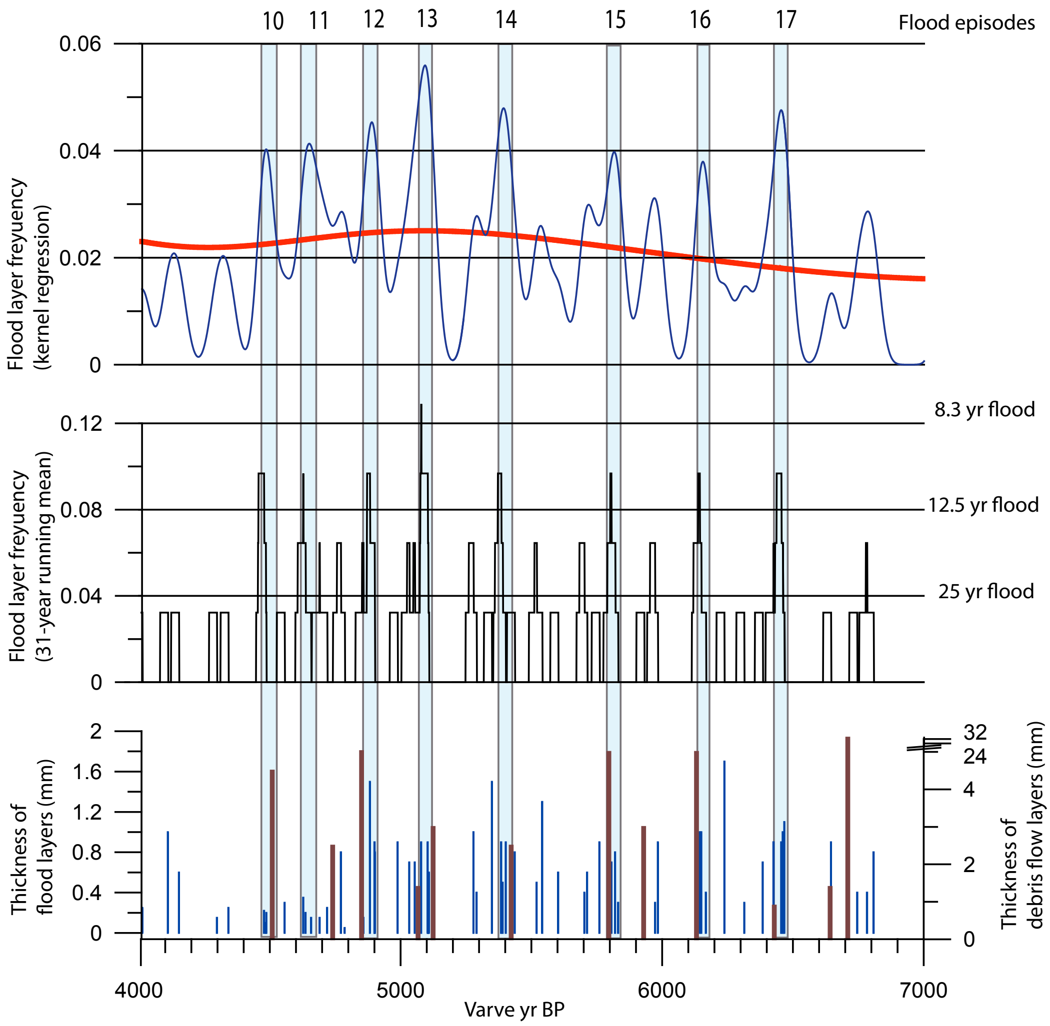

Figure 4.5. Thickness of debris flow (detrital layer type 1) and flood layers (detrital layer type 2). Flood layer frequency as calculated by a 31-year running mean and kernel regression with different bandwidths (blue line: 30 years, red line: 500 years). Eight main flood intervals (FE 10 to FE 17) are identified according to multi-decadal flood recurrence.

On a multi-centennial to millennial time scale (kernel bandwidth of 500 years), the flood activity is highest (mean flood recurrence of 40–50 years) between ca. 5900 and 4450 varve years BP compared to the whole interval under investigation (Fig. 4.5). By using a kernel bandwith of 30 years, eight distinct episodes of increased flood frequency (FE 10 to FE 17; flood episodes FE 1 to FE 9 during the period younger than ca. 4000 varve yr BP are described in detail in Swierczynski et al. (2012) and Swierczynski et al. (subm.), each of ca. 50 years duration and with flood recurrence rates of ~10 years can be been identified in the Neolithic Lake Mondsee sediment record: FE 10 (4450–4500 varve yr BP), FE 11 (4650–4700 varve yr BP), FE 12 (4850–4900 varve yr BP), FE 13 (5050–5120 varve yr BP), FE 14 (5380–5420 varve yr BP), FE 15 (5800–5850 varve yr BP), FE 16 (6120–6170 varve yr BP) and FE 17 (6420–6470 varve yr BP). While floods have a recurrence of mainly >31 years prior to ca. 5900 varve yr BP, only interrupted by two major multi-decadal flood episodes (FE 16 and 17), flood activity clearly increased between 5900 and 4450 varve years BP, revealing six distinct flood episodes (FE 10 to 15) with flood recurrence rates of 10–16 years. Particularly the interval between ca. 5150 and 4500 varve years BP is characterized by frequent flood episodes (four FE within ca. 650 years) with high flood recurrence (<10 years). The period younger than 4450 varve years BP shows, compared to the interval 5900–4450 varve yr BP, a relatively low flood activity with recurrence rates of 31 years or more.

4.6 Discussion

According to phase modelling with OxCal 4.1 (Ramsey, 2009) for the available radiocarbon dates from the three archaeological sites at Lake Mondsee, two settling phases can be distinguished. The first settling phase (SP I; Fig. 4.3), incorporating the sites “Scharfling” and “See” at the southern and southeastern shores of Lake Mondsee, respectively, lasted from ca. 5750 to 5200 cal. yr BP, while the second settling phase (SP II), represented by the settlement “Mooswinkel” at the northern shore, lasted from ca. 5400 to 4650 cal. yr BP. In addition to these chronological and spatial disparities, also a diverging construction technique distinguishes the two settling phases. While the lake-dwellings of SP I were constructed on wetlands with the basement of the houses being probably only ca. 20-30 cm above the ground (Offenberger, 1989; Ruttkay, 2003), those of SP II were built on piles, likely indicative for buildings standing in the water (Offenberger, 1986, 2012). In the following, the settlement history is compared with the observed decadal- to centennial-scale flood variability and regional-scale climatic changes.

Although climate in the Central Alps is generally regarded warmer and drier than today between ca. 10 500 and 3300 cal. yr BP (Ivy-Ochs et al., 2009), there is indication from pollen (Bortenschlager, 1970), tree-line (Nicolussi et al., 2005), lake-level (Magny, 2004) and glacier records (Holzhauser, 2007; Holzhauser et al., 2005; Ivy-Ochs et al., 2009) that this period was punctuated by several regional-scale climate deteriorations. In this context, the slight increase in flood variability at Lake Mondsee after ca. 6500 varve years BP and particularly the more pronounced clustering of flood events after ca. 5900 varve years BP are in good agreement with a phase of wetter and colder climate conditions in the Alps between 6300 and 5500 cal. yr BP, the Rotmoos I cold oscillation (Bortenschlager, 1970; Patzelt, 1977). Also the peaking flood activity in Lake Mondsee around 5100 varve years BP is synchronous to a regional-scale cold/wet phase, the Rotmoos II oscillation (Bortenschlager, 1970; Patzelt, 1977), which lasted from ca. 5400 to 5000 cal. yr BP. This climate deterioration is also reflected by the burial of the Neolithic ice man from the Similaun by advancing glaciers, dated to ca. 5300–5050 cal. yr BP (Baroni and Orombelli, 1996; Bonani et al., 1994), revealing the regional significance of this short-term cold/wet event across the Alps. Increased precipitation and lake-level highstands due to climate deterioration during these intervals and possible consequences for Neolithic lake-dwellings have also been reported from other sites in Switzerland, Italy and France (Magny, 2004; Magny et al., 2006). Increased flood activity at Lake Mondsee between ca. 5900 and 4500 varve years BP is furthermore in good correspondence with cold and wet climate conditions reported from the Austrian Central Alps for the periods between 5800 and 5400 cal. yr BP and around 5100 cal. yr BP (Schmidt et al., 2009; Schmidt et al., 2006). A drier episode around 5200 cal. yr BP in the Central Austrian Alps (Schmidt et al., 2009) is likely equivalent to the period of low flood recurrence in Lake Mondsee between FE 13 and 14.

Although an increase in flood frequency in the Lake Mondsee record is already visible after ca. 5900 varve yr BP, the first lake-dwellings of SP I were apparently established during a period of relatively low flood recurrence around 5750 cal. yr BP. Considering that flood-related lake-level changes of up to 3 m within a few days have been observed at Lake Mondsee during the last century (Swierczynski et al., 2009), the lake-dwellings “Scharfling” and “See”, which were both constructed directly on the southern wetland plains, should be expected to be particularly vulnerable to increased flood risk after ca. 5900 varve yr BP. However, both lake-dwelling sites existed even during this interval, which culminated during FE 14 around 5400 varve yr BP (Fig. 4.6), and beyond. The abandonment of the SP I lake-dwellings (5505 ± 111 cal. yr BP at site “Scharfling”, 5369 ± 147 cal. yr BP at site “See”) apparently only occurred around 5200 cal. yr BP, during an interval of relatively low flood risk after FE 14. Hence, a causal relation between increased flood risk and both the change in the settlement location and the construction type cannot be definitely verified. In addition to flood risk, both settlements must also have been vulnerable to the effects of hydrologically triggered surface erosion processes, i.e. debris flows, after strong precipitation events as they were located close to the steep slopes of the Northern Calcareous Alps (maximum slope of 34% in the Kienbach creek and cascades of up to 60 m close to the settlement “Scharfling”; personal communication Wildbach- und Lawinenverbauung), which are the source of local debris flows. Such erosion events are documented for recent times (Swierczynski et al., 2009) and also occurred during the Neolithic settlement period (Fig. 4.3), but since there is no significant clustering of debris flows around the time of

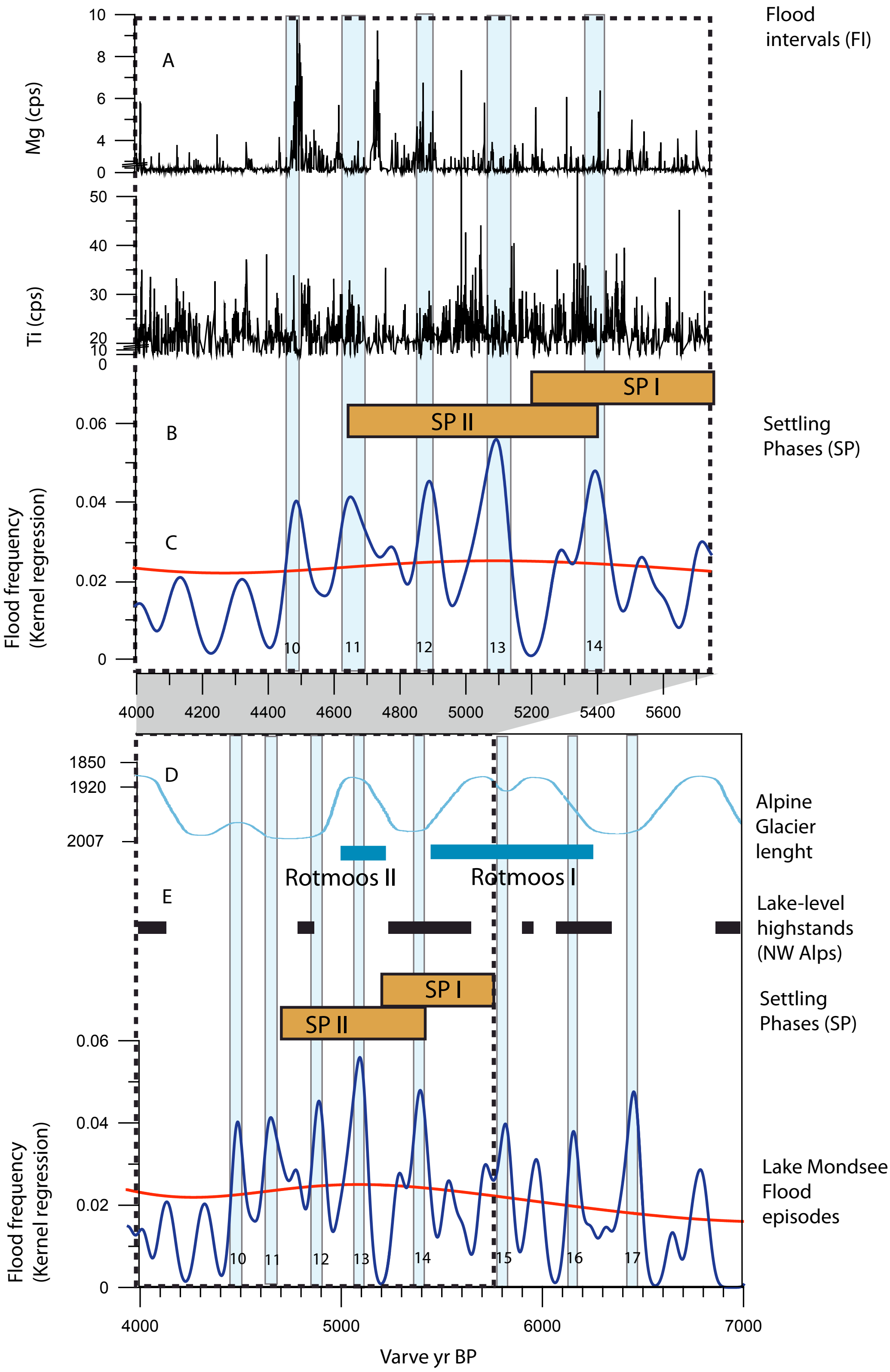

Figure 4.6. Comparison of Lake Mondsee sediment data and identified flood episodes (FE 10 to FE 17) with other proxy data. (A) μXRF element scans for Ti and Mg from Lake Mondsee sediments. (B) Settling phases SP I and SP II. (C) Flood occurrence (Kernel regression with 30 (blue) and 500 years (red) bandwidth). (D) Alpine glacier lengths (Holzhauser, 2007) and phases of the Rotmoos Oscillation (Bortenschlager, 1970). (E) Lake-level highstands in the NW Alps (Magny, 2004).

the abandonment of the lake-dwellings at the southern shores of Lake Mondsee, a causal connection between both can be excluded. In summary, there is no clear indication that either increased flood risk or debris flow activity triggered the end of SP I at Lake Mondsee. However, evidence that hydrological changes other than floods or debris flows could have indeed influenced the end of SP I comes from a sediment core obtained close to the settlement "See". Abundant clastic Flysch material, deposited below the cultural horizon and dated to 5055–5661 cal. yr BP, as well as erosion marks have been interpreted as indicators for a transgression phase and lake-level oscillations during the settlement phase (Schmidt, 1986). Probably the abandonment of the settlement "See" around 5369 ± 147 cal. yr BP was related to this transgression phase, as this site has been constructed on the flat wetland plain at the lake outlet, which experiences flooding when the lake-level increases. As highlighted by Schmidt (1986), the construction of the lake-dwellings indicates that they might have been able to sustain the normal annual lake-level oscillations and even small-scale floods but not a permanent lake-level increase of more than ca. 1 m.

Despite the evidence from several climate archives for significant climatic changes in the Alpine region during the second half of the fourth millennium BC and an apparently closely corresponding increase in flood risk at Lake Mondsee, the contemporaneous abandonment of the lake-dwelling sites "Scharfling" and "See", and the subsequent shift of Neolithic settlement activity to the northern shore of Lake Mondsee is not necessarily attributable solely to climatic changes. Although the onset of the second settling phase (SP II) at the site "Mooswinkel" falls within an interval of increased flood activity, incorporating the prominent flood episodes FE 11, 12 and 13, and the shift in the location as well as the construction of the "Mooswinkel" buildings on piles upon the water might hence be interpreted as a possible adaptation to increased flood risk or lake-levels, archaeological investigations suggest that these lake-dwellings might have rather been constructed for a special purpose (a ferry landing, Ruttkay et al., 2004) than being a consequence of increased flood risk. However, geochemical analyses on the Lake Mondsee sediments reveal a change from predominantly siliciclastic sediment supply, reflecting rather regional scale flooding, to enhanced dolomitic sediment supply, reflecting more frequent local runoff events from the Northern Calcareous Alps (close to the SP I settlements) at about 5000 varve yr BP. At this time no lake dwelling was re-established at Site "Scharfling" or "See" at the southern lake shorelines. This indicates that changing/increasing flood risk might have played a role in the changed settlement strategy of the Mondsee Culture but was certainly not the only cause. Other possible influences might have been socio-cultural changes (Magny, 2004) or a climate-induced general lake-level increase, which has been proposed from sedimentological observations close to the site "See" (Schmidt, 1986) but is also seen in other Alpine lake records (Magny, 2004; Magny et al., 2006) during the respective interval between ca. 5650 and 5200 cal. yr BP. However, this remains speculative and further research is necessary to clarify this.

