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A model approach for in- and outflow calculation of Upper Lake Constance

– An investigation of a 60 year time span and observations about the flood of 1999 –

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Abstract

The revised empirical model for in- and outflow calculation of Upper Lake Constance has provided satisfying results supported by measured values. The given model was implemented to simulate total water inputs of the lake during the period from 1941 to 2000 with emphasis on the flood conditions of 1999. Analysis of annual water input development reveals a tendency toward slight increases until the 1960s. Thereafter, a reduction in inputs can be noted. This trend probably continues to hold true to present. Weather conditions of given individual years have caused distinct fluctuations to the water budget.

Unusual meteorological conditions led to extreme flooding in early May of 1999. Daily water inputs of up to 200 mio m^3 generated the highest water levels ever observed for this time of the year. Continual extraordinarily high water inputs occurring from February until July and then again from September until the end of 1999 resulted in the second largest annual total water input recorded since 1941.

Key words: Hydrological modelling – Upper Lake Constance – lake inflow and outflow – water balance – flood 1999

Introduction

Lake Constance is divided into "Upper" and "Lower" Lake regions which are connected by the Seerhein River. The total lake basin of Upper Lake Constance covers an area of 10919 km^2, most of which belongs to Switzerland, but also to a lesser degree to Austria and Germany (Fig. 1). The surface of the lake measures 472.3 km^2 and its volume is 47.6 km^3 (PETERLE 1993). The Alpine Rhine River, with a catchment area of 6200 km^2, is the greatest inflow contributor to the lake and mainly draining Swiss mountainous areas (DE HAAR 1968; SCHÄDLER 1985; ASCHWANDEN & WEINGARTNER 1985). This river delivers up to 2/3 of the total water input to the lake.

Due to melt waters annually recurring alterations of water level of Upper Lake are caused. So the outflow is considerably less than the inflow during flood phases in spring and summer due to the outlet configuration of the lake. On the other hand the outflow exceeds the inflow during low water situations, mainly in autumn and winter (LEHN 1978; NAEF 1989; VISCHER 1990).

Daily water levels of Upper Lake Constance have been recorded at a gauge located near Constance since 1817. From 1887 onwards, these data have been analysed respective to hydrographical reliability (LUFT et al. 1990; LUFT & VIESER 1990; LUFT & EERTWEGH 1991). A water balance model for Upper Lake Constance (WAGNER et al. 1994) uses the statistical data of the

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water levels to simulate the total water input into the lake. In revising this model, the following criteria have been fulfilled:

- additional measurements of discharge at the outlet of Upper Lake Constance into the Seerhein River (LFU B-W)
- more exact insights concerning the morphology of the lake retention volume (BRAUN & SCHÄRPF 1994; PETERLE 1993)
- a more extensive knowledge about precipitation on the lake surface and evaporation (STROBEL 1994)
- verification of the calculations by comparing the results with the sum of the different measured tributaries and the estimated remaining lake inputs (GURTZ et al. 1997)
- analysis and consideration of effects of different gradients between Upper and Lower Lake Constance within the Seerhein River (by introduction of a sinus term in the model approach).

On this way the model approach was improved and validated (GURTZ et al. 1997). Nowadays it is applied for the calculation of long-term inflow and outflow of Upper Lake, balances of matter and for forecasting of flood situations. In this paper the improved version of the model is used for simulation of in- and outflows from 1941 to 2000 especially under consideration of the extreme flood situation in 1999 at Upper Lake which was one of the highest within the past century.

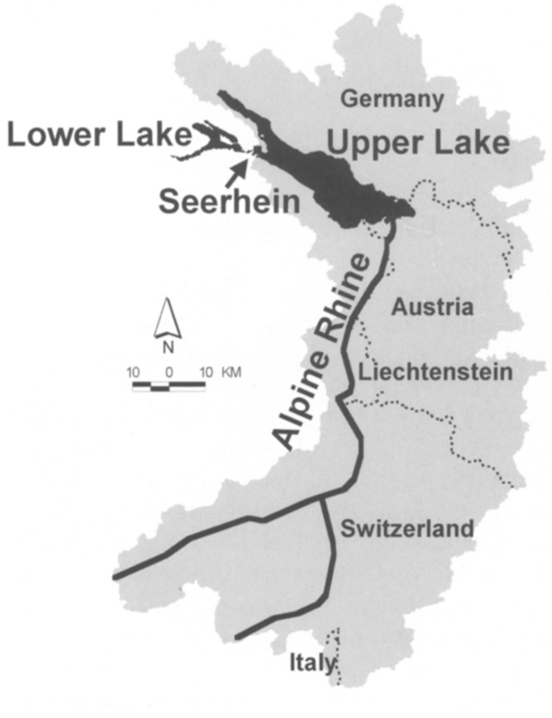

Fig. 1. Location map of Lake Constance basin.

