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Water level variability and trends in Lake Constance in the light of the 1999 centennial flood

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Abstract

The extreme flood of Lake Constance in 1999 focused attention on the variability of annual lake levels. The year 1999 not only brought one of the highest floods of the last 180 years but also one of the earliest in the season. The 1999 extreme event was caused by heavy rainfall in the alpine and pre-alpine regions. The influence of precipitation in the two distinct regional catchments on lake level variations can be quantified by correlation analysis. The long-term variations in lake level and precipitation show similar patterns. This is seen through the use of spectral analysis, which gives similar bands of spectral densities for precipitation and lake level time series. It can be concluded from the comparison of these results with the analysis of climate change patterns in northern Europe, i.e. the index of the North Atlantic Oscillation, that the regional effects on lake level variations are more pronounced than those of global climate change.

Key words: Lake Constance – lake level – climate change – spectral analysis – extreme values – reed decline

Introduction

Lake Constance has a surface area of 529 km^2 and is max. 253 m deep, making it the largest northern pre-alpine lake (Ostendorp et al. 2003). It receives the largest part of its water from its alpine catchment area (62.4% by area, 79.7 % by water volume) and from the pre-alpine catchment area (13.3 % resp. 8.6%) (Luft et al. 1990). The seasonal course of the lake level is mainly determined by the alpine climate. The lake level declines in winter, reaching its minimum at the end of February, when precipitation in the catchment is to a large extent stored as snow. It reaches its maximum level in June/July due to increased precipitation and snowmelt in spring. Lake Constance, aside from Lake Walensee, Switzerland, is the only large, unregulated lake of the alpine region, and variations in lake level are to a large extent the result of regional climate conditions. Changes in precipitation and therefore run-off in the catchment area of Lake Constance directly influence extreme values and the main trend of the water level. Regular daily water gauge records started in 1816 covering till now a time series of more than 185 years, making it one of the longest, continuously recorded hydrological time series. The severe flood of 1999, which not only caused economic damage but also a decline in reed stands (Schmieder et al. 2002; Dienst et al. 2004), led to the question to what extent is the lake level driven by regional or global climate fluctuations.

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The water level time series of the years 1817–2000 are based on the readings at Konstanz corresponding to a zero level of 391.89 m above sea level. The data provided were corrected for reading errors occurring between 1817 and 1825 (Hydrographisches Zentralbureau – HZ 1913). As a result of the correction, the extreme lake levels of 1817 and 1821 were changed from 636 cm to 623 cm (HZ 1913), and from 591 cm to 568 cm (HZ 1913) respectively. This implies that in the analysis of extreme values, the year 1821 does not rank second, as in, for example, Petrascheck & Hegg (2000), but third.

The extreme flood of 1999

The flood of 1999 was the result of three low-pressure systems that caused heavy precipitation in front of the alpine main divide between May 11–14, May 19–21 and June 2–3. As a consequence of the precipitation the water level of Lake Constance (Fig. 1) rose approximately 5 cm/d until May 11 increasing thereafter by 20 cm/d, so that on May 15 a level of 492 cm was reached. Immediately after May 21 the level increased by another 39 cm/d and reached the highest water level of 564 cm on May 24. After an intermediate drop, the level of Lake Constance responded to heavy rain between June 2–3 with an increase up to 562 cm on June 5, and after heavy precipitation on June 10 rose to 564 cm, the highest level in June. The water level decreased quickly by 4–5 cm/d in the period of low rain that followed. By the end of June the level of Lake Constance had decreased to 495 cm, which was only approximately 61 cm above the long-term average for this date.