Concerning the final abandonment of lake-dwellings at Lake Mondsee and the decline of the Mondsee Culture, equivalent to the end of SP II at the site "Mooswinkel" around 4650 cal. yr BP, increased flood risk was most likely not the main trigger as flood frequency was already high during the establishment of this settlement and the shift to more regional-scale floods around 5000 varve yr BP with frequent input of siliciclastic material from the Flysch hills indicating higher precipitation (Swierczynski et al., 2012) that must have affected also this site. Moreover, there is no indication for a re-appearance of lake-shore settlements after ca. 4450 varve years BP, when flood risk in the Lake Mondsee region decreased. Hence, changes in flood risk might have influenced the Late Neolithic communities at Lake Mondsee to a certain degree but clearly did not cause the decline of the whole culture. More likely a complex interplay of climatic and socio-cultural changes (Magny, 2004) and/or a change in the subsistence strategy (Menotti, 2003, 2009), e.g. hinterland migration or the beginning of alpine pasturing during the Late Neolithic (Bortenschlager and Oeggl, 2000), caused the abandonment of the lake-dwellings.

Besides the possible climatic influence, also a single catastrophic rockfall event has been proposed to have caused the abrupt abandonment of the lake-dwellings, at least at the southern shores of Lake Mondsee (Schulz, 2008). However, in contrast to the hypothesis of increased flood risk or a rising lake-level, which cannot be absolutely excluded, such a catastrophic event can be clearly rejected as the cause for the decline of the Neolithic Mondsee Culture from archaeological (Breitwieser, 2010; Offenberger, 2012) and sedimentological evidence. Within the whole investigated sediment sequence, there is no indication for a prominent event layer other than the normal mm- to cm-scale flood and debris flow layers that might be related to a large rockfall/landslide event. Such event must have supplied large amounts of suspended detrital material into the lake and thus should be reflected by a turbiditic event layer of outstanding thickness in the sediment record as shown for earthquake-related (Chapron et al., 1999; Fanetti et al., 2008; Lauterbach et al., 2012) or gravitationally triggered mass wasting deposits (Girardclos et al., 2007; Schnellmann et al., 2005), but there is none such layer or indication for mass movements, rock falls or a hiatus in the entire lake sediment record. Hence, a single exceptional flood, debris flow or rock fall event can be rejected as the cause for the decline of the Neolithic Mondsee Culture.

4.7 Conclusions

We investigated the recurrence of extreme hydro-meteorological events (local debris flows and regional floods) in the sediment record of Lake Mondsee (Upper Austria) during the interval of Neolithic settlement activity between 4000 and 7000 varve years BP. Increased abundance of flood events characterizes the interval between ca. 5900 and 4450 varve yr incorporating five flood episodes of ca. 50 year duration (FE 11 (4650–4700 varve yr BP), FE 12 (4850–4900 varve yr BP), FE 13 (5050–5120 varve yr BP), FE 14 (5380–5420 varve yr BP), FE 15 (5800–5850 varve yr BP). This time is featured by a significant change in the Neolithic settlement strategy from lake-dwellings built on the wetlands at the southern and southeastern shores of Lake Mondsee (5750–5200 cal. yr BP) to lake-dwellings built on piles upon the water at the northern lake shore (5400–4650 cal. yr BP). The observed changes in settlement strategy at Lake Mondsee correspond to a general and most probably climate-related decline of Neolithic settlements in the Alpine region between 5650 and 5200 cal. yr BP. Increased flood risk at Lake Mondsee during this interval is in agreement with highly variable lake-levels and also glacier advances during the Rotmoos cold oscillations, indicating colder and wetter climate conditions in the Alpine region. However, although the Lake Mondsee sediment record shows evidence of enhanced flood risk during the Neolithic, this is unlikely to be the only cause for the change in settlement strategy around 5300 cal. yr BP. More likely a combination of several factors, including increased flood recurrence, a rising lake-level but probably also socio-economic changes was responsible for the observed shift in human activity. Additionally, the final decline of the Mondsee Culture around 4650 cal. yr BP cannot be related solely to climatic changes because flood risk decreased after ca. 4500 varve yr BP but no new settlements were established thereafter. In order to better understand the effects of climate variability on pre-historic lake-dweller societies, more highly resolved lake sediment records, which consider regional and seasonal peculiarities of climate development as well as more interdisciplinary research between archaeologists and palaeoclimatologists are needed.

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Chapter 5

Summary

Annually laminated lake sediments provide a large potential for paleoflood reconstruction, because these archives enable precise dating of the sediments and the annual (seasonal) reconstruction of environmental conditions and processes (Brauer et al., 2009). Within my thesis I analyzed detrital layer deposition in varved sediments of Lake Mondsee throughout the last 7000 years in order to establish a continuous runoff chronology for the past. For that, I carried out a novel methodological approach based on combination of microfacies analyses and geochemical and geophysical methods (µXRF, magnetic susceptibility). Using a precise chronology provided by varve counting of sediments of Lake Mondsee, my investigation focused on the sedimentary imprint of debris flows and floods (**5.1**); the variability of runoff events under changing climate boundary conditions on millennial to multi-decadal timescales (**5.2**); and the flood variability during the Neolithic (**5.3**).

Within this chapter, I present the main results of three individual articles (Chapters 2–4). Finally, I draw conclusions for Lake Mondsee sediments as an flood archive (**5.4**) and provide an outlook for future research (**5.5**).

5.1 The sedimentary imprints of flood and debris flow events

Detrital layers intercalated within Lake Mondsee sediments during the last 100 years show distinct geochemical compositions and microfacies that allows distinguishing between different deposition mechanism of detrital layers by debris flows and floods (Fig. 5.1, see further information in Chapter 2 and Appendix A). Detrital layers enriched in Ti and Mg, range in thickness between 0.05 and 6 mm and show a basin wide distribution with higher thickness in the northern lake basin (0.1-8 mm) and lower thickness in the southern lake basin (0.05-1.4 mm). These ranges in thickness indicate a significant proximal to distal pattern with a sediment transport from the northern lake catchment, which is predominantly composed of siliciclastic Flysch sediments (Detrital layer type1/DL type 1). The main tributary “Griesler Ache” (syn.: Fuschler Ache) is supposed to supply most of the clastic material from the Flysch sediments during flood events. These layers are composed of siliciclastic Flysch sediments and were deposited within the entire basin of Lake Mondsee during flood events by the tributary Griesler Ache with a predominant sediment transport from the North to the South. In contrast, detrital layers enriched in Mg (counts > 4 cps), range in thickness between 0.2 and 25 mm, are graded and occur only in the southern part of the lake basin. High variability in thickness (0.3–25 mm) occurs within sediment cores nearby the river Kienbach (ca. 0.4 km), whereas thinner detrital layers (0.2–1 mm) occur within distal coring positions to the river Kienbach (ca. 0.8 km). This proximal to distal pattern, in addition to Mg enriched clastic sediments reveal a dolomitic provenance of the sediments from the Northern Calcareous Alps. Due to high thickness variability and gradation, these layers reflect turbidites with large sediment concentration delivered by debris flow deposits from the Kienbach river as documented for a historical debris flow on 18. July 1986.

Because of distinguished runoff processes, Ti together with Mg peaks can be used as an indicator of high-magnitude spring and summer floods, whereas only Mg peaks higher than 4 cps indicate the occurrence of local debris flows events (1923, 1941 and 1986). Additionally, detrital background sediments as reflected by Ti counts (equal to PC1, explaining 52 % of the total variability of the dataset) can be used as a proxy for changes the amount of runoff and ultimately for lake water level oscillations (total ratio of three-days lake water level).

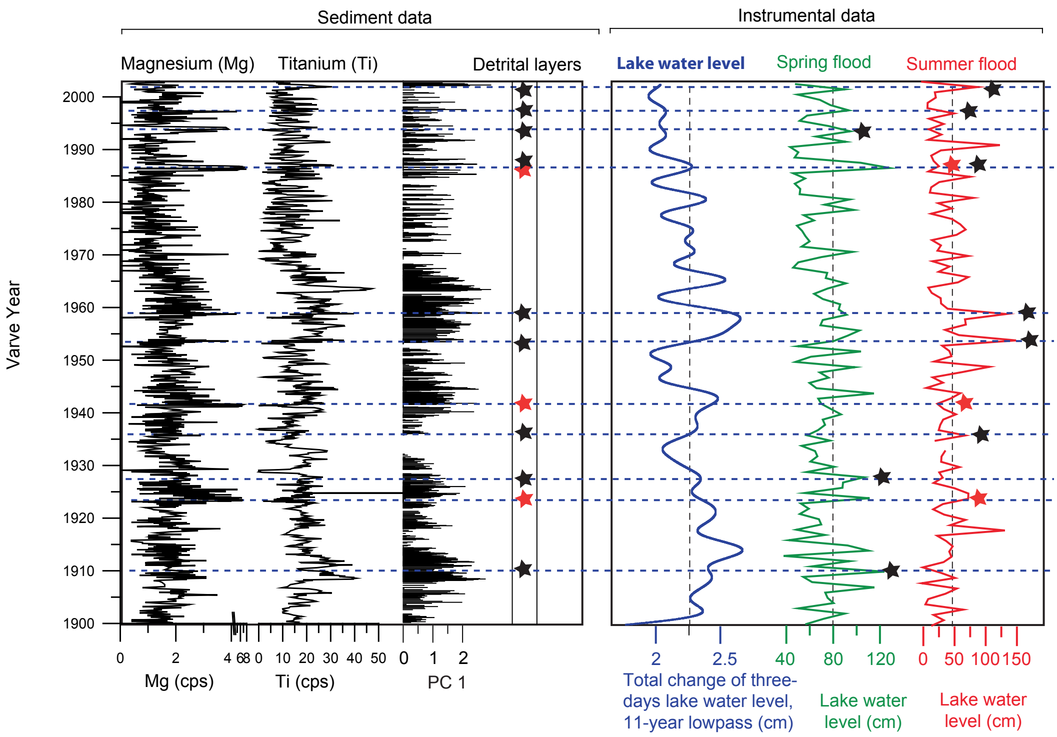

Figure 5.1. Sediment data from Lake Mondsee sediments (Mo-05P3) versus lake water level from Lake Mondsee of the last 100 years. PC1 indicates the siliciclastic material supply (Ti, K, Al, Si) that well corresponds to the total change in three-days lake water level (11-year lowpass) indicating changes in runoff. Debris flow layers (red stars) occurred in summer during years of low summer floods, whereas flood layers (black stars) are formed during spring or summer floods.

The detailed intra-basin short core correlation shows that surface sediments near the main inflowing river in the western part of Lake Mondsee (Griesler Ache) comprise 31 distinct detrital flood layers, whereas sediments in a more distal position from the river Griesler Ache (ca. 3 km) include nine distinct detrital flood layers and additional three debris flow layers for the last 100 years. The flood layers within the sediments of the distal location are related to three spring floods (1910, 1928, 1994) and six summer floods (1936, 1954, 1959, 1986, 1997, 2002). These basin wide distributions of these flood layers indicate inter- and overflowing processes of sediment particles (Sturm and Matter, 1978), which are delivered by flood events. However, while extreme summer floods are recorded within cores of a distal coring position from the main river input, infrequent autumn and winter floods are not documented within these coring sites. This is most likely due to reduced or absent inter- and overflows as a cause of a mixed water column and/or the predominance of high-density currents in autumn/winter. Thus, sediment particles may not reach the distal coring sites, but are preferably deposited near the river delta. Other case studies also consider different seasonal sediment budgets because of changing catchment characteristics, which influence the mobility of soils, such as vegetation and soil moisture (Richards, 2002). At this point, I can only speculate about the reasons for a spring/summer runoff record in Lake Mondsee. However, the hypotheses about distinguished sediment transport in the catchment and lake system should be furthermore tested in future studies.

For the last 100 years, Ti shows a good correlation (r = 0.34) with annual precipitation of the climate station Kremsmünster, located in ca 70 km distance from Lake Mondsee (Fig. 5.2), suggesting a siliciclastic sediment input from the catchment that is mainly contrrolled by precipitation, and thus can be used as a long-term proxy.

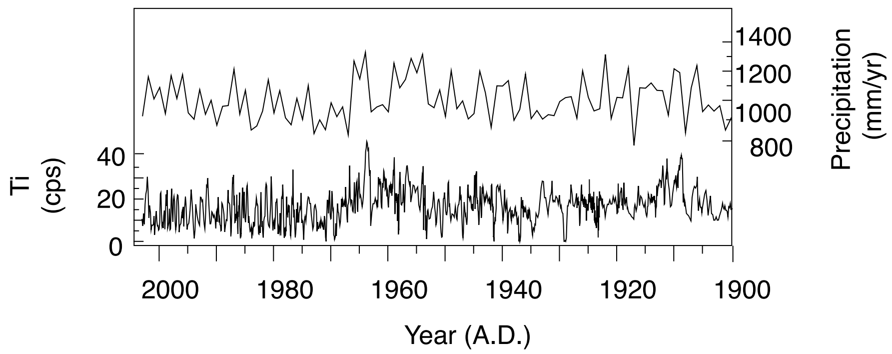

Figure 5.2. Annual mean of Ti counts anchored to the varve chronology and annual precipitation from meteorological station of Kremsmünster with a correlation r= 0.34.

5.2 Flood variability on various timescales

The 7000-year record of spring/summer flood and debris flow deposits preserved in the Lake Mondsee sediments reveals a clear non-stationarity of runoff events through time. However, variability of floods and debris flows occurs not only on multi-decadal time scale, but shows also variations on a millennial time scales throughout the last 7000 varve yr (Fig. 5.3). The flood frequency was lowest during the mid-Holocene (~ 7000–3500 varve yr BP). A period of modest increase prevailed between ~3500–1500 varve yr BP. A general trend towards higher runoff events occurred during the last 1500 varve years. This millennial-scale pattern is observed from European riverine and paleoflood records in Great Britain (Macklin et al., 2010), Poland (Starkel et al., 2006), Spain (Macklin et al., 2006; Thorndycraft and Benito, 2006), Germany (Hoffmann et al., 2008) and the alpine realm (Debret et al., 2010). Although these studies report different onsets of flood activity ranging from 2800 to 1500 cal. yr BP, increased European flood activity is contemporaneous with an overall advance of main alpine glaciers with largest advances during the LIA (Ivy-Ochs et al., 2009, chapter 3).

Additionally, this millennial scale increase in flood activity is accompanied by multi-decadal scale flood episodes mainly lasting 30–50 years with a flood recurrence time of ca 4–6.6 years and ca 90 years for debris flows (Fig. 5.3). During the last 4000 years, highest flood frequencies occur during flood episodes (FE) 430–470 (FE1), 620–650 (FE2), 780–810 (FE3), 1200–1250 (E4), 1310–1360 (FE5), 1470–1500 (FE6), 1950-2100 (FE7), 2700–2800 (FE8) and 3250–3350 varve yr BP (FE9) (see further information in Chapter 2 and 4). Lowest flood activity is detected during the Roman climatic optimum (0–200 AD) as well as during the Maunder Minimum (ca AD 1645–1715), the coldest stage within the Little Ice Age. Flood-poor episodes are more frequent prior to 3500 varve yr BP. The reconstruction of flood events from the Lake Mondsee sediments during the last 4000 years reveals increased frequency of extreme summer floods in transition from warmer to colder phases as indicated by centennial-scale alpine glacier advances (Ivy-Ochs et al., 2009, chapter 3).

The transition into the LIA is characterized by substantial changes in atmospheric circulation patterns in Central Europe (Jacobeit et al., 2006) that is accompanied with a more negative North Atlantic Oscillation (NAO) (Trouet et al., 2009) and possibly affected enhanced spring/summer floods in NE Alps at the transition from warmer into colder periods. Interestingly, siliciclastic sediment input in Lake Mondsee decreased at the onset of the LIA at around AD 1300. This implies an overall decreased trend in precipitation, coinciding with negative NAO values, that is obviously decoupled with enhanced spring/summer flood activity at Lake Mondsee. Today, extreme spring/summer floods in NE Alps are predominantly caused by Mediterranean moisture supply (meridional atmospheric circulation pattern with the prominent flood-prone weather regime “Vb” (= northwards flow-

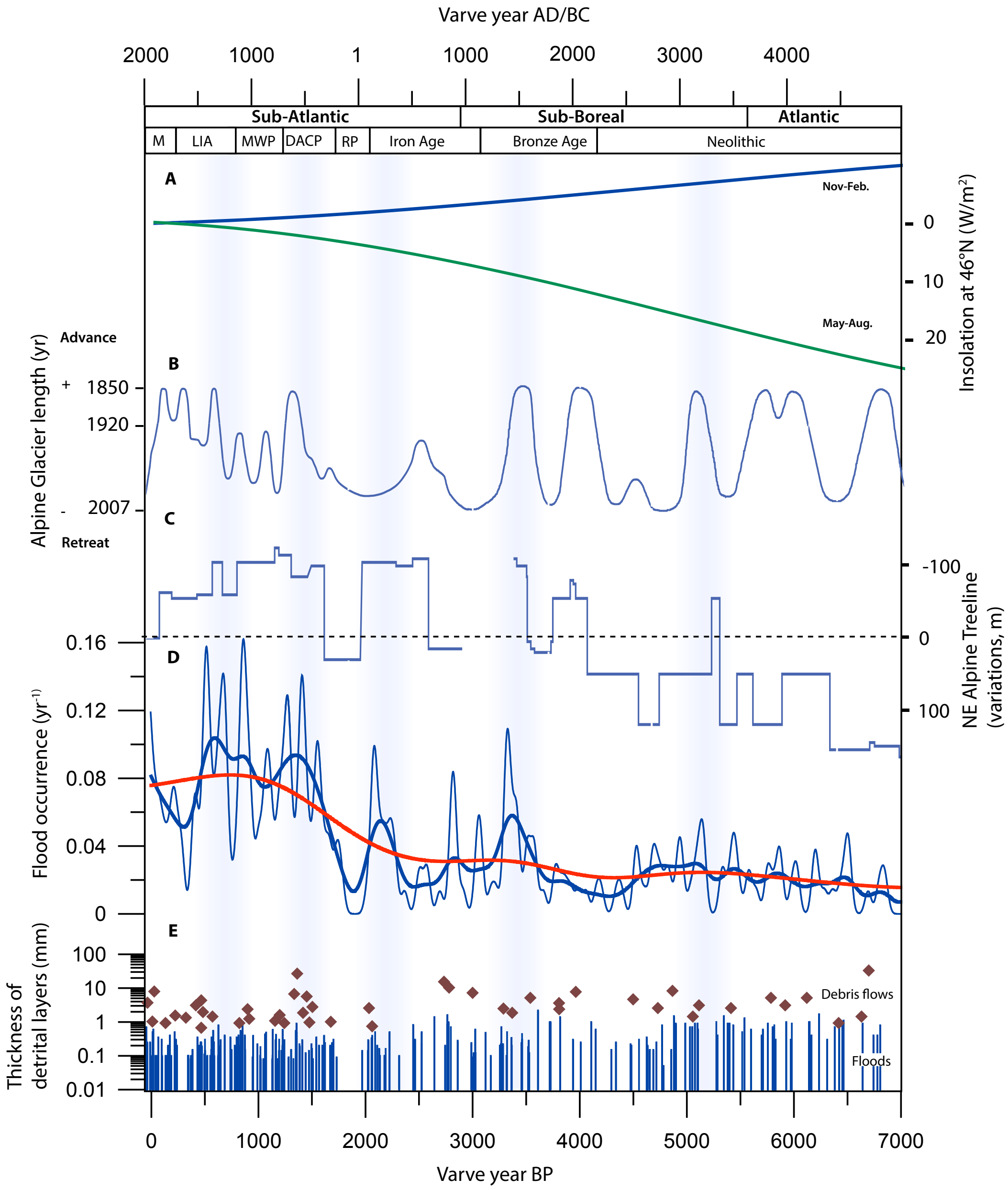

Figure 5.3. Sediment data inferred from Lake Mondsee sediments covering the last 7000 years BP (D, E) in comparison with proxy records (A-C). Thickness of detrital layers (E) indicates different runoff processes of floods and debris flows revealing thinner flood layers (ca. 0.05-2.2 mm) and thicker debris flow layers (ca. 0.65-32 mm). Kernel regression of flood layers (D) with different bandwidths (thin blue line = 30 year, thick blue line = 100 year, thick red line = 500 year) reveals a centennial/ millennial to decadal time scale variability of floods. (C) Higher flood activity agrees with low Austrian treelines (Nicolussi et al., 2005) that indicate main cooling periods (blue columns), e.g. during the Late Neolithic, Bronze Age, Iron Age, Dark Ages Cold Period (DACP), and Little Ice Age (LIA). Roman Period, Medieval Warm Period (MWP) and Modern Times (M) present warm climate conditions with low flood activity. (B) Decadal-scale glacier fluctuations from Alpine Glacier lenght in Switzerland (Holzhauser, 2007). (A) Mean orbital insolation at 46 °N in boreal summer (Mai-August) and winter (November-February) relative to today (Laskar et al., 2004).

ing moist air-masses from the Mediterranean which are blocked by high pressure cells over Siberia and lead to extreme floods in East-Central Europe by quasi-stationary low pressure cells) (Gerstengabe and Werner, 2005). I hypothesize that enhanced meridional atmospheric circulation patterns that prevailed during cooling episodes (e.g. LIA) have lead to higher cyclonic genesis in the Mediterranean Sea (Fig. 5.4), which may have affected extreme summer floods in NE Alps particularly during the transition towards climate cooling. This circulation pattern ceased during coldest climate conditions because of increased continental climate conditions that might have blocked the pathways of Mediterranean cyclones over Central Europe (chapter 2).

Although the driving climatic mechanisms remain unknown, cooling climate conditions is reasonable to have influenced atmospheric circulation patterns in the Alpine realm. However, the variability of floods at Lake Mondsee suggests a non-straightforward correlation of climatic cooling and flood events since warmest and coldest climate present lowest flood activity. This confirms the hypothesis of principle changes in atmospheric circulation patterns as a response to significant climate shifts (Jacobeit et al., 2006). However, this contradicts to scenarios of increased flood activity under global climate warming (Milly et al., 2002). Interestingly, a flood record inferred from Lake Ammersee, a pre-Alpine lake ~ 165 km more to the northwest, report enhanced floods during climate cooling that is linked to a minimum in solar activity (Czymzik et al., 2010). This contrasts to Lake Mondsee,

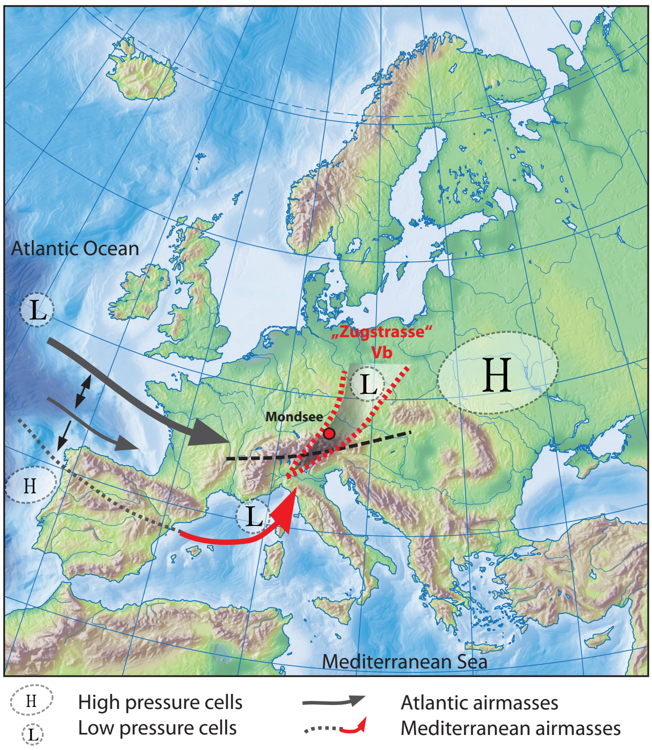

Figure 5.4. Atmospheric circulation patterns in Europe with principle moisture inflow from the Atlantic Ocean and Mediterranean Sea (dotted black line indicates the Alpine N-S dipole). Flood prone weather regime of „Zugstrasse" Vb (red dotted line) triggered by Mediterranean air masses and caused extreme historical summer floods in the NE Alps and East-Central Europe. Southward migration of Westerlies is triggered by negative NAO modes (Jacobeit et al., 2006).

revealing higher flood frequencies only during the transition into cooler climate conditions, and thus emphasizes large regional disparities of flood activity on multi-decadal time scale.

5.3 Modest flood activity during the Neolithic

At Lake Mondsee, three Late Neolithic settlements have been found by archeological excavation. These settlements indicate two settling phases (5750 – 5400 and 5200 - 4650 cal. yr BP). During 5900 and 4500 varve yr BP, higher variability of floods and debris flows coincide with alpine glacier advances (Rotmoos I and II) and the lowering of the Alpine treelines (Nicolussi et al., 2005) (Fig. 5.3). Lake level high-stands in NW Alps occurred between 5650 and 5200 cal. yr BP (Magny and Haas, 2004), which suggest a wetter period during the Neolithic lake dwelling period. At Lake Mondsee, Lake dwellings site I and II (during Rotmoos I oscillation) were built on wetlands, whereas lake dwellings site III (during Rotmoos II oscillation) were built on piles in the water (Offenberger, 1986) possibly due to a socioeconomic change and/or general environmental changes. Higher hydrological activity on multi-decadal time-scale might have resulted in an early adaptation of Neolithic lake dwellers to ‚flood risk‘, however, the abandonment of lake dwellings at Lake Mondsee cannot be solely attributed to hydro-climatic changes. The reconstruction of flood events from varved lake sediments linked with the archaeological sites of the Mondsee Culture reveals a complex interplay between past climatic changes, hydroclimatic extreme events and socio-economic changes of human settlements.

5.4 Conclusion

Holocene sediments from Lake Mondsee are composed of calcite laminas and intercalated, well defined detrital event layers (Lauterbach et al., 2011), which are deposited during extreme runoff events (Swierczynski et al., 2009). Microscopic inspection of the last 7000 years reveals endogenic calcite precipitation in summer (light sub-layers) and the deposition of fine detrital material composed of dolomitic and siliclastic material during winter (dark sub-layers), which can be used for provenance analysis. Because of its varved nature, Lake Mondsee sediments provide a new flood archive of high quality:

1. The combination of microfacies analysis and geochemical measurements enable a precise characterisation of detrital layer deposition in Lake Mondsee and a better understanding of different runoff process of debris flows and floods. The seasonality of the long-term flood record (spring/summer flood) enables the insight into changes of hydrological extremes in response to climatic changes.

2. The combination of instrumental data and sediment data from Lake Mondsee improved the understanding of different extreme local and regional runoff events. This enables a better interpretation of the runoff event with respect to event type and seasonality.

In combination with instrumental data, Lake Mondsee sediments show that a general correlation of flood deposits in lake sediments to the most extreme annual floods might be misleading since the deposition pattern of detrital layers of the last 100 years correspond exclusively to spring/summer floods. For instance, the sediments do not reflect autumn and winter floods (September 1920, December 1974) that is most likely due to the different seasonal formation of turbidity currents and the distal position of the coring site (Mo-05P3, southern lake basin) to the main river inflow Griesler Ache (northern lake basin).

3. Detrital "event" layers intercalated within Lake Mondsee sediments reflect the frequency of extreme spring/summer runoff events, however, there is no correspondence found between thickness of event layers and magnitude of runoff events.

4. Relatively low detrital matter supply into the lake basin as suggested by magnetic susceptibility, µXRF element scanning data and the comparison of flood layer record with available pollen data and historical archives imply that human impact is not a primary trigger for detrital layer deposition in Lake Mondsee. In comparison with other studies, smaller catchments (<100 km^2) show a higher response of erosional processes towards increased human activity (Enters et al., 2008), whereas changes in detrital material supply from larger catchments appear to be more constant as it has been shown for the Alpine Lakes Lac de Bourget (Debret et al., 2010), Lac d'Annecy (Dearing et al., 2001) and Lake Mondsee.

5. Flood events as recorded within Lake Mondsee sediments show a clear non-stationary behaviour of flood frequencies and a complex relationship between floods and climate change. This contradicts to the common opinion about the general increase in flood occurrance under warmer climate conditions. Instead, seasonality of flood generation and regional disparities play an important role in the hydro-climatic system. Thus, estimating floods in the future remains a complex challenge necessitating consideration of potential changes in large-scale atmospheric circulation.

5.5 Further perspectives

Identifying flood series from varved lake sediments

As shown for Lake Mondsee sediments, the analysis of long flood series from varved lake sediments holds a great potential for establishing seasonal flood series. This can be also transferred to other varved lake sediments in order to gain highly resolved flood series from other European sites, and thus to refine the hydro-climatological picture of European regions during climate transitions. Until now, varved lake sediments are still scarcely exploited. A recent doctoral project has investigated flood events as recorded within varved sediments of Lake Ammersee during the last 5500 years, showing that increased flood frequencies occurred during coldest climate conditions, e.g. during solar minima of the

LIA (Czymzik et al., 2010). In order to investigate high-resolution flood records from lake sediments, it is recommendable to choose comparable lakes such as Lake Mondsee and Lake Ammersee (lake surface ca. 10-50 km^2, catchment ca. 250-800 km^2), which exhibit both, an efficient mobilization of sediments during runoff events (Gilli et al., 2013) and a minimal effect of human impact on the hydrology (Blöschl et al., 2007).

A dual monitoring approach to catchment and in-lake processes at Lake Mondsee

The knowledge of return periods of floods is a prerequisite for flood hazard estimation (Merz and Thieken, 2009). The variability of floods on several time scales and results from trend tests of flood occurrence (Petrow, 2009b; Petrow and Merz, 2009) propose the application of instationary flood frequency analysis in hydrological models. The hydrological community may largely benefit from paleoflood reconstructions, if a better understanding of flood magnitudes triggering detrital layer deposition is furthermore attained. At Lake Mondsee, the sedimentary record of floods and debris flows has been verified with instrumental data, which confirm the underlying runoff events. However, the detrital flood layer record poses questions and reveals further perspectives for varved lake sediments as flood archives. Lake Mondsee sediments reveal a considerable sediment transport into the Lake Mondsee basin during spring/summer floods. In contrast, historical autumn and winter floods are not recorded within the core position in distal position (ca. 3 km) to the incoming Griesler Ache. Therefore, different hypothesis need to be tested: What distinguishes seasonal floods and sedimentary transport? Is the sediment stored within the catchment or within the river delta when entering the lake? The long sedimentary sequence of Lake Mondsee provides the unique opportunity to study surface runoff processes and their relation to natural climate variability and human impact during the entire Holocene in detail. However, the complex mechanistic relation between the formation of detrital event layers and their hydro-climatic forcing still needs to be better elicited. This includes the complete process chain of precipitation events, erosion and sediment transport processes as well as the season-specific distribution of detritus within the lake basin. To better understand flood records and fluvial as well as sedimentary processes behind, it is essential to combine the flood record in Lake Mondsee sediments with instrumental data. This goal is currently attained by the project "Extreme Events in Geoarchives" within the frame of PROGRESS (Potsdam Research Cluster for Georisk Analysis, Environmental Change and Sustainability). The project intends to implement a dual monitoring approach to estimate the runoff generation and sediment dynamics within the lake catchment and to improve the understanding of the sediment transport into the lake and the deposition in the lake itselves.

Another doctoral thesis within this project, done by Phillip Müller, runs the lake catchment facilities containing five river monitoring stations equipped with instruments recording basic hydrological and meteorological parameters and for measuring sediment transport (turbidity, automated water samples). The arrangement of the stations along the main tributary Griesler Ache follows a nested catchment approach and continues into the lake basin, where four novel monitoring buoys are installed, recording meteorological and hydro-sedimentary data within the water column. The monitoring stations working since January 2011 (river monitoring) and summer 2012 (lake monitoring) provide detailed data for runoff and sediment modelling. Further perspectives might include detailed analysis of rainfall-runoff events of the past 30 years (runoff coefficient, peak, slope of seasonal runoffs, etc.) in order to characterize seasonal runoff characteristics, which affect sediment transport. A semi-distributed model (e.g. HBV) might help to infer principle processes of runoff in Lake Mondsee catchment.

Another current doctocal project, which is perfomed by Lukas Kämpf, deals with the recent detrital layer formation in the lake sediments. Since January 2011 sediment flux into Lake Mondsee is trapped by two chains of sediment traps at two different sites, one within the northern and one the southern lake basin in order to link the monitoring data to sediment deposits at the lake floor. The chains consist of two sequential sediment traps 2 m over the lake floor (samples every 3–6 days) and three cylindrical traps in different water depths, cleared every 1–3 months. These data gain high-resolution data about the suspended matter transport from the river catchment on an event scale. This forwards a better interpretation of detrital layer deposition on the lake bottom. Additional series of new short cores will help to dense the net of transects within the lake to track the detrital layer record during the last 30 years.

The Lake Mondsee project is an outstanding interdisciplinary project of its kind because of combining different disciplines of paleoclimate, hydrology and sedimentology system that aims at investigating the complex relationship within lake and its catchment. The interplay of comprehensive monitoring of recent processes will help a better understanding of detrital layer deposition in lake sediments caused by extreme flood events. On the other hand, detailed information about the characteristics of floods and flood variability from long flood series will benefit the modelling community to estimate the natural flood return periods on different time scales.

Combination of flood reconstructions: lake sediments and alluvial deposits from Lake Mondsee catchment

Long-term changes in sedimentation processes can be approached by linking sedimentary processes in the catchment and lake sediment record on long-term scale e.g. dating techniques of ^{14}C and OSL (Optically Stimulated Luminescence) of the delta sediments from river Griesler Ache as applied in several investigations (e.g. Hoffmann et al., 2008; Lang and Nolte, 1999). It has been previously shown that sedimentary processes in a catchment-lake system are complex, varying through time (Dearing et al., 2001; Dearing and Jones, 2003). The investigation of sedimentary transport on long times-scales could be approached by parallel investigation of long flood series from alluvial sediments in floodplains and on lake sediments. Alluvial deposits can be linked to extreme historical floods that has been shown in another case study (Benito et al., 2004). Furthermore, dating alluvial deposits within Lake Mondsee catchment might indicate changes in the magnitude of large-scale flood events though time. This might complement the picture of flood activity at Lake Mondsee considering both: frequency and magnitude of floods.