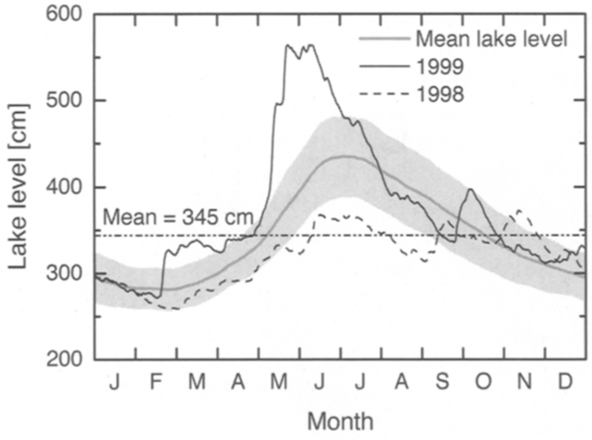

Fig. 1. Daily lake levels at Konstanz for the years 1998 and 1999, mean daily values and standard deviation (grey band) for the period 1817–2002. The values shown are not corrected with respect to break points and trends.

Analysis of lake level time series

Trend analysis

Both the height of the water level and the timing of the flood of 1999 may be regarded as extraordinary events. Hence, the flood of 1999 should be viewed in the context of the available long-term time series of the levels of Lake Constance, which allows a detailed analysis of water levels for time-scales from weeks to many decades.

Beside the natural variations in water flow into the lake determined by precipitation and storage in the form of snow and ice, anthropogenic changes play a role, especially the building of power station reservoirs in the alpine Rhine catchment area and the changing of hydraulic discharge conditions at Stein am Rhein. The extension of power station reservoirs took place primarily in the time from approximately 1950 to 1970 (Luft & Vieser 1990; Luft et al. 1990), but detailed figures of stored or released water volumes are not available. As a result of these technical measures a small increase in the low water inflows and a small decrease in the high water inflows have been observed since the 1960's, which accordingly affected the water levels of Lake Constance.

Seasonal trend decomposition based on Loess (Cleveland et al. 1990; Insightful Corp. 2001) applied to the daily time series yields local trends and seasonal variations (Fig. 2). A decrease in seasonal variation ap-

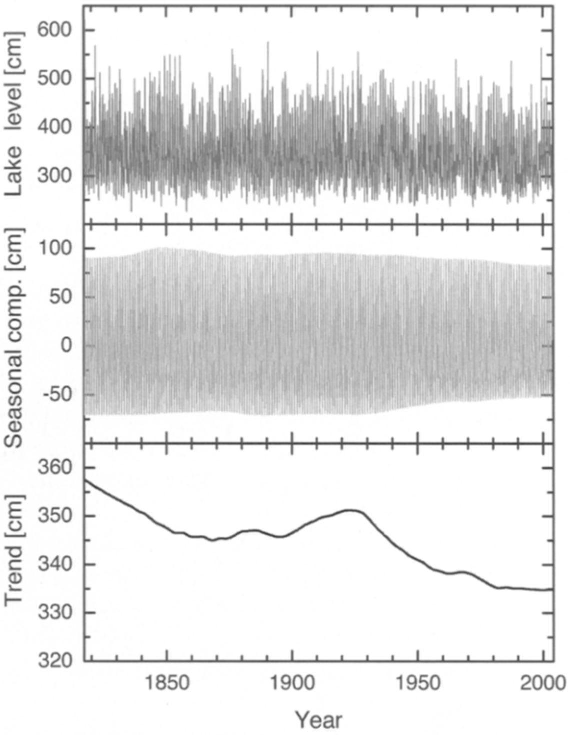

Fig. 2. Decomposition of the lake level time-series into seasonal component and trend.

pears from 1940 onwards. The decrease in seasonal variation from approximately 175 cm at the beginning of the 19th century to approximately 140 cm at the end of the 20th century can only partially be explained by the construction of the power station reservoirs, as this took place in the 50s and 60s of the last century.

Along with the seasonal components, the trend in the actual level of Lake Constance also shows significant change. A general decline, interrupted by a plateau from 1860 to 1895, followed by a short-term increase in the years up to 1925 is detected. Thereafter, a strong decrease in water level was established. The trend over the last two decades shows a decrease of 0.13 cm/year and seems to weaken nowadays. While the strong changes around 1940 had been already discussed many times (LUFT & VIESER 1990; LUFT et al. 1990; DIENST 1994), it appears that the phase of temporary increase in the average water level from 1895 to 1925 went largely unnoticed. In fact, it was pointed out, that "*the water levels during the time from 1817 to 1900 did not show any spectacular trends or inhomogeneities*" (LUFT & VIESER 1990). This must be objected to, if one looks at the computed trend in Fig. 2. Up until now, no clear explanation for the break point of the time series around 1940 could be given (LUFT & VIESER 1990; LUFT et al. 1990). To what extent these tendencies have been caused by the changes in the hydraulic discharge conditions can only be speculated upon since no detailed hydraulic model simulations are available. A climatic influence on the lake level of Lake Constance must also be considered.