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Appendix A

Distinguishing floods, debris flows and hydrological changes in a 100-year varved sediment record from Lake Mondsee (Upper Austria)

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Abstract Eleven varved short cores from Lake Mondsee were subjected to sedimentological analyses in order to track distinct detrital layers deposited in the lake basin during the last 100 years. The age model is based on varve counting controlled by independent ^{137}Cs dating. We combined analyses of varve microfacies and µXRF-element counts. Principle component analysis of the element data served to distinguish allochtononous sediment supply from the Flysch in the northern (N) lake catchment and the dolomitic bedrock in the southern (S) lake catchment. While the Flysch sediments contain high contents of Ti, K, Al, Si, and Fe, the dolomitic detritus reveal increased Mg counts. Two detrital layer types are distinguished according to microfacies analysis and geochemical composition: DL type 1 and DL type 2. Thirtyone DL type 1 were deposited in the N lake basin (0.1–3.9 mm), which are characterized by increased Ti and Mg contents as well as organic matter, while only nine of these DL type 1 were found in the S lake basin with a layer thickness ranging from 0.05 to 1.6 mm. A higher thickness and larger grain sizes of detrital layers in the N lake basin indicate the proximity of sediment supply to the N-catchment. Their synchronicity with high daily discharge and lake level changes indicate their correspondence to floods in spring and summer. Additionally, three DL-type 2 were deposited in the southern lake basin ranging in thickness between 0.2 to 30 mm. These layers are turbidites with grain-size grading. They have high Mg contents and occur in the S lake basin proximal to the Kienbach river, suggesting debris-flow origin such as for the debris flow deposit in 1986. Their thickness decreases with the distance from the inflow. Frequent flood layers

between 1910–1960 and 1985–2005 document high-magnitude floods in spring and summer, whereas flood activity was decreased between 1960 and 1980. In contrast, the three debris flow events in 1923, 1941 and 1986 are not clustered. However, their deposition is related to intense (convective) rainfall events.

A.1 Introduction

Floods and debris flows are one of the most frequent and destructive natural hazards affecting human habitats (MunichRE, 2011), especially in mountainous regions. Global warming is widely assumed to affect and intensify hydrological extremes (Allen and Ingram, 2002; Kundzewicz et al., 2006; Milly et al., 2002), the seasonality and trends of flood occurrence (Beurton and Thieken, 2009; Kundzewicz et al., 2005b; Mudelsee et al., 2003; Petrow, 2009b). Instrumental records rarely exceed the last 150 years (Kundzewicz et al., 2005a) and longer historical records are scarce. Both, the natural recurrence of extreme floods and changes in seasonality of floods remain challenging key issues for natural hazard research in alpine regions, thus calling for new approaches to investigate hydrological extremes of the past.

Geoarchives such as lake sediments provide information about hydrological changes for pre-instrumental time (Debret et al., 2010; Martin-Puertas et al., 2008; Moreno et al., 2008; Støren et al., 2010; Thorndycraft et al., 1998). Distinct detrital layers intercalated within annually laminated (varved) lake sediments can be used to identify runoff events of the past (Hsü and Kelts, 1985; Irmler et al., 2006; Kelts and Hsü, 1980; Ludlam, 1974; Osleger et al., 2009; Siegenthaler and Sturm, 1991; Wirth et al., 2011). Precise dating of detrital layers by means of reproducible varve counting (Brauer et al., 1999a) allows even a seasonal reference of detrital layer deposition. A study of varved sediments from Lake Ammersees showed that flood layers correspond with with high-magnitude spring/summer floods (Czymzik et al., 2010). This study, however, revealed that not all high-magnitude floods were presented in the sedimentary record and that seasonal runoff processes of detrital layer deposition is not completely understood. Because studies from varved lake sediments provide exact time control, these archives can be adequately used to gain the seasonality of extreme events (Czymzik et al., 2010; Mangili et al., 2005). Until now there is still scarce information about flood layer deposition in varved lake sediments, through the triggering hydrological processes and seasonality of flood events remains rather unclear.

We investigated the recent deposition of detrital layers intercalated within varved lake sediments from the pre-alpine lake Mondsee. Multiple short cores were studied as they provide detailed information about the related runoff process of detrital layer deposition. We also compared detrital layer record and clastic sediment supply with daily lake water level data and annual precipitation of the last 100 years in order to relate hydrological processes with sedimentological imprints.

A.2 Study Site

Lake Mondsee is located at the northern ridge of the European Alps (47°48'N, 13°23'E) at an altitude of 481 m (Fig. A.1). The lake has a size of 14 km^2 and a maximum water depth of 68 m. Lake Mondsee is a meromictic hardwater lake. Since the lake is rarely covered by ice in winter (Jagsch and Megay, 1982), the lake has commonly one mixing period in autumn/winter. A thermal stratification of the lake column is established during May-September (Dokulil and Skolaut, 1986) with maximal lake surface temperatures of about 22 °C. Recently, the lake exhibits oligotrophic- mesotrophic conditions reaching relatively high water temperatures in summer. Because of increased touristic and economic development, Lake Mondsee exhibited strongly degraded water quality during the 1960 ies (Dokulil and Skolaut, 1986; Herrmann, 1990; Horsthemke, 1986; Irlweck and Danielopol, 1985; Klee and Schmidt, 1987). The lake reached re-oligotrophic conditions in 1983, seven years after a sewage treatment plant was constructed in the catchment (Schmidt et al., 1991).

The lake constitutes of a shallow northern lake basin (max. depth 50 m) and a deep southern lake basin (max. depth 68 m) (Jagsch and Megay, 1982). Three main rivers (Griesler Ache/syn.: Fuschler Ache, Wangauer Ache and Zeller Ache) drain into the northern lake basin; smaller streams feed the southern lake basin. Lake Mondsee has a small outlet at the southern end of the lake, which drains into Lake Attersee.

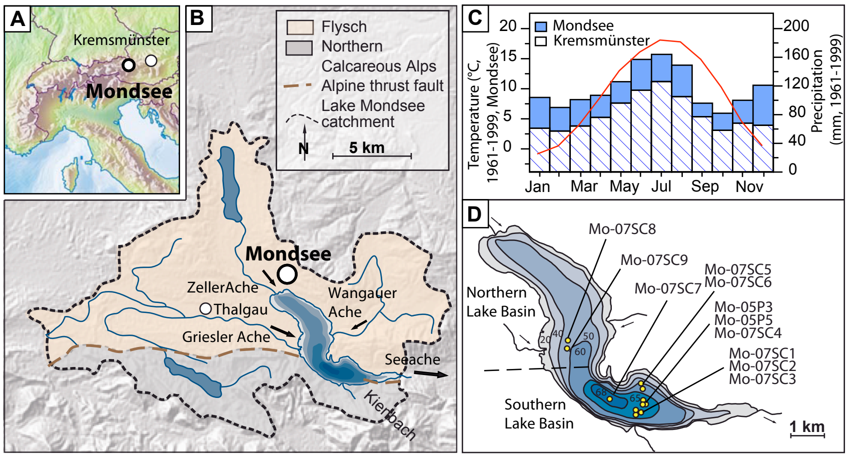


Figure A.1 (A) Location of Lake Mondsee within the European Alps. (B) Lake Mondsee catchment and simplified geological map. Main lithological units of Northern Calcareous Alps and Flysch sediments are separated by a main alpine thrust fault. Digital Elevation Model indicates steep slopes of the Northern Calcareous Alps in the southern Lake Mondsee catchment. (C)Climate data from stations of Mondsee (temperature and monthly precipitation) and Kremsmünster (monthly precipitation). (D) Lake Mondsee with bathymetry and drilling location (yellow dots) of the short cores.

A main alpine thrust fault (van Husen, 1989) sub-divides the total of the catchment (247 km^2) into two sub-catchments. The northern catchment (~75 %), which is drained by the main rivers, reaches elevations of 1000 m and constitutes of Cretaceous Flysch sediments (Sandstones, Argillite) and is partly covered by moraines formed by latest Pleistocene glacier activity (van Husen, 1989). The southern sub-catchment (~25%) has maximum elevations of 1700 m a.s.l., belongs to the Northern Calcareous Alps and is drained by smaller rivers (e.g. river Kienbach with a total catchment of 2.1 km^2). The bedrock are Jurassic and Triassic units of limestone and dolomite building steep slopes at the southern shoreline of the lake with northwestern exposition. For instance, the Kienbach creek include slopes of 30–60%; around 90% of the total area is forested (personal communication local authority for stream treatment Salzburg).

The region is characterised by Atlantic and Mediterranean weather regimes, which result in mild and humid climate conditions. The mean annual air temperature at climate station Mondsee (reference period 1971–2000, ZAMG- Central Institute for Meteorology and Geodynamics) is 8.7 °C with temperatures of -0.5°C and +17.5 °C in January and July, respectively. The mean annual precipitation is 1550 mm with annual peaks in summer. During the 20th century, exceptional floods in September 1920, July 1954, August 1959, July 1997 and August 2002 were caused by prolonged or convective rainfall events. Rare flood events in winter known as “Christmas floods”, are caused by rain-on snow events or dammed ice floods, e.g. in December 1974.

Previous investigation of Lake Mondsee sediments concentrated on lake water quality throughout the last 30 years (e.g. (Dokulil and Skolaut, 1986; Helbig et al., 1985; Irlweck and Danielopol, 1985; Klee and Schmidt, 1987; Schmidt, 1991; Schmidt et al., 1985), sediment and vegetation changes during the Late Glacial and early Holocene (Lauterbach et al., 2011; Schultze and Niederreiter, 1990; Schultze E. and Niederreiter, 1990).

A.3 Methods and data

A.3.1 Coring

Eleven short cores (42-103 cm) were obtained in 2005 and 2007 using a gravity corer (UWITEC, 90 mm liner diameter). Two cores (Mo-07SC8 and Mo-07SC9) were retrieved from the shallower northern lake basin, approximately 800 m off the inlet of the main tributary Griesler Ache. Nine cores were retrieved from the deeper southern lake basin, along a transect from the Kienbach river inflow towards the northern shoreline. The cores Mo-07SC1-3 were taken close to the delta of Kienbach river (ca. 400 m), Mo-05P3 + P5 and Mo-07SC4 derived from in the lake centre of the southern lake basin (ca. 800 km) and Mo-07SC5 + 6 were recovered in most distal position to the Kienbach river (ca. 1000 m), but close to the northern shoreline.

A.3.2 Microfacies and Chronology

All cores were opened and the surface of a split core half was photographed. Samples (blocks of 100 x 20 x 10 mm) for large- scale thin sections (120 x 35mm) were taken with an overlap of 2 cm from the fresh sediment. The procedure of thin section preparation is described in (Brauer et al., 1999b). Thin sections were analyzed with a petrographic microscope (Carl Zeiss Axiophot; Carl Zeiss, Germany) using magnifications of 25–100x. Images were obtained by using an integrated digital camera (Carl Zeiss Axiocam). Selected sediment sections were additionally analysed by Scanning Electron Microscopy (SEM, Zeiss NTS DSM 962).

The age-depth model of all sediment sequences was established by varve counting. The short core Mo-05P3, which is located in the centre of the southern basin, shows best varve preservation and was subjected to ^{137}Cs dating (Lauterbach et al., 2011). We used distinct marker layers for correlation among the sediment sequences to each other (described in ‘results‘).

A.3.3 Geochemical and mineralogical analyses

Major element scanning (Ti, Fe, Mg, K, Ca, S, Si, Mn, Al) of the uppermost 26 cm of the master core Mo-05P3 was carried out by a µXRF spectrometer (EDAX Eagle III XL) with a spot size of 250 µm and a step size of 200 µm by means of counts per second (cps) with a mean error of +/- 0.01 cps. The tube voltage has been fixed to 40 kV and the tube current to 300 µA. For element counting (n=1300) we applied Principle Component Analyses (PCA) by using the program Matlab and recipes for data analysis (Trauth, 2010). The element data were anchored to the age-depth-model by linear interpolation between the varve boundaries. Therefore, the beginning of a varve year was set to the lower boundary of the light sub-layers.

Mineralogical analyses were performed by X-ray diffraction analysis (Siemens Diffractometer 5000) of the three thickest detrital layers. The quantification of the mineral content was implemented using BGMN software (Seifert, Freiberg, Germany).

A.3.4 Instrumental hydro-climatic data

We used daily discharge data of the main tributary Griesler Ache (St. Lorenz gauging station) since 1976 (Hydrographic Service of Austria) in order to investigate the seasonality of runoff events. We compared daily precipitation data as recorded at the climate station of Kremsmünster for the time period 1900-2005 and Mondsee/Scharfling for the time period 1961-2005 (ZAMG- Central Institute for Meteorology and Geodynamics) and daily lake water level of Lake Mondsee covering the time period 1900–2005 (Hydrographic Service, Upper Austria and Monastery of Kremsmünster). Until 1976, daily lake level data are based on manual measurements at the lake outlet, whereas automatic records were obtained from a station in Mondsee since 1976. Lake level data show an artificial trend that is due to the elevation of lake water levels following two dam installations at the lake outlet. The first dam was constructed between 1918-1920 (manually controlled) and a second dam was constructed in 1972 (automatically controlled).

A.4 Results

A.4.1 Varve microfacies and lithostratigraphy

The sediments of Lake Mondsee are annually laminated presenting biochemical calcite- varves (Lauterbach at al., 2011). Each varve consists of a light and a dark sublayer and ranges in thickness from 1 to 6 mm (Fig. A.2, Fig. A.3). Light sublayers are composed of clay to fine silt-sized endogenic calcite (<5 µm), whereas dark sub-layers consist of clay to silt sized organo-minerogenic material and diatom debris (Fig. A.3). Cores from the northern lake basin additionally include higher amounts of clastic material with sand-sized material (100-200 µm), which form matrix-supported dark clastic sublayers. The principle processes for calcite-varve formation are biogenic calcite precipitation in spring/summer (Koschel et al., 1983) and the deposition of organo-clastic material in autumn and winter (Lotter, 1989; Lotter and Lemcke, 1999).

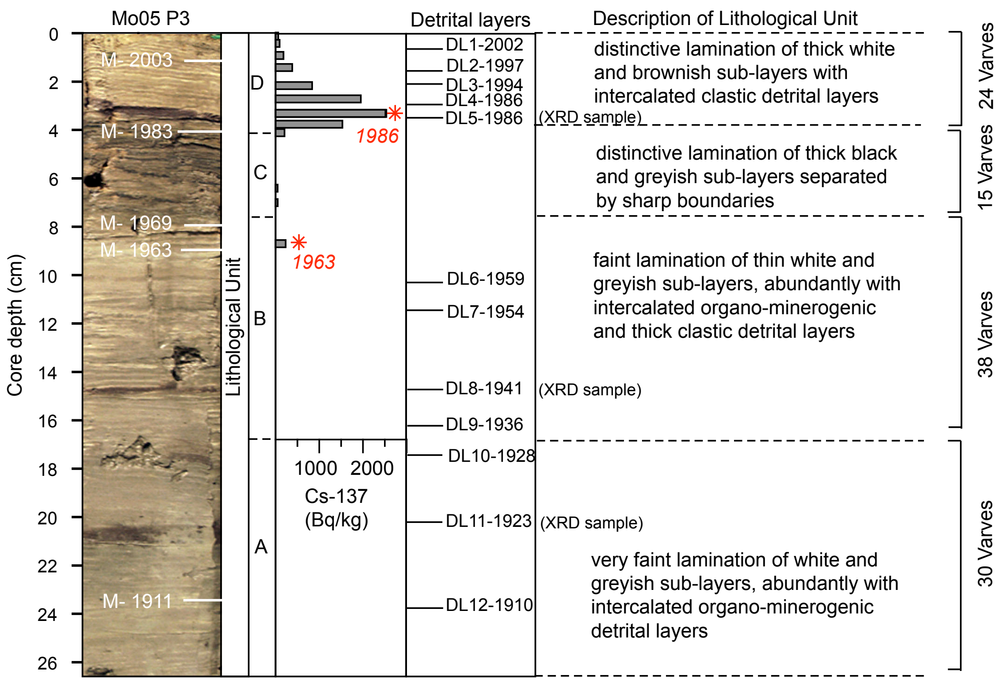


Figure A.2. Core photo of Mo-05P3 with intercalated detrital layers and description of lithological units A-D. ^{137}Cs dating (Lauterbach et al. 2011) marks fallout peaks (red stars): Chernobyl accident in 1986 and nuclear weapon tests in 1963. White lines mark distinct layers (M-2003, M-1983, M-1969, M1963, M-1911) used for core-to-core correlation.