Extreme value distribution

The analysis of extreme values taking into account the local trends provide a more detailed picture of the appearance of high and low water levels and their changes over the last centuries. In Table 1 the five largest flood events on Lake Constance are shown, according to the data used here.

Table 1. Rank of the five largest flood levels during the period 1817–2000 for the original and detrended time series. The values are based on the corrected lake levels for the years 1817–1826 (HZ 1913). Uncorrected values are given in brackets. The second figure in each column gives the rank of the event.

Year	Flood level / rank [cm]	Flood level / rank detrended [cm]
1817	623 (636) / 1	623 / 1
1890	576 / 2	587 / 3
1821	568 (591) / 3	570 / 5
1999	565 / 4	589 / 2
1876	561 / 5	573 / 4

The extreme flood of 1999 is distinguished not only by the water level that was reached, but also by its very early occurrence of the maximum level in the year. Usually the maximum level is reached during early July, however, the flood peak of 1999 occurred in May. Except for the years 1818 and 1964, in which the maximum water level (although far below the high water mark) was reached eight and two days earlier, respectively, it was the earliest day of maximum flood level since begin of the recordings.

In order to quantify the significance of the 1999 flood under the trend of the water level during the last two centuries, the distribution of the annual highest daily levels of the corrected water levels and the trend-eliminated time series were fitted using general extreme value distributions,

$$G_{\gamma,\mu,\sigma}(x) = \exp\left(-\left(1+\gamma\frac{(x-\mu)}{\sigma}\right)^{-1/\gamma}\right)$$

with average μ, standard deviation σ and shape parameter γ (GUMBEL 1958; REISS & THOMAS 2001). The distribution function for the trend-eliminated time series is shown in Fig. 3. The fitted standard deviations for original and trend-eliminated time series differ only slightly (43.4 cm and 43.0 cm, respectively) as did the shape parameters (–0.184 and –0.199, respectively). However, the differences in recurrence periods are obvious (Table 2). Analysis of the original time series shows that a flood like the one in 1999 has a probability of occurring once in every 44 years. However, when one takes into consideration a non-linear trend, it has an average return-period of 96 years. A trend-elimination results in an increase in the water levels of approximately 9 cm for a return period of 100 years.

Thus accounting for the non-linear trend, the flood of 1999 has to be described as a centennial flood. If in addition the effect of the reservoirs is taken into considera-

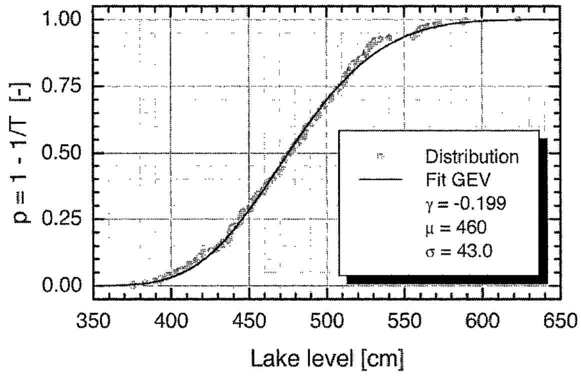

Fig. 3. Sample distribution of detrended annual maximum lake levels and fit with a generalized extreme value (GEV) distribution, where p is the probability and T the return period.

Table 2. Return periods (T) of some flood levels for original (HW) and detrended (HW-trend) lake levels.