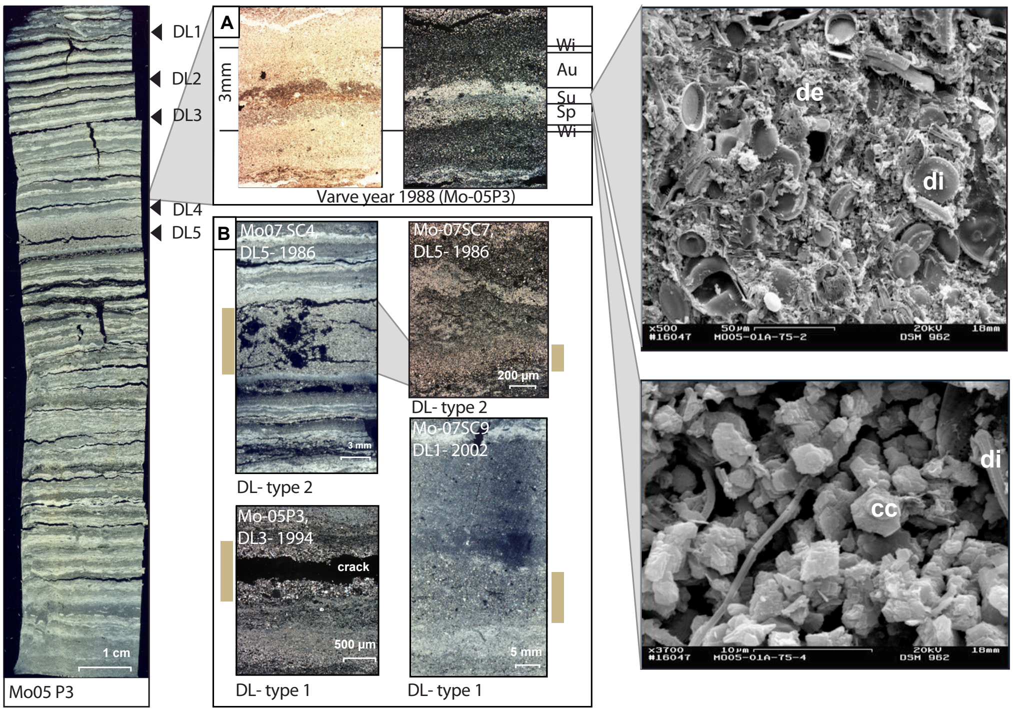


Figure A.3. Thin section image from core Mo-07SC4. (A) Varve model of Lake Mondsee sediments with seasonal sublayers of winter (Wi), spring (Sp), summer (Su) and autumn (Au): The varve year 1988 under normal and polarized light. Scanning electron microscopy (SEM) shows spring sub-layer with euhedral calcite crystals (cc) and autumn sub-layer with diatom frustules (di) and clastic/organic detritus (de). (B) Three types of detrital layers. Correlation of thick graded detrital layer (DL5-1986, DL-type 2) intercalated within cores from the southern lake basin (Mo-07SC4). Thin detrital layer (DL-type 1) intercalated within cores from the southern lake basin (Mo-05P3) and detrital layer (DL1-2002) as deposited in lake sediments from the northern lake basin (Mo-07SC9, DL-type 1).

The varved sediments of the “master core“ Mo-05P3 additionally comprise a total of 12 intercalated brownish detrital layers, which range in thickness between 0.05 and 30 mm (Fig. A.2). The seasonality of detrital layer deposition is determined according to the stratigraphic position relative to the endogenic calcite sublayer that reveals a deposition in spring and summer. Microscopic inspection of detrital layers reveals silt-to-sand sized (50–200 µm) minerogenic calcite, quartz, feldspars, dolomite and organic matter (fragments of leaves, etc.). According to the varve preservation, four main lithological units (A-D) are distinguished in each sediment core (Fig. A.2). Unit A is characterized by very faint lamination of white and greyish sublayers (30 varves) and three intercalated detrital layers. The layer structure gets slightly more distinct in sediment unit B, which comprises 38 varves and four intercalated detrital layers. Diatom frustules of *Stephanodiscus spec*. increased within the dark sublayers. Unit C is composed of thick black and greyish sublayers (15 varves), which are separated by sharp boundaries. No detrital layer was detected in sediment unit C. Unit D is characterized by distinct lamination of thick white and brownish sublayers (24 varves) with five intercalated detrital layers. This uppermost sediment deposits have the best varve preservation.

A.4.2 Chronology and core-to core correlation

All short cores were subjected to varve counting covering the last 100 years. The cores in the northern lake basin yielded only 67 and 69 years (Mo-07SC8: AD 1938-2007, Mo-07SC9: AD 1940-2007) that is due to a shorter core lenght. Coring sites in the centre of the southern lake basin (Mo-07SC4, Mo-05P3, Mo-05P5) present the best varve quality, thus providing the "master chronology" for the time period 1900-2007. The varve chronology agrees with results from ^{137}Cs measurements in the short core Mo-05P3 (Lauterbach et al., 2011) exhibiting two fallout peaks in 1986 and 1963 (Fig. A.2) that is due to the Chernobyl accident and nuclear weapon tests, respectively. Additional independent time markers are changes of diatoms species from unit B to C and C to D. *Aulacoseira islandica* is substituted by *Aulacoseira italica ssp. subarctica* (Unit C), which marks the beginning of eutrophication since 1968 (Klee and Schmidt, 1987; Schmidt, 1991). The re-occurrence of *Aulacoseira islandica* (Unit D) indicates the re-oligotrophication in 1983 (Klee and Schmidt, 1987; Schmidt, 1991).

The master chronology comprises the last 100 years. To gain a reliable chronology for all cores, the single varve chronologies were fitted to the "master chronology" of the southern lake basin (Mo-07SC4, Mo-05P3, Mo-05P5) according to five pronounced calcite or diatom layers. These marker layers (Fig. A.2) correspond to the varve years 2003 (thick calcite layer), 1985 (diatom layer: *Stephanodiscus spec.*), 1969 (thick calcite layer), 1963 (thin calcite layer) and 1911 (thin calcite layer).

Shorter chronologies due to poor varve preservation are derived for Mo-07SC2 (1920–2007), Mo-07SC3 (1935–2007) and Mo-07SC7 (1935–2007). The core Mo-07SC6 exhibits a hiatus in the uppermost sediment deposits (ca. 20 varves), whereas the parallel profile Mo-07SC5 is almost entirely disturbed, suggesting the occurrence of slumps at the southwestern shoreline near the outlet of the lake. In total, the sedimentation rates vary between 2.5 mm/year to 6.7 mm/a (Fig. A.4) and are highest (3.0–6.7 mm/a) in the northern lake basin. Lowest sedimentation rates and lowest variability in sedimentation rates (2.5–2.9 mm/a) occur in central coring locations of the southern lake basin. All core profiles, and especially cores near the inflow of the river Griesler Ache (northern lake basin), exhibit increased sedimentation rates in lithological Units B and C.

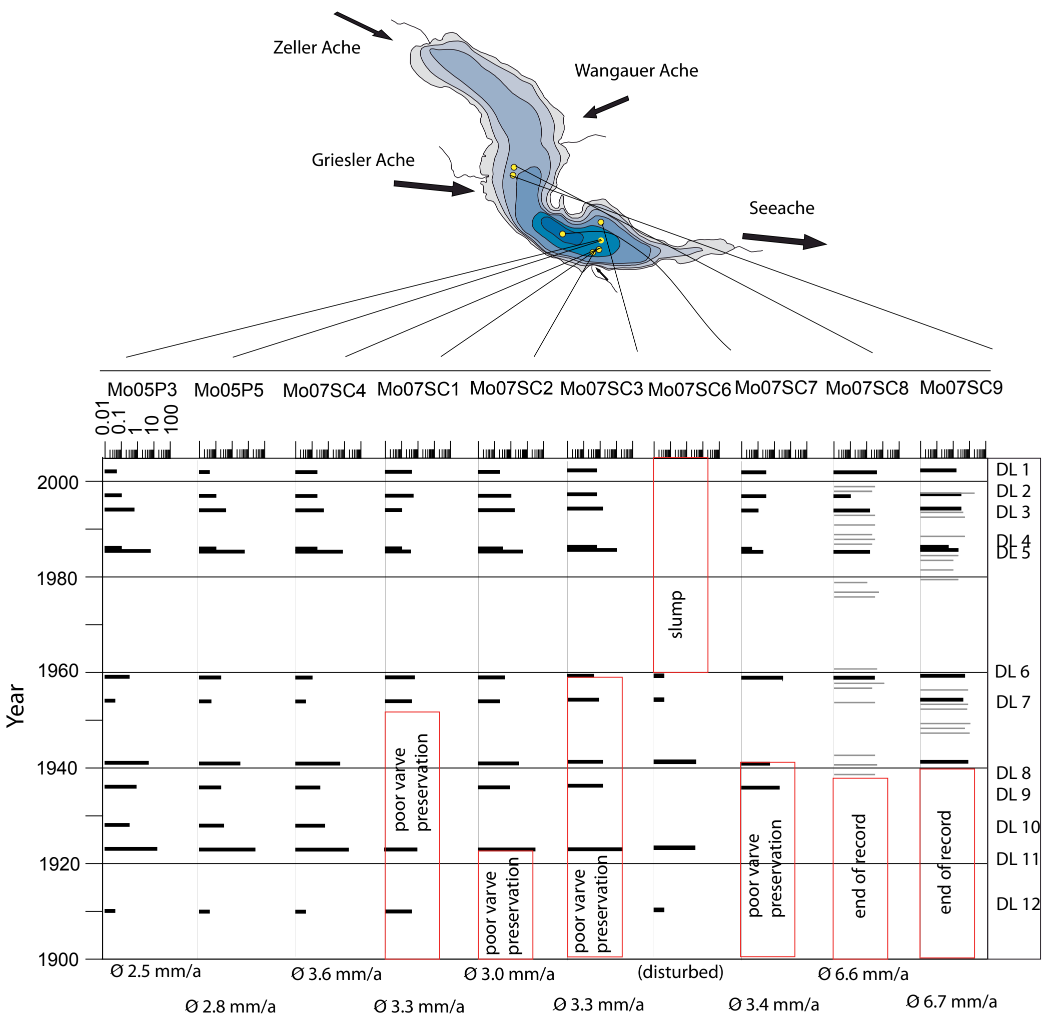


Figure A.4. Thickness of detrital layers within the sediment cores. Red boxes mark sediments of bad varve preservation or end of the sediment core. Black line indicates varve thickness for the last 100 years. Numbers below the diagram indicate sedimentation rate above the 100-year average of each core.

A.4.3 Geochemical composition

The geochemical composition of the Lake Mondsee sediments was obtained from the µXRF analysis of the short core Mo-05 P3 (Fig. A.5A). A general increase of Ca and S counts occurs in unit C and D, whereas Ti and Mg counts decreased at the same time. Principal Component Anlaysis (PCA) of the element data revealed three principal components that explain 76.7 % of the total variance of the dataset (DR Table A.1 and DR Table A.2). Of these totals, 52,4 % are explained by PC1, 15,4% and 8.8 % are explained by PC2 and PC3. Principal Component 1 (PC1) is controlled by Al, K, Si, Ti and Fe (Fig. A5 and Fig. A.6). These elements are of siliciclastic origin indicating the Flysch catchment as the main sediment source. Count rates of siliclastic elements are elevated within the dark sub-layers (autumn/winter). However, a secondary source of Si is related to the bloom of diatoms in spring and summer. This is confirmed by the cross-correlation of Si and the clastic element Ti within units A–D. (Fig. A.5B). High Si and low Ti-values within unit C and unit D reflect abundant bloom during 1968–2007, whereas high content in Si and Ti reflect increased input of siliciclastic material as indicated by high PC1 scores in units A and unit B (Fig. A.5A)

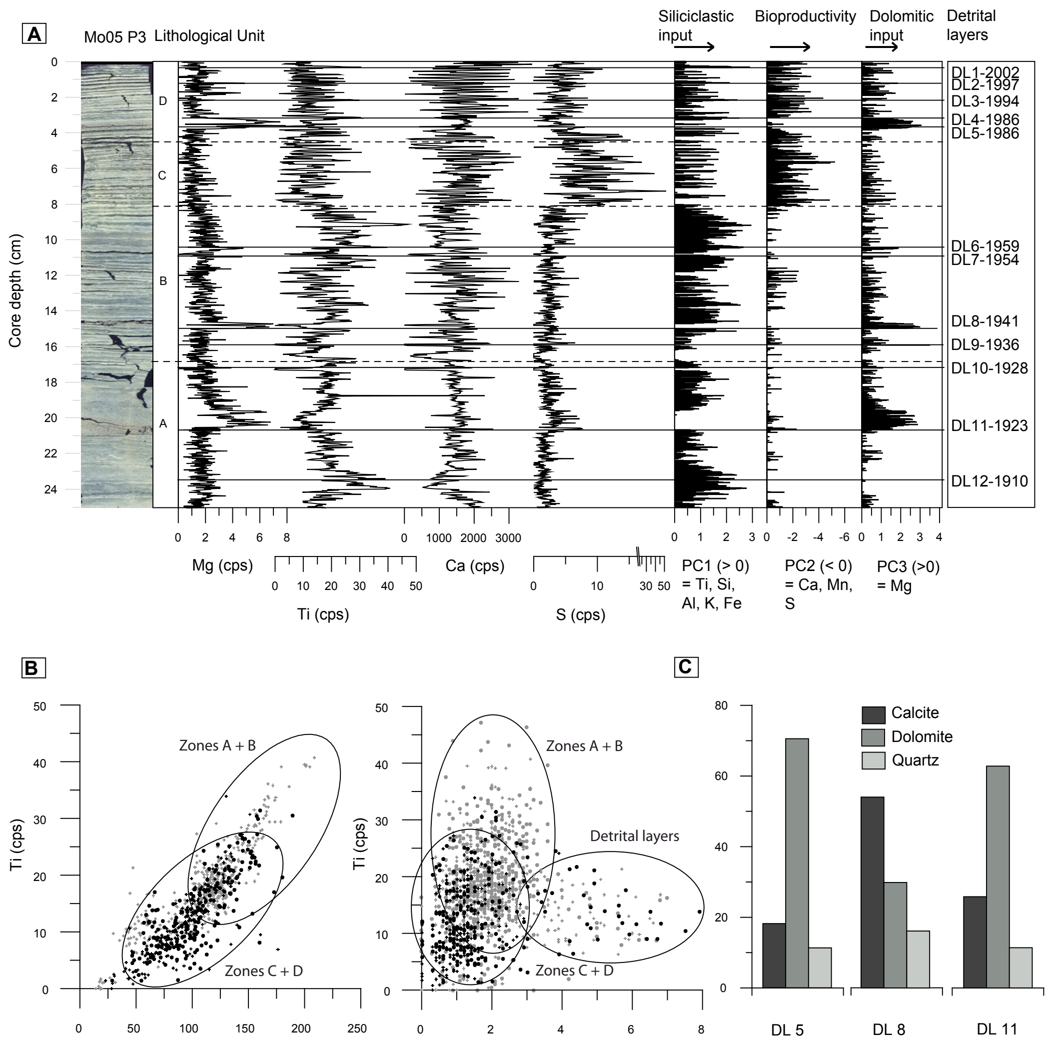


Figure A.5. (A) Thin section image from sediment core Mo-05P3 with element composition of Ti, Ca, Mg and S and three principal components (PC1-PC3) relating to siliciclastic input (PC1), in-lake processes/bioproductivity (PC2) and dolomitic input (PC3). Zones A-D indicate main lithological units of the sediment profile. (B) Cross-correlation of the elements Si/Ti and Mg/Ti for lithological units A-D. Units A and B exhibit higher content of the elements Si, Ti and Mg than Zones B and C. High Mg values are related to detrital layers. (C) Mineral composition by XRD analysis of DL 5, DL 8 and DL11.

Negatively related to the PC2 are the elements Mn, S and Ca (Fig. A.5 and Fig. A.6). Light sublayers (spring/summer) exhibit increased calcium contents (Ca) that result from in-lake processes (algae bloom and biogenic induced calcite precipitation). Although a second source of Ca must be considered concerning the clastic calcitic supply from the Northern Calcareous Alps, the PCA reveals that Ca is primarily related to in-lake processes (PC2). Due to high lake productivity in summer and abundant anoxia at the lake bottom, spring/summer sublayers also reveal an enrichment in S and Mn. Microscopic inspection reveals the abundance of pyrite framboides imbedded in organic material (algae) of the late summer sub-layer. Corresponding to high lake productivity and anoxic condition in summer, Mn is commonly reduced and dissolved at the lake water-sediment interface (Davison and Woof, 1984). In contrast, increased Mn counts indicate re-oxidation and deposition of Mn in the sediments during thermal lake mixing in late summer. This process has been observed from other alpine lakes (Schaller and Wehrli, 1996) and is related to the seasonal cycling of sulfides, iron and humic substances. Values of PC2 remain low in the sediment units A and B and increased sharply in Zone C that is related to lake eutrophication.

PC3 is related to the dolomitic element Mg (Fig. A.5 and Fig. A.6) and reflects clastic sediment input from the Northern Calcareous Alps. Three short-term peaks occur in sediment units A, B and C.

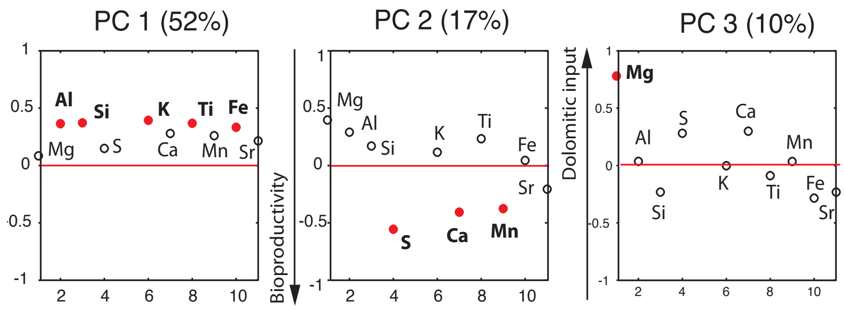


Figure A.6. Factors loadings from principal component analysis (PCA) of measured μXRF data. PC1 includes the elements Al, K, Fe, Si and Ti, whereas PC2 groups Ca, S and Mn and PC3 represents the element content of Mg. For more information about PCA see the description in the text.