Year	HW [cm]	T [years]	HW-trend [cm]	T-trend [years]
1999	565	44	589	96
1890	576	75	587	86
1821	561	37	573	41
	527	10	538	10
	581	100	590	100
	616	1000	621	1000

tion, increased values are obtained. In the time period May 10–24, 1999, approximately 82 x 10^6 m^3 of water was withheld in reservoirs (Petrascheck & Hegg 2000), corresponding to a water level difference of approximately 15 cm in Lake Constance. The trend of decreasing water levels and the retention of water in the reservoirs has clearly decreased the probability of damage with regard to floods.

Time series analysis and climatic influence

The very long time series of the water levels, with approximately 68000 daily measurements spanning 187 years, allows very precise analysis of the contained periodical cycles. Correlations with climatic processes can be identified by comparison with the spectra of other time series.

European climate variability has been shown to be strongly linked to the North Atlantic Oscillation (NAO), which has a distinctive impact on winter temperatures and precipitation over much of Europe (Hurrell 1995). Its intensity is usually expressed by the NAO index (NAOI), defined as the anomaly in air pressure difference between the Azores High and the Icelandic Low (Hurrell 1995). Winterly air temperatures in the Lake Constance region are strongly correlated with the NAOI and have a strong impact on freshwater ecosystems (Straile et al. 2003a, 2003b). As there is a strong association between the NAOI and precipitation we expect to see also a link between the NAO and the water levels of Lake Constance.

By comparing with two long precipitation time series from the Global Historical Climate Network (Peterson & Vose 1997) the expected correlations can be highlighted. We used data from weather stations on Säntis, Switzerland (mountain station, height 2496 m, approximately 20 km south of Lake Constance, monthly precipitation data 1883 to 2000) and data from the station Friedrichshafen (station in immediate proximity to Lake Constance, monthly precipitation data 1834 to 1980).

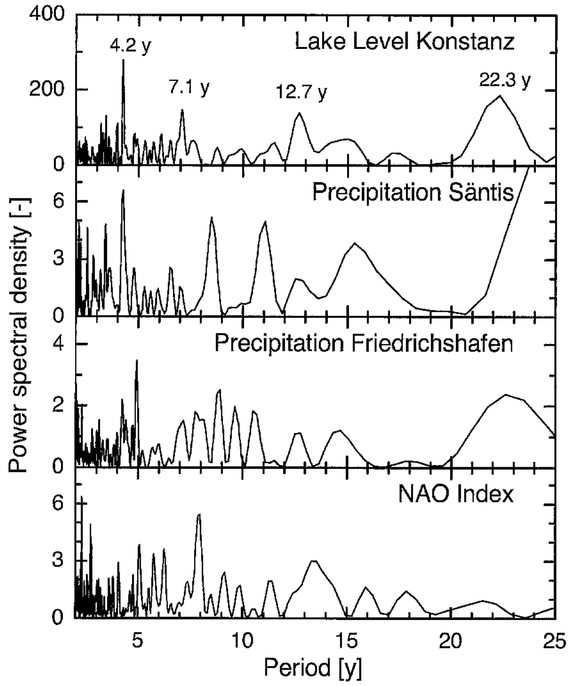

Fig. 4. Lomb periodograms for time-series of Lake Constance lake levels, precipitation at stations Säntis and Friedrichshafen, and NAO index.

Causal correlations between the periodicities may be assessed comparing power spectra of the water level, precipitation, and NAOI time series. In Fig. 4 the Lomb periodograms (Press et al. 1992) are plotted. Spectral bands – discussed here in terms of periods – are identified around peaks of 4.3, 7.1, 12.7 and 22.3 years. The periodicity of 4.3 years is clearly an effect of precipitation appearing also in the regional precipitation time series. Especially the data of the Säntis weather station, representative of the alpine region catchment area, contain a strong spectral component of approximately the same periodicity in a band between 4 and 5 years. In contrast, the appropriate spectral band in the pre-alpine precipitation time series from Friedrichshafen is less pronounced. The spectral band of periodicities of around 7 years in water level data points to a correlation with the NAOI, which has a strong periodicity between 7 and 8 years. The periodicity bands around 12.7 and 22.3 years coincide with bands in the NAOI and the precipitation data, respectively. Equivalent bands of periodicity can also be found in analyses of climatic time series like the Central England temperatures since 1659 (Plaut et. al. 1995) or the NAOI (Mann & Park 1994) using different analysis methods.

Advanced studies using wavelet analysis techniques which show shifts in periodicities, point to a weak direct correlation between the NAOI climate index and the water level fluctuations, whereas the influence of pre-

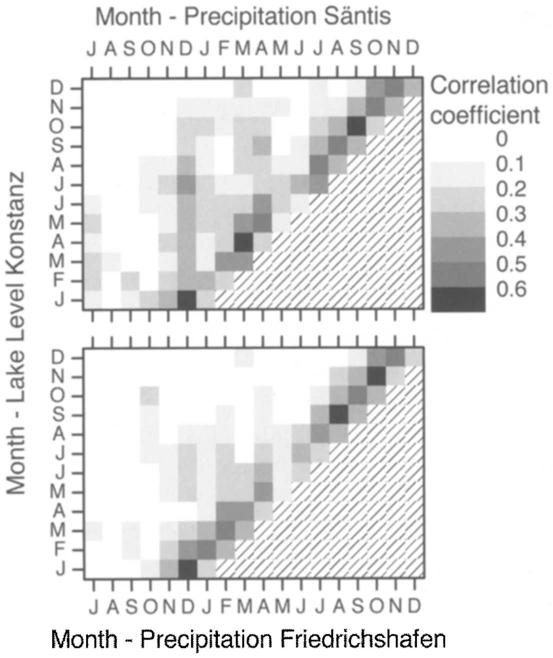

Fig. 5. Correlations between mean monthly precipitation values at Säntis and Friedrichshafen and lake levels of Lake Constance. The hatched region denotes areas with non-causal relations.

cipitation and its variation on scales up to decades is much more clearly correlated with water level variations especially in the above mentioned period band of 4–5 years (JÖHNK et al., in prep.).

The relation between precipitation and lake level within short time scale is quantified using correlation analysis. The correlations between the monthly mean lake level and the monthly precipitation data with different time lags for the stations Säntis and Friedrichshafen are shown in Fig. 5. Here water level data for a specific month were correlated with precipitation data of the same or previous months. Precipitation in the Säntis region in December and precipitation in Friedrichshafen from December until February show strong correlations with the water level of Lake Constance in the corresponding subsequent month. This is the low water period of Lake Constance. The lake levels during the annual phase of lake level increase in the months April and May exhibit stronger correlations with precipitation in the Säntis area (precipitation during March and April) than with those in the area around Friedrichshafen. No definitive results can be derived solely on basis of the two stations mentioned above. However, from the findings, it appears likely that variations in the low water level depend on the precipitation regime in the pre-alpine area. Precipitation in the alpine area during winter is largely stored in form of snow and ice. The situation reverses later in spring when lake levels are more strongly correlated with precipitation in the alpine region. Thus, fluctuations in the increase of the lake level may be explained by fluctuations in precipitation in the alpine catchment area. Precipitation on Säntis back to December of the previous year influences lake levels up until July through the storing and melting effect of snow.

Discussion

The centennial flood of 1999 on Lake Constance has highlighted the urgent need for an enhanced analysis of water levels and climatic parameters using modern mathematical methods and the development of scenarios for anthropogenic influences as well as climatic changes in the hydrological regime for this region. Such a procedure is especially promising for the unregulated Lake Constance with its lake level records back until the year 1816.