A.4.4 Detrital layers and inta-basin correlation

The characteristic microfacies and their occurrence in the lake basin reveal two types of detrital layers: DL-type1 and DL-type 2 (Fig. A.3B).

DL- type 1 are intercalated within the spring or the summer sub-layer as revealed by short cores from the southern lake basin. Because of higher clastic input, the identification of seasonality of detrital layers inferred from short cores of the northern lake remains diffecult. In general, detrital layers are composed of sorted fragments of minerogenic calcite, siliciclastic particles (50-200 µm) and organic fragments (leaves, etc.). Element data scans of the core Mo-05P3 show elevated values in Ti (PC1) and Mg (PC3) revealing detrital sediment input from both, the Flysch and the Calcareous Alps. Thirtyone DL-type 1 were deposited in the northern lake basin. These layers range in thickness between 0.1 and 8 mm and are composed of fragments from leaves and/or sorted siliciclastic and calcitic particles (100-200 µm). Only nine of these 31 DL-type 1 found in the northern lake basin correspond to thinner detrital layers deposited in the southern lake basin (Fig. A.4). These layers range in thickness between 0.1 and 1.6 mm and were deposited in the entire southern lake basin, with some exceptions (disturbed core sections in Mo-07SC5+6, Mo-07SC7). In few cases, some cores show scattered detrital material without forming a discrete layer (e.g. DL 7, DL 9, DL 10, DL 12 in cores Mo-07SC1, Mo-07SC5, Mo-07SC6, Mo-05SC7) (DR Table A.3). Because of a distinctive proximal to distal deposition pattern from the northern to the southern lake basin, DL type 1 reveals the river Griesler Ache as the main riverine input from the Northern Lake catchment, which partly flows through the Northern Calcareous Alps, and thus transferring siliciclastic and dolomitic material into Lake Mondsee.

DL- type 2 are deposited in summer. These layers are predominantly composed of Mg (PC3) and are depleted in Ti (PC1). XRD analysis from core Mo-05P3 reveals calcite and dolomite as the main constituents (Fig. A.5C). All layers are graded with sharp boundaries to the calcite sub-layers below and above. In total, three DL-type 2 were exclusively found in the southern lake basin and deposited during summer. Coring sites near the river Kienbach delta (Mo-07SC1-3) reveal thickest deposits (0.4-30 mm) and contain up to sand-sized (100–200 µm) clasts and high contents of organic macrorests (e.g. leaves). In the lake centre (Mo-07SC4, Mo-05P3, Mo-05P5) detrital layers reach 3–25 mm in thickness and contain clastic calcite and dolomite (50-200 µm) and abundantly organic fragments (leaves, etc.) on top. The layers thin out towards the north (Mo07SC5 + 6: 3.2–4 mm) and the deepest part of the lake centre (Mo-07SC7: 0.2–0.5 mm), and their maximal grain size decreases (<50 µm). Abundantly, some detrital layers are missing at the most distal sites (DL 8 in Mo-07SC5 and DL 11 in Mo-07SC7). The three DL-type 2 were dated to 1923 (DL 11 range in thickness from 3.2 to 30 mm), 1941 (DL 8 range from 0.5 to 5 mm) and 1986 (DL 5 range from 0.2 to 7.3 mm), respectively. According to their dolomitic composition and their distinct proximal to distal pattern, detrital layer type 2 are related to sediment supply from the Northern Calcareous Alps via the river Kienbach.

A.4.5 Flood events in the Lake Mondsee catchment 1900-2002

Summer is the main season for flood occurrence in the Lake Mondsee area (Fig. A.7) with highest amount of annual precipitation occuring from June to August (34%). The classification of daily rainfall events between 1976-1999 shows that high-magnitude precipitation (above 50 mm, n=38) occur predominately in summer (47 %) as convective rainfall. Correspondingly, more than 50 % of extreme discharge events (above 40 m^3/s, n=23) occurred during the summer months June, July, and August.

High Pearson's correlation of lake water level and discharge (0.77) allows using lake levels to identify historical flood events for the time before automatic discharge measurements (1900-1976). Despite water level regulation after 1972, which is caused by a dam construction at the lake outlet, the good correlation of lake level and discharge values allows us to identify flood events back to AD 1900 based on lake level data. During summer, six prominent flood peaks with a water level increase of at least 100 cm occurred in 2002, 1991, 1954, 1959, 1950 and 1918 (Fig. A.8E). However, two flood peaks in 1918 and 1991 mark a possibly amplification in water level increase that is caused by dam failures at the lake outlet. However, two flood events of the same magnitudes are indentified in spring 1910 and 1987 (Fig. A.8D), one flood event in autumn 1920 (Fig. A.8F) and two events in winter 1923 and 1974 (Fig. A.8G).

To investigate flood activity for the last 100 years, we use low pass filtered time series of three-days increase of lake water level (Fig. A.8C). Two periods of high flood activity occurred during 1910-1925 and 1945-1960. A period of moderate flood activity occurred between 1960-1980 and three periods of low flood activity occurred prior to 1910, between 1925-1945 and after 1980.

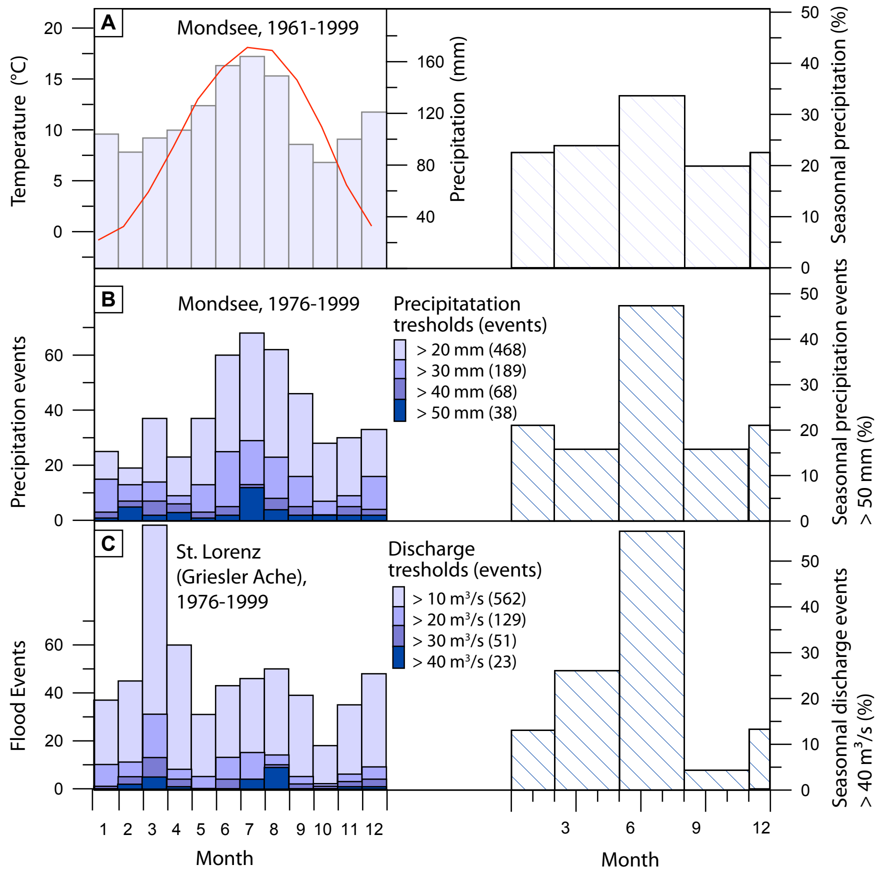
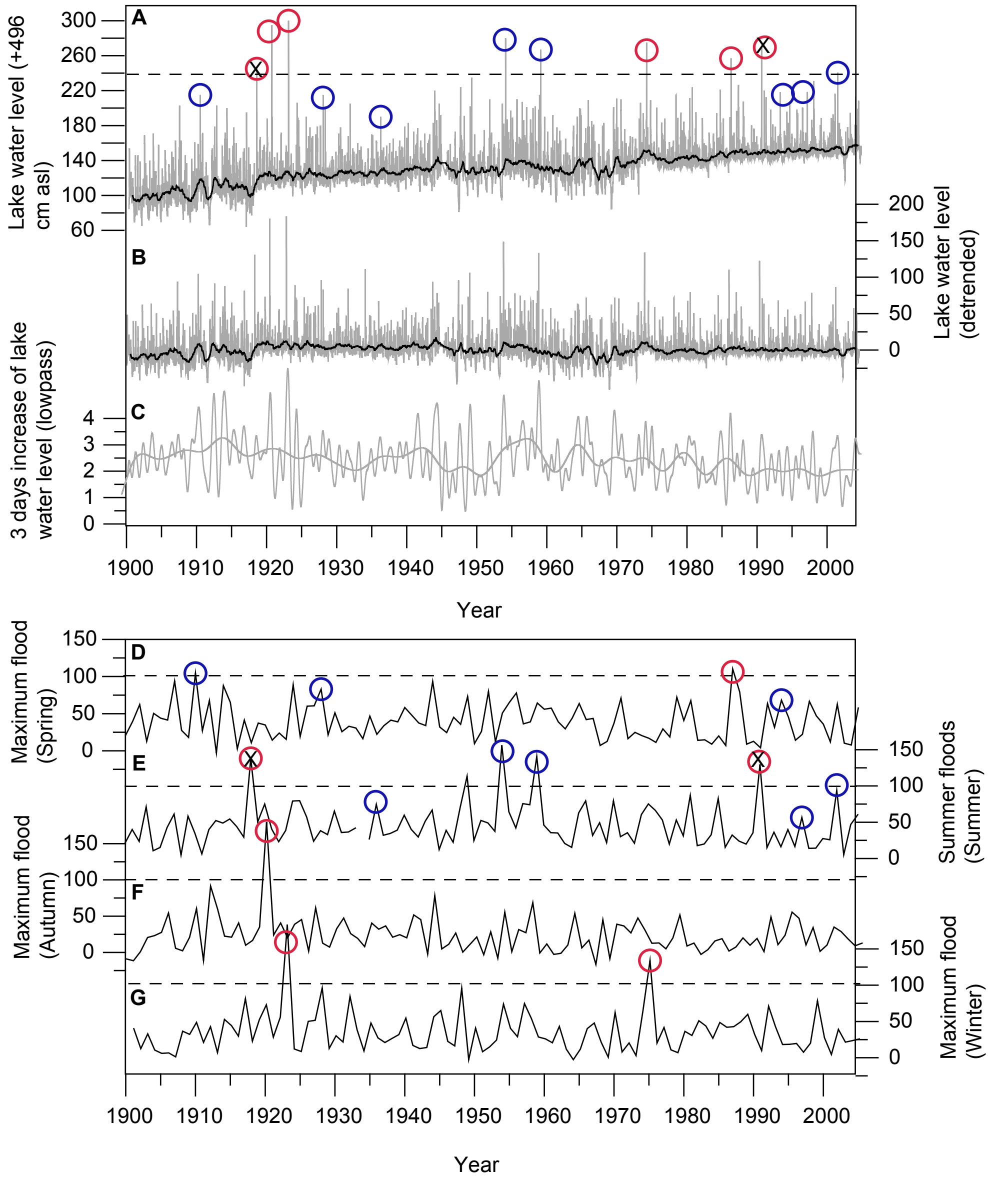


Figure A.7. (A) Hydro-climate for Lake Mondsee (1961-1999) and seasonal fraction of precipitation (%). (B) and (C) Daily precipitation data from climate station of Mondsee and hydrological data from gauging station St. Lorenz (1976-1999) with seasonal fraction of precipitation events > 50 mm and seasonal fraction of discharge events > 40m^3/s. Four classes above thresholds and the total amount of events are selected to estimate monthly distribution of hydro-meteorological events.

(Figure A.8 is on the next page)

Figure A.8. Historical flood events from daily lake water level (cm+ 496 cm a.s.l) of the last 100 years. Blue circles indicate flood event deposits, red circles indicate historical flood events with no flood event deposit and red circles with x –mark indicate dam failures in 1918 and 1991. (A) Daily water level of Lake Mondsee for the last 100 years. (B) Daily water level of Lake Mondsee for the last 100 years (detrended time series). (C) Flood events as indicated by three days of water level increase (approx. one- year and five-year low pass filtered time series). (D-G) Flood events as indicated by annual maximum water levels for spring (D), summer (E), autumn (F) and winter (G).



A.5 Discussion

A.5.1 Detrital layer deposition

Varved sediments from Lake Mondsee of the last 100 years present a succession of twelve detrital layers in the southern lake basin and thirty-one detrital layers in the northern lake basin. The distinction between DL-type 1 and DL-type 2 according to their geochemical composition and distribution indicate different deposition processes and provenances.

DL-type 1 reveal a total of nine detrital layers, which are deposited only in the southern and northern lake basin. Additional 22 detrital layers are deposited in the northern lake basin close to the inflow of river Griesler Ache. All layers are composed of siliciclastic and dolomitic material, which is supplied by the Griesler Ache. Due to the basin wide distribution of DL-type 1, the sediments are most likely supplied by river floods. During flood events, low concentrated turbidity currents enter the lake and move laterally through the water column along the thermocline as overflows or interflows (Sturm and Matter, 1978; Shanmugam, 2000). The sediments settle on the lake bottom according to the density of inflowing turbidity current and surrounding lake water. The thermocline of Lake Mondsee is established during Mai-September (Dokulil and Skolaut, 1986) and controls the sedimentary transport into the southern lake basin ca. 3 km off the river inlet Griesler Ache.

DL-type 2 reveal a total of three layers, which are predominantly composed of dolomitic material. Since the thickest layers occur proximal to the river Kienbach, sediment supply derived from the Northern Calcareous Alps. In addition, gradation indicates the occurrence of turbidites, which result from underflows/high-concentrated turbidity currents and are released by slumps or debris flow deposits (Sturm and Matter, 1978). Such a turbidite was deposited after a debris flow event occurred on 18th July 1986. This debris flow was generated by a thunderstorm event during an exceptional dry summer. The rainfall event (32.7 mm) took two hours and caused a local flash flood with peak discharges of 20-40 m^3/s (15 min time series) in the Griesler Ache, which lasted for approximately three hours without rising the lake level significantly (Fig. A.9). The local flash flood in the upper Kienbach catchment (2.1 km^2) mobilised large amounts of unconsolidated material, which was transported along its 2.7 km length via steep creeks downwards into Lake Mondsee (person. comm. by local service for river maintenance). Exceptional high concentrations of ^{137}Cs in the 1986 detrital layer indicate that the transported soil material has been largely contaminated through the Chernobyl accident three months before, in April 1986. Due to similar microfacies and geochemical composition, two other thick detrital layers (1941 and

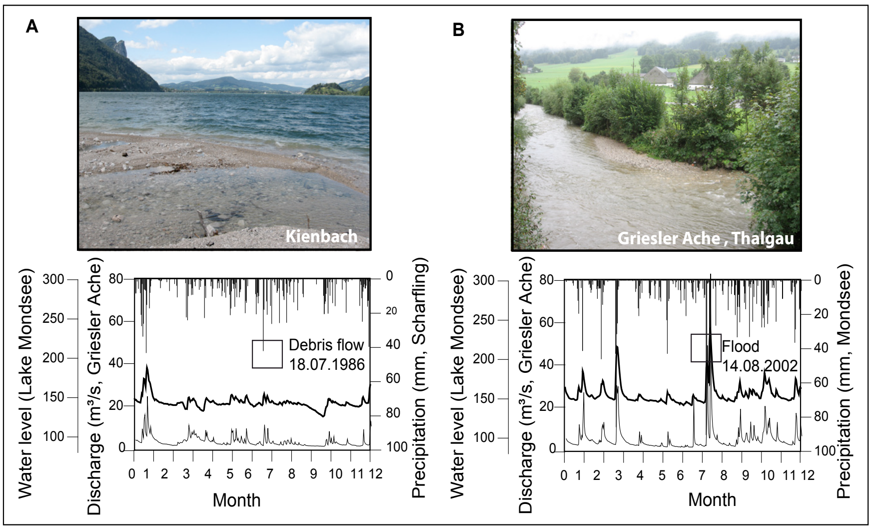


Figure A.9. Documentation of floods and debris flow in Lake Mondsee catchment. (A) above: Kienbach river and debris flow deposit near the river mouth, below: Hydrograph, lake water level and precipitation for the year 1986. A debris flow is documented on 18.07.1986 during dry summer. (B) above: River Griesler Ache, below: Hydrograph, lake water level and precipitation for 2002. An extreme flood is documented on 14.08.2002 after preceding rainfall events in June and July.

1923) might be also caused by such debris flow events. The latter mobilised the largest amount of material that resulted in the thickest detrital layer in the southern lake basin.

A.5.2 Flood event layers and sediment supply versus historical floods from Lake Mondsee

The deposition of nine detrital layers (detrital layer type 1) within the entire lake basin reflect flood occurrences in spring/summer. The sedimentary flood record agrees with discharge data of the last 30 years, which show a predominant flood occurrence in spring/summer after heavy precipitation events >50 mm/d (Fig. A.7). The most severe floods of the last 100 years within Lake Mondsee catchment occurred during the summer months of 2002, 1997, 1959 and 1954. All of them are recorded in the lake sediments. Additional floods as recorded in the sediments occurred in 1910, 1928, 1936, 1986 and 1994. These floods exhibit moderate flood peaks in the daily instrumental records. However, these floods are related to highest precipitation as recorded by instrumental data during the last 100 years (e.g. 27.05.1928: 108 mm at Kremsmünster, 03.07.1997: 103 mm at Mondsee/Scharfling, 11.04.1994: 98 mm at Mondsee/Scharfling) possibly have resulted in only short-term runoffs, which are not reflected by the daily mean runoff or lake level fluctuation. Interestingly, rare autumn and winter floods, which caused high lake water levels (e.g. December 1974, September 1920, February 1923), never caused detrital layer deposition. Also spring floods are only partly recorded in the sediment (Fig. A.8). A significant decrease in flood layer deposition occurs between 1960 and 1980 and corresponds to low spring/summer flood activity.