The time series analysis demonstrates how the risk of flooding and also the risk of extremely low water levels may be assessed. The trend analysis shows a steady decrease in water levels, which weakened, however, near the end of the 20th century. It is unclear how long-term climate change will affect precipitation distributions, along with the hydrological regime of Lake Constance. A long-term decrease in water levels is beneficial for the protection against floods, as the occurrence of extreme flood events will probably be decreased on a long-term scale. This can be recognized from the values for the return periods for the 1999 flood (see Table 2). In the absence of a decreasing trend, a 100 year flood would exceed a calculated level of 590 cm. However, in relation to the extreme value distribution used here, this event would actually 'only' amount to 581 cm. The 9 cm difference means a reduction in the risk to flood-prone areas. On the other hand the water level is dependent on the inflow from the alpine Rhine, as well as that from the pre-alpine catchment area. This crude subdivision of the precipitation regimes brings in an additional time factor. Correlations of the precipitation time series with the water levels show that the water level during the first months of the year is influenced by precipitation in the pre-alpine area while the inflows from the alpine area are more dominant later on. The 1999 flood shows that a change in precipitation events in the Lake Constance catchment area may have grave consequences; especially when heavy precipitation in the pre-alpine area coincides with an early snowmelt. An earlier occurrence of the snowmelt in the Alps caused by global warming may increase the risk of floods, especially in late spring. The importance of incorporating reservoir effects into such analyses and into flood management becomes apparent if one considers the ability of the reservoirs to hold back as much as 15 cm in lake level in 1999 (PETRASCHECK & HEGG 2000).

On first impression no strong correlation appears between the increase in global temperatures, as expressed in long-term changes in NAOI, and Lake Constance water levels. Fundamentally, long-term lake level variations are correlated to equivalent changes in precipitation. This direct coupling is also evident in the correlation between time series reflecting the short-term behavior of the Lake Constance system. A more in-depth analysis of hydro-meteorological time series (precipitation, temperature, lake level) in the Lake Constance catchment area is in preparation (JÖHNK et al., in prep.).

Although the risk of extreme flood level peaks is alleviated to a certain extent by a decreasing trend in water levels, future variations in the precipitation regime in the alpine region suggest a shift of the annual rise in water level into the early months of the year. Such a shift of the lake level rise period will result from an increase in air temperature and an earlier snowmelt (BENISTON & JUNGO 2002). Furthermore, an increased probability of precipitation has been predicted for the northern part of the alpine regions (QUADRELLI et al. 2003).

The large amplitude in water levels on a seasonal basis but also the large interannual variability will have a direct influence on the biota, especially reed populations. Floods early in the year cause considerable damage to reed populations and may lead to large-scale losses, e.g., in Lake Constance as a result of the June flood 1965 with a maximum water level of 540 cm, and the flood of 1999 (OSTENDORP 1990, 1991; SCHMIEDER et al. 2002; DIENST et al. 2004). Also, due to the importance of reed populations at Lake Constance, this will cause significant changes in the lakeshore biocoenosis. Such influences may be quantified using the information from time series analysis to build prognostic lake level models (e.g., JÖHNK 2003).

Summary

An overview was given on the extreme flood of 1999 at Lake Constance, its causes from precipitation in alpine and pre-alpine regions, and its possible connection to climate change. Trend analysis shows that the mean water level of Lake Constance only has been decreasing in the last decades since around 1925. This period was preceded by a stand still and a slight increase during the periods from 1860 to 1895 and 1895 to 1925, respectively, in contrast to previous findings, which used linear trend analysis to find decreasing lake levels since 1887. Using the non-linear trend curve, extreme value analysis shows that the return periods of floods are increased, and the level for the centennial flood 1999 for example increases from 581 cm to 590 cm, when compared to the results for the original time series. Future climate scenarios used to predict the extreme value distributions of the lake level must take into account such trends as it was shown here. The causes of long-term lake level variations were derived using spectral analysis techniques. Comparing the periodograms of lake level, precipitation in the alpine and pre-alpine region, and the index of the North Atlantic Oscillation shows that the pronounced low period bands in the range of 4 to 5 years can be attributed to regional variations in precipitation, whereas the longer period structures are more likely caused by global climatic variations. Due to climate change studies precipitation on the northern side of the Alps is increasing and in the same time temperature rises and therefore snowmelt is shifted to earlier periods. Both effects in combination lead to the assumption, that the occurrence of extreme flood peaks will be earlier in future. Although the mean lake level is decreasing, this shift in occurrence time of flood peaks might cause problems for reed growth and it is associated with a shift in lakeshore biocoenosis.

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