The detrital layer record of Lake Mondsee reflects the occurrence of spring and summer floods, whereas winter and autumn floods are missing. This particular detrital layer record is possibly due to multiple factors within the lake-catchment system. We consider three main limitations characterizing the sediment transport during flood events in Lake Mondsee: the rainfall characteristics, the sediment availability in the Griesler Ache catchment and the lake's thermal structure:

(i) Convective rainfall is particularly important for runoff generation especially in smaller river catchments and/or alpine regions (Merz and Blöschl, 2009). Intense rainfall is caused by convective meteorological processes and predominantly occurs in summer causing enhanced runoff and quick flow with a higher erosive potential than long-rain floods in autumn and winter (Merz et al., 2008). These processes might be particularly important for the Lake Mondsee catchment and the detrital layer formation in spring/summer.

(ii) Seasonal sediment availability. Although the vegetation cover is densest in summer and thus theoretically limits erosion power, the crop time is also influences sediment mobility (Richards, 2002). Dry summers favour the formation of a crusty soil surface, and higher sediment detachment is possibly enhanced by additional agricultural activities. During winter floods, frozen soils inhibit sediment erosion. For instance, the rain-on-snow event in December 1974 led to extreme flooding but without detrital layer deposition.

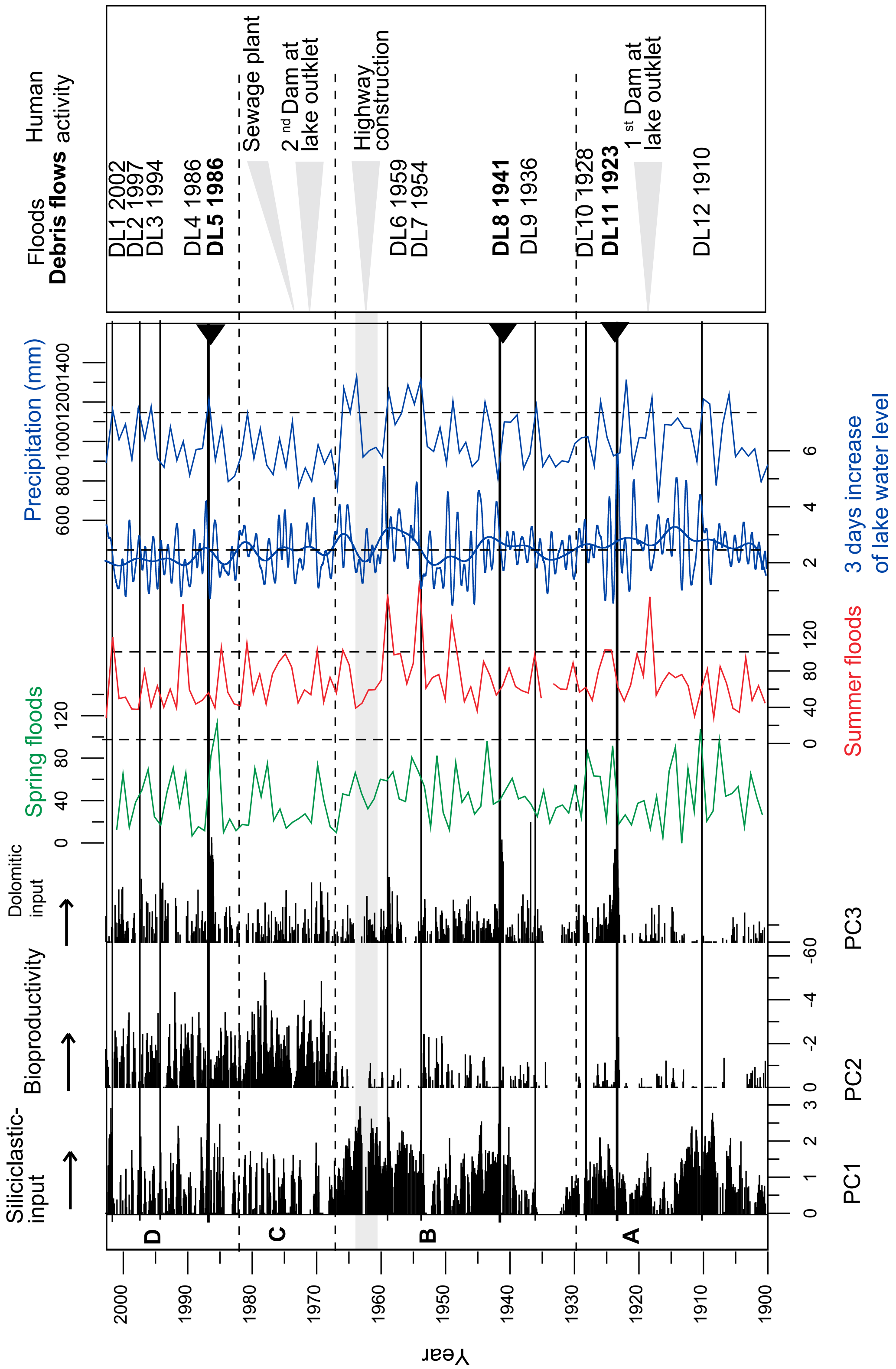
(iii) The thermal stratification of the lake water in summer promotes the generation of interflows along the thermocline along which catchment material into can be distributed basin-wide (Sturm and Matter, 1978). In contrast, a mixed lake water column favours a fast sediment deposition of the river water when entering the lake either by high- density underflows or low density dispersed flows (Mulder and Alexander, 2001). This might be the case in autumn and in winter when the lake water is mixed and overflowing/interflowing processes of turbidity currents are diminished.

The detrital layer record from Lake Mondsee reflects a series of flood events reflecting no significant human impact on layer abundance (Swierczynski et al., 2012). Despite a good correspondence between sediment supply and precipitation (Swierczynski et al., 2012), we detected a time period of sediment supply during 1960-1963, which is related to human activity, while precipitation was considerable low (Fig. A.10). This was due to the transport of material across the lake (shipping) that was used for the nearby highway construction (Einsele, 1963).

During the last 100 years, the variability in siliciclastic sediment supply to Lake Mondsee coincides with hydro-climatological changes as revealed from annual sums of precipitation (Swierczynski et al., 2012) and lake-level changes (Fig. A.10). Lake level changes coincide with wet phases during 1910-1915, 1920-1926, 1942-1946, and 1955-1962 (Fig. A.10), which are reflected by elevated sediment input during 1908-1915; 1924-1928; 1940-1947 and 1954-1966. Drier intervals with lower sediment supply (1916-1923; 1929-1940; after 1966) are in coincidence with lower lake water levels and generally decreased annual precipitation. However, while sediment supply is decreased after 1968 (unit C and D), five of twelve flood layers are deposited during that time indicating the occurrence of floods. Accordingly, flood layer deposition is not necessarily correlated to periods of the highest sediment supply and increased precipitation. This shows a decoupling of background sediment supply, which is introduced by the general runoff, and extreme flood events, which lead to distinct detrital layer deposition in Lake Mondsee.

(Figure A.10 is on the next page)

Figure A.10. Compilation of sediment data, instrumental time series and historical flood data about human activities within the catchment. Sediment core Mo-05P3 (Units A-D) with varve thickness and three main principal components (PC1-PC3). Instrumental data: Seasonal maximum of lake water level for spring and summer (red and green line, detrended time series), three-days-increase of lake water level (blue line, one-year and five year lowpass) and annual precipitation from climate station of Kremsmünster (blue line). Black lines indicate detrital layers.


Floods
Debris flows
Human activity
DL1 2002
DL2 1997
DL3 1994
DL4 1986
DL5 1986
Sewage plant
2 nd Dam at lake outklet
Highway construction
DL6 1959
DL7 1954
DL8 1941
DL9 1936
DL10 1928
DL11 1923
1 st Dam at lake outklet
DL12 1910
Precipitation (mm)
3 days increase of lake water level
Summer floods
Spring floods
Dolomitic input
Bioproductivity
Siliciclastic- input
PC1
PC2
PC3
A
B
C
D
Year

Interestingly, the occurrence of debris flow events introducing large amount of sediments into the lake occur during relatively dry summers. However, heavy precipitation (convective rainfall) potentially causing extreme flood events in this area may increase the probability for enhanced debris flow events such as on 18. July of 1986 and as assumed for the summers of 1941 and 1923.

A.6 Conclusion

Annually laminated sediments of Lake Mondsee of the last 100 years contain detrital layers of minerogenic and organic catchment material. By using a combination of microfacies analysis and µXRF element data, we were able to distinguish between different processes of debris flows in summer and floods in spring and summer. Thin detrital layers with a basin-wide distribution, are related to spring and summer runoff events, which increase the lake water level of at least 50 cm within one to four days. Interestingly, autumn and winter floods are not reflected by geochemical data from the short core of the southern lake basin nor by microfacies analysis. We conclude that the relation of seasonal hydrological-meteorological processes and detrital layer deposition in the lake basin can be better understood when applying a combined lake-catchment approach including monitoring of recent processes.

The identification of the seasonality of detrital layers within varved lake sediments for pre-instrumental time helps to understand hydrological variability in sub-annual resolution under changing climate boundary conditions. Nowadays, the occurrence of boulders and enrooted trees in the creeks suggest a large potential for recurring debris flow events at the same order. Identifying debris flow events in the past, helps to assess the risk of instantaneous mass movements for the present-day human settlements in the vicinity of the lake.

Acknowledgements

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A.7 Data repository (DR)

Table A.1. Correlation coefficients for elemental composition of the sediment core Mo-05P3.

	Mg	Al	Si	S	K	Ca	Ti	Mn	Fe	Sr
Sr	-0.071595	0.33945	0.38704	0.21373	0.42231	0.44917	0.33433	0.28674	0.33027	1
Fe	0.056441	0.62606	0.78787	0.22563	0.71647	0.38675	0.75129	0.53029	1	0.33027
Mn	-0.054842	0.33528	0.42666	0.47132	0.48788	0.62504	0.41706	1	0.53029	0.28674
Ti	0.25661	0.86467	0.84268	0.10908	0.87819	0.39742	1	0.41706	0.75129	0.33433
Ca	0.055779	0.38782	0.38239	0.56788	0.58866	1	0.39742	0.62504	0.38675	0.44917
K	0.23062	0.90436	0.85681	0.21939	1	0.58866	0.87819	0.48788	0.71647	0.42231
Rh	-0.16403	-0.67315	-0.64603	-0.28947	-0.71169	-0.58642	-0.61437	-0.41375	-0.4639	-0.39003
S	-0.10299	0.082104	0.16753	1	0.21939	0.56788	0.10908	0.47132	0.22563	0.21373
Si	0.11414	0.86918	1	0.16753	0.85681	0.38239	0.84268	0.42666	0.78787	0.38704
Al	0.35847	1	0.86918	0.082104	0.90436	0.38782	0.86467	0.33528	0.62606	0.33945

Table A.2. PCs from PCA of elemental composition of the sediment core Mo-05P3 with loadings and total variances.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
Variance (%)	52.957	16.984	9.55	7.7452	4.7087	3.8256	2.4818	1.4579	0.80442	0.48558
Mg	0.087659	0.39758	0.79522	-0.19458	0.14807	-0.34775	0.019213	-0.075135	0.064354	-0.10487
Al	0.38318	0.2861	0.041369	-0.048453	-0.17457	0.23574	-0.32231	-0.17947	-0.25701	0.69215
Si	0.3943	0.16358	-0.21253	0.10117	-0.18985	-0.032129	-0.14737	-0.54326	0.56229	-0.30376
S	0.15395	-0.55821	0.30955	0.14714	-0.6489	-0.2876	-0.17919	0.092979	-0.051373	-0.0068
K	0.41489	0.11082	0.011007	-0.029168	-0.07617	0.30173	0.016647	0.048915	-0.59515	-0.60074
Ca	0.28742	-0.40836	0.29823	-0.18104	0.11832	0.49383	0.53081	-0.1181	0.23359	0.14413
Ti	0.39177	0.22693	-0.060402	0.086797	-0.047292	0.044923	-0.002987	0.79452	0.38464	0.01922
Mn	0.27786	-0.38233	0.092164	0.31231	0.66983	-0.070178	-0.46543	-0.0051391	-0.015376	-0.01037
Fe	0.36099	0.035239	-0.22286	0.29131	0.10261	-0.54629	0.5724	-0.090022	-0.2318	0.18837
Sr	0.22487	-0.20918	-0.27213	-0.83926	0.096207	-0.31538	-0.12493	0.051381	-0.017413	-0.00015

Table A.1. Thickness of detrital layers (mm) as recorded in the short cores covering the last 100 years. Detrital layers, which are mainly composed of organic fragments (leaves, etc.), are indicated by ‘org’

Detrital layer (no.)	Varve year	Mo05 P3	Mo05 P5	Mo07 SC1	Mo07 SC2	Mo07 SC3	Mo07 SC4	Mo07 SC5	Mo07 SC6	Mo07 SC7	Mo07 SC8	Mo07 SC9
		mm										
DL1	2002	0.05	<0.05	0.4	0.2	0.6	0.2	slump	slump	0.3	4	1.5
DL2	1997	0.1	0.1	0.5	1	0.6	0.2	slump	slump	0.3	0.1	3
DL3	1994	0.6	0.4	0.1	1.6	1.4	0.5	slump	slump	0.1	1.5	3
DL4	1986	0.1	0.1	0.1	0.3	0.6	0.2	slump	slump	<0.05	1.5	0.5
DL5	1986	6	5.5	0.4 (org)	5.2	10 (org)	7.3	slump	slump	0.2	-	2
DL6	1959	0.3	0.2	0.6	0.4	0.4	0.1	<0.05	<0.05	3.2	3	5
DL7	1954	<0.05	0.05	0.4	0.2	0.8	<0.05	<0.05	<0.05	-	-	3.9
DL8	1941	4.5	3	-	3 (org)	1.4 (org)	5	-	3.6	0.5	no data	8
DL9	1936	0.8	0.2	-	0.8	1.4	0.3	-	slump	2	no data	no data
DL10	1928	0.3	0.3	-	-	-	0.6	-	slump	-	no data	no data
DL11	1923	15	25	1 (org)	30 (org)	20 (org)	17	4	3.2	-	no data	no data
DL12	1910	<0.05	<0.05	0.4	-	-	<0.05	<0.05	<0.05	-	no data	no data

org: high content of phyto-macrorests (e.g. leaves)

Appendix B

Composite Depth	Varve years	Varve years	Detrital layer	Event layer	Debris flows layers	Flood layers	seasonality				
(mm)	(A.D. / B.C.)	(yr B.P.)	(no.)	(mm)	(thickness in mm)	(thickness in mm)	Spring	Summer	Autumn	Winter	?
0.35	2002	-52	DL1	0.06		0.06		1			
1.30	1997	-47	DL2	0.1		0.1		1			
1.80	1994	-44	DL3	0.7		0.7	1				
3.30	1986	-36	DL4	0.25		0.25		1			
3.80	1986	-36	DL5	3.6	3.6			1			
10.40	1959	-9	DL6	0.25		0.25		1			
11.50	1954	-4	DL7	0.1		0.1		1			
15.10	1941	9	DL8	1	1			1			
16.20	1936	14	DL9	0.5		0.5		1			
17.50	1928	22	DL10	0.6		0.6	1				
20.90	1923	27	DL11	7.7	7.7			1			
23.60	1910	40	DL12	0.1		0.1	1				
25.60	1897	53	DL13	0.1		0.1		1			
27.70	1882	68	DL14	0.35		0.35		1			
32.60	1850	100	DL15	0.3		0.3			1		
33.10	1847	103	DL16	0.1		0.1			1		
37.50	1818	132	DL17	0.45	0.9			1			
39.20	1814	136	DL18	0.1		0.1		1			
41.00	1802	148	DL19	0.1		0.1		1			
43.20	1791	159	DL20	0.2		0.2		1			
44.30	1784	166	DL21	0.1		0.1	1				
45.80	1773	177	DL22	0.4		0.4		1			
47.60	1762	188	DL23	0.1		0.1		1			
53.70	1729	221	DL24	0.5		0.5		1			
54.20	1727	223	DL25	1.5	1.5			1			
55.80	1717	233	DL26	0.3		0.3	1				
57.10	1708	242	DL27	0.2		0.2	1				
70.20	1628	322	DL28	1.3	1.3			1			
73.75	1605	345	DL29	0.1		0.1	1				
73.95	1603	347	DL30	0.1		0.1		1			
74.30	1600	350	DL31	0.1		0.1		1			
78.10	1580	370	DL32	0.08		0.08	1				

78.90	1576	374	DL33	0.1		0.1	1				
82.20	1562	388	DL34	0.15		0.15		1			
86.80	1535	415	DL35	3	3			1			
89.20	1517	433	DL36	0.35		0.35		1			
91.00	1505	445	DL37	0.15		0.15			1		
92.30	1497	453	DL38	0.2		0.2					?
94.00	1489	461	DL39	0.2		0.2		1			
94.20	1488	462	DL40	0.09		0.09		1			
94.30	1487	463	DL41	0.1		0.1		1			
94.50	1486	464	DL42	0.25		0.25		1			
94.80	1485	465	DL43	0.65	0.65			1			
95.30	1484	466	DL44	4.2	4.2			1			
95.40	1483	467	DL45	0.08		0.08		1			
95.50	1482	468	DL46	0.25		0.25		1			
95.75	1481	469	DL47	0.1		0.1		1			
96.80	1476	474	DL48	0.19		0.19		1			
98.50	1468	482	DL49	1.9	1.9			1			
101.95	1453	497	DL50	0.11		0.11				1	
102.90	1446	504	DL51	0.3		0.3	1				
103.00	1445	505	DL52	0.14		0.14	1				
106.90	1424	526	DL53	0.1		0.1		1			
110.45	1397	553	DL54	0.1		0.1	1				
112.50	1387	563	DL55	0.15		0.15		1			
112.95	1384	566	DL56	0.35		0.35		1			
113.30	1380	570	DL57	1.4	1.4			1			
115.20	1370	580	DL58	0.55		0.55		1			
116.30	1362	588	DL59	0.25		0.25	1				
116.50	1360	590	DL60	0.1		0.1		1			
118.00	1351	599	DL61	0.1		0,1		1			
122.80	1324	626	DL62	0.09		0.09	1				
122.95	1323	627	DL63	0.1		0.1	1				
123.30	1321	629	DL64	0.8		0.8	1				
123.95	1318	632	DL65	0.11		0.11	1				
124.10	1317	633	DL66	0.09		0.09	1				

124.30	1315	635	DL67	0.19		0.19	1				
124.50	1314	636	DL68	0.08		0.08	1				
127.30	1301	649	DL69	0.1		0.1		1			
127.40	1300	650	DL70	0.29		0.29		1			
134.50	1262	688	DL71	0.4		0.4				1	
141.80	1209	741	DL72	0.35		0.35		1			
143.50	1199	751	DL73	0.15		0.15		1			
148.20	1168	782	DL74	0.2		0.2	1				
148.90	1164	786	DL75	0.08		0.08		1			
149.20	1162	788	DL76	0.1		0.1	1				
151.00	1150	800	DL77	0.35		0.35		1			
152.00	1146	804	DL78	0.09		0.09	1				
152.25	1145	805	DL79	0.15		0.15		1			
153.50	1138	812	DL80	0.15		0.15		1			
154.00	1135	815	DL81	0.35		0.35		1			
154.35	1133	817	DL82	0.4		0.4		1			
154.65	1131	819	DL83	0.07		0.07		1			
154.75	1130	820	DL84	0.2		0.2		1			
154.95	1129	821	DL85	0.9	0.9			1			
156.80	1115	835	DL86	0.15		0.15		1			
156.90	1114	836	DL87	0.55		0.55		1			
159.35	1095	855	DL88	1		1					?
162.10	1074	876	DL89	0.4		0.4	1				
162.30	1073	877	DL90	0.35		0.35	1				
162.40	1072	878	DL91	0.1		0.1	1				
162.50	1071	879	DL92	0.15		0.15	1				
164.90	1052	898	DL93	2.3	2.3			1			
167.30	1036	914	DL94	1.2	1.2			1			
173.05	1001	949	DL95	0.09		0.09	1				
173.50	997	953	DL96	0.06		0.06	1				
173.60	996	954	DL97	0.39		0.39	1				
179.70	957	993	DL98	0.22		0.22		1			
183.15	931	1019	DL99	0.1		0.1		1			
183.50	929	1021	DL100	0.08		0.08		1			

183.60	928	1022	DL101	0.18		0.18		1			
183.80	926	1024	DL102	0.08		0.08		1			
187.40	901	1049	DL103	0.08		0.08	1				
187.50	900	1050	DL104	0.07		0.07	1				
189.10	886	1064	DL105	0.43		0.43		1			
190.00	876	1074	DL106	0.15		0.15		1			
190.25	875	1075	DL107	0.49		0.49		1			
196.50	817	1133	DL108	0.08		0.08					?
196.80	816	1134	DL109	0.1		0.1					?
197.30	813	1137	DL110	0.59		0.59					?
200.30	795	1155	DL111	1.05	1.05			1			
202.00	786	1164	DL112	0.29		0.29		1			
202.65	783	1167	DL113	0.42		0.42		1			
206.00	765	1185	DL114	0.08		0.08		1			
207.45	754	1196	DL115	0.14		0.14		1			
207.55	753	1197	DL116	0.3		0.3	1				
207.90	752	1198	DL117	1.55	1.55			1			
210.20	732	1218	DL118	0.14		0.14	1				
211.50	722	1228	DL119	0.29		0.2		1			
211.60	721	1229	DL120	0.52		0.59	1				
211.90	719	1231	DL121	0.11		0.11	1				
212.10	717	1233	DL122	0.21		0.21	1				
212.30	715	1235	DL123	0.14		0.14	1				
212.70	711	1239	DL124	0.24		0.24		1			
213.00	709	1241	DL125	0.9	0.9			1			
213.45	704	1246	DL126	0.29		0.29		1			
218.30	665	1285	DL127	0.09		0.09		1			
221.80	642	1308	DL128	0.15		0.15		1			
224.60	620	1330	DL129	0.08		0.08		1			
225.95	617	1333	DL130	6.5	6.5			1			
229.00	597	1353	DL131	0.55		0.55		1			
229.20	596	1354	DL132	0.15		0.15		1			
229.50	594	1356	DL133	0.12		0.12		1			
229.55	593	1357	DL134	0.11		0.11		1			

229.75	592	1358	DL135	0.49		0.49	1				
230.00	591	1359	DL136	0.9		0.9	1				
230.10	590	1360	DL137	0.25		0.25	1				
230.20	589	1361	DL138	0.49		0.49	1				
232.00	588	1362	DL139	26	26			1			
235.80	564	1386	DL140	0.22		0.22			1		
236.20	561	1389	DL141	0.19		0.19		1			
239.50	538	1412	DL142	0.29		0.29		1			
239.70	537	1413	DL143	0.15		0.15		1			
240.00	534	1416	DL144	1.8	1.8			1			
244.25	506	1444	DL145	0.12		0.12		1			
245.80	500	1450	DL146	5.5	5.5			1			
249.20	475	1475	DL147	0.14		0.14		1			
249.30	474	1476	DL148	0.94	0.94			1			
253.70	451	1499	DL149	0.22		0.22	1				
253.90	450	1500	DL150	0.09		0.09		1			
254.10	449	1501	DL151	0.08		0.08		1			
254.30	448	1502	DL152	0.06		0.06		1			
254.40	447	1503	DL153	0.16		0.16		1			
254.70	446	1504	DL154	2.7	2.7			1			
255.70	439	1511	DL155	0.08		0.08		1			
260.55	407	1543	DL156	0.21		0.21		1			
260.65	406	1544	DL157	0.35		0.35		1			
264.75	381	1569	DL158	0.2		0.2	1				
269.70	350	1600	DL159	0.2		0.2		1			
272.40	334	1616	DL160	0.39		0.39			1		
274.05	325	1625	DL161	0.24		0.24			1		
280.50	276	1674	DL162	0.2		0.2	1				
280.63	275	1675	DL163	0.98	0.98			1			
282.50	259	1691	DL164	0.24		0.24		1			
284.50	246	1704	DL165	0.3		0.3		1			
288.50	217	1733	DL166	0.09		0.09		1			
324.64	-22	1972	DL167	0.14		0.14					?
331.33	-76	2026	DL168	0.14		0.14					?

331.50	-77	2027	DL169	0.12		0.12					?
331.67	-78	2028	DL170	0.29		0.29					?
331.83	-79	2029	DL171	0.16		0.16					?
332.00	-80	2030	DL172	0.06		0.06					?
332.17	-81	2031	DL173	0.27		0.27					?
332.33	-82	2032	DL174	2.5	2.5			1			
336.33	-110	2060	DL175	0.33		0.33					?
336.50	-111	2061	DL176	0.72	0.72			1			
337.50	-116	2066	DL177	0.39		0.39					?
340.70	-143	2093	DL178	0.5		0.5					?
343.10	-162	2112	DL179	0.2		0.2					?
345.50	-181	2131	DL180	0.16		0.16					?
346.40	-188	2138	DL181	0.1		0.1					?
352.70	-230	2180	DL182	0.1		0.1					?
352.95	-232	2182	DL183	0.1		0.1					?
354.50	-241	2191	DL184	0.16		0.16					?
359.40	-277	2227	DL185	0.3		0.3					?
359.50	-278	2228	DL186	0.5		0.5					?
372.20	-368	2318	DL187	0.1		0.1					?
392.50	-498	2448	DL188	0.82		0.82					?
395.00	-516	2466	DL189	0.3		0.3					?
403.90	-577	2527	DL190	0.22		0.22					?
404.00	-578	2528	DL191	0.5		0.5					?
420.10	-697	2647	DL192	1.4		1.4					?
433.80	-782	2732	DL193	15	15			1			
435.80	-797	2747	DL194	0.2		0.2					?
437.90	-815	2765	DL195	0.84		0.84					?
438.30	-818	2768	DL196	1.6		1.6					?
438.50	-820	2770	DL197	0.86		0.86					?
438.80	-822	2772	DL198	0.82		0.82					?
439.50	-828	2778	DL199	0.99		0.99					?
441.10	-830	2780	DL200	10	10			1			
443.20	-850	2800	DL201	0.7		0.7					?
451.50	-914	2864	DL202	0.28		0.28					?

468.40	-1042	2992	DL203	0.24		0.24					?
469.13	-1048	2998	DL204	0.09		0.09					?
469.38	-1050	3000	DL205	7	7			1			
471.50	-1064	3014	DL206	0.12		0.12					?
473.00	-1078	3028	DL207	0.06		0.6					?
473.30	-1081	3031	DL208	0.12		0.12					?
484.50	-1174	3124	DL209	0.48		0.48					?
489.63	-1223	3173	DL210	0.1		0.1					?
499.20	-1308	3258	DL211	0.2		0.2					?
499.63	-1312	3262	DL212	0.1		0.1					?
500.25	-1317	3267	DL213	0.22		0.22					?
500.80	-1322	3272	DL214	0.7		0.7					?
501.61	-1330	3280	DL215	0.22		0.22					?
502.17	-1335	3285	DL216	0.18		0.18					?
502.28	-1336	3286	DL217	0.12		0.12					?
502.39	-1337	3287	DL218	0.22		0.22					?
502.50	-1338	3288	DL219	2.4	2.4			1			
505.80	-1370	3320	DL220	0.1		0.1					?
506.30	-1375	3325	DL221	0.5		0.5					?
510.28	-1415	3365	DL222	0.1		0.1					?
510.39	-1416	3366	DL223	0.34		0.34					?
510.50	-1417	3367	DL224	0.2		0.2					?
511.60	-1418	3368	DL225	0.2		0.2					?
511.70	-1419	3369	DL226	1.8	1.8			1			
524.45	-1510	3460	DL227	0.24		0.24					?
525.00	-1515	3465	DL228	0.44		0.44					?
525.20	-1516	3466	DL229	0.3		0.3					?
531.50	-1572	3522	DL230	0.18		0.18					?
532.30	-1577	3527	DL231	0.28		0.28					?
532.90	-1582	3532	DL232	0.12		0.12					?
533.50	-1588	3538	DL233	5	5			1			
541.90	-1664	3614	DL234	2.2		2.2					?
553.50	-1773	3723	DL235	1		1					?
554.35	-1780	3730	DL236	0.35		1					?

561.40	-1832	3782	DL237	0.05		0.05					?
564.80	-1857	3807	DL238	3.5	3.5			1			
564.90	-1858	3808	DL239	2.3	2.3			1			
566.50	-1870	3820	DL240	1.4		1.4					?
572.50	-1920	3877	DL241	0.25		0.25					?
579.50	-1990	3940	DL242	0.3		0.3					?
582.00	-2013	3963	DL243	7.5	7.5			1			
587.40	-2063	4013	DL244	0.25		0.25					?
598.00	-2161	4111	DL245	1		1					?
602.50	-2203	4153	DL246	0.6		0.6					?
615.30	-2348	4298	DL247	0.15		0.15					?
618.80	-2392	4342	DL248	0.25		0.25					?
629.70	-2528	4478	DL249	0.22		0.22					?
630.20	-2535	4485	DL250	0.1		0.1					?
630.40	-2537	4487	DL251	0.2		0.2					?
631.30	-2548	4498	DL252	4.5	4.5			1			
636.00	-2607	4557	DL253	0.3		0.3					?
641.70	-2678	4628	DL254	0.35		0.35					?
642.40	-2687	4637	DL255	0.2		0.2					?
644.10	-2708	4658	DL256	0.15		0.15					?
647.00	-2741	4691	DL257	0.15		0.15					?
649.00	-2770	4720	DL258	0.25		0.25					?
649.80	-2780	4730	DL259	2.5	2.5			1			
653.40	-2822	4772	DL260	0.8		0.8					?
654.60	-2837	4787	DL261	0.05		0.05					?
660.70	-2908	4858	DL262	0.15		0.15					?
661.40	-2917	4867	DL263	8	8			1			
662.80	-2933	4883	DL264	1.5		1.5					?
663.30	-2951	4901	DL265	0.9		0.9					?
664.40	-2952	4902	DL266	0.8		0.8					?
671.80	-3039	4989	DL267	0.9		0.9					?
675.60	-3084	5034	DL268	0.7		0.7					?
677.40	-3105	5055	DL269	0.7		0.7					?
677.50	-3106	5056	DL270	1.4	1.4			1			

679.50	-3129	5079	DL271	0.9		0.9					?
681.60	-3154	5104	DL272	0.9		0.9					?
681.80	-3156	5106	DL273	0.5		0.5					?
682.00	-3159	5109	DL274	0.6		0.6					?
682.40	-3163	5113	DL275	3	3			1			
696.50	-3329	5279	DL276	1		1					?
697.50	-3341	5291	DL277	0.4		0.4					?
702.50	-3399	5349	DL278	1.5		1.5					?
705.80	-3435	5385	DL279	0.9		0.9					?
706.00	-3441	5391	DL280	0.5		0.5					?
707.00	-3452	5402	DL281	0.9		0.9					?
707.80	-3462	5412	DL282	2.5	2.5			1			
709.90	-3487	5437	DL283	0.8		0.8					?
717.00	-3571	5521	DL284	0.5		0.5					?
718.80	-3592	5542	DL285	1.3		1.3					?
724.00	-3653	5603	DL286	0.6		0.6					?
732.50	-3753	5703	DL287	0.4		0.4					?
733.40	-3764	5714	DL288	0.6		0.6					?
737.40	-3811	5761	DL289	0.9		0.9					?
739.50	-3835	5785	DL290	5	5			1			
741.30	-3856	5806	DL291	0.7		0.7					?
742.50	-3871	5821	DL292	0.8		0.8					?
743.50	-3882	5832	DL293	0.3		0.3					?
750.80	-3968	5918	DL294	3	3			1			
752.00	-3982	5932	DL295	1		1					?
755.50	-4023	5973	DL296	0.3		0.3					?
756.40	-4034	5984	DL297	0.9		0.9					?
768.00	-4170	6120	DL298	5	5			1			
770.00	-4194	6144	DL299	1		1					?
770.50	-4200	6150	DL300	1		1					?
772.40	-4218	6168	DL301	0.4		0.4					?
778.00	-4288	6238	DL302	1.7		1.7					?
784.50	-4364	6314	DL303	0.3		0.3					?
790.50	-4435	6385	DL304	0.7		0.7					?

	793.30	-4468	6418	DL305	0.9	0.9			1			
	794.00	-4476	6426	DL306	0.9		0.9					?
	796.50	-4506	6456	DL307	0.9		0.9					?
	797.00	-4512	6462	DL308	1		1					?
	797.50	-4518	6468	DL309	1.1		1.1					?
	811.30	-4681	6631	DL310	1.4	1.4			1			
	812.50	-4696	6646	DL311	0.9		0.9					?
	816.70	-4749	6699	DL312	32	32			1			
	820.50	-4796	6746	DL313	0.4		0.4					?
	823.50	-4834	6784	DL314	0.4		0.4					?
	825.50	-4859	6809	DL315	0.8		0.8					?
	847.30	-5131	7081	DL316	1.1		1.1					?

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Erklärung

Hiermit erkläre ich gemäß § 9 Abs. 7 der Promotionsordnung der Mathematisch- Naturwissenschaftlichen Fakultät der Universität Potsdam, dass ich die von mir vorgelegte Dissertation mit dem Titel

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Swierczynski, T., Brauer, A., Lauterbach,S., Martín-Puertas, C., Dulski, P., Grafenstein,U.v., Rohr, C. (2012). A 1600-year seasonally resolved record of decadal-scale flood variability from the Austrian pre-Alps. *Geology. Doi: 10.1130/G33493.1*

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Swierczynski, T., Lauterbach, S., Brauer, A. (2012). The Late Neolithic Mondsee Culture-living on lakes and living with floods. *In pre-review, to be submitted to Climate of the Past*

Potsdam, den 02.10.2012