Methods

The daily outflow of Upper Lake Constance Q_{out} can be calculated based on the following elements of the lake water budget:

$$Q_{out} = Q_{basin} + P_{lake} + V_0 - V_{24} - E_{lake} - Q_{export} \text{ km}^3/\text{d} \qquad [1]$$

where: Q_{out} = outflow from the Upper Lake into the Seerhein River (see [5]);
Q_{basin} = sum of the entire lake inflow resulting from river inflows to the Upper Lake and from catchment areas, which drain directly into the lake;
P_{lake} = precipitation on the surface of the Upper Lake;
V_0 = volume of the lake at 0.00 o'clock at the begin of the day (km^3; see [6]);
V_{24} = volume after 24 hours at the end of the day (km^3);
E_{lake} = evaporation from the surface of the Upper Lake;
Q_{export} = sum of the water diversion from the Upper Lake for drinking water purposes.

With the difference between V_0 and V_{24}, the change of the relevant retention volume within a day is taken into account.

The total water input into the lake Q_{tot} is given by the following equation:

$$Q_{tot} = Q_{basin} + P_{lake} \text{ km}^3/\text{d} \qquad [2]$$

The aim of the investigations was to establish the total water input derived from the behavior of the lake water level. This is reached by substitution of equation [2] into equation [1]:

$$Q_{out} = Q_{out} - V_0 + V_{24} + E_{lake} + Q_{export} \text{ km}^3/\text{d} \qquad [3]$$

The model calculations are based on this equation [3].

The actual outflow Q of Upper Lake Constance into the Seerhein River is described as dependant on the water level of the lake and the succession of the annually high and low water level conditions. A single empirical function including a sinus term as an approximation is used:

$$Q = a + b * \frac{W + d * \sin [K_1 * (N + e)]}{\exp (c/W)} \qquad [4]$$

where: Q = actual outflow of Upper Lake Constance into the Seerhein River (m^3/s);
W = actual water level of the lake at the gauge near Constance (cm);
N = numeric position of a day within the year;
K_1 = constant for the annual water level oscillation = 360°/365.25 days;

a to e = actual regression coefficients (a = −117.0793877057; b = 4.147385673036; c = mean water level at the gauge Constance = 357.6 cm; d = 28.61; e = temporal shifting of the sinus oscillation = 48.35 days).

The multiple correlation coefficient r = 0.995 has been derived from 30 triples of measured Q, W and N.

Simplifying it is postulated that the outflow within the span of one day changes time proportionally:

$$Q_{out} = \frac{(Q_0 + Q_{24}) \cdot K_2}{2} \qquad [5]$$

where: Q_{out} = mean discharge of the Seerhein River during changes of water level within one day [km^3/d];

Q_0 = outflow at 0.00 o'clock at the begin of the day [m^3/s];

Q_{24} = outflow after 24 hours [m^3/s] at the end of the day;

K_2 = constant for outflow conversion from m^3/s into $km^3/d = 8.64 \cdot 10^{-6}$.

A parabolic function has been adapted to the morphological data (BRAUN & SCHÄRPF 1994) in order to calculate the actual lake volume (see [1] rsp.[3]) depending on a designated water level within the range of the Upper Lake gauge near Constance:

$$V = f + g \cdot W + h \cdot W^2 \qquad [6]$$

where: V = actual volume of the Upper Lake (km^3);

W = actual water level (cm);

f = 46.11 km^3 volume of the lake below the zero point water level of the gauge Constance (391.89 m a.s.l.);

g, h = regression coefficients ($g = 4.275845 \cdot 10^{-3}$; $h = 5.6673 \cdot 10^{-7}$).

The multiple correlation coefficient r = 1.0000 has been derived from 64 couples of measured V and W.

Equation [6] is used for calculation of V_0 and V_{24}. Estimated long-term mean evaporation values of the lake surface E_{lake} (GURTZ et al. 1997) and measured diversion of drinking water Q_{export} to external drainage basins are used to fulfill equation [3].

The described procedure uses the runoff rate and the daily water levels to simulate the daily inflow and outflow of Upper Lake Constance. To calculate the remaining water level from the total water input, the inverse function can be applied iteratively.

Model validation

Verification of the model configuration and the simulated results has been executed by using the sum of all measured or balanced inflows, considering the estimated runoffs from the near shore catchment areas which drain into the lake directly, the estimated precipitation on and the evaporation from the lake surface, as well as the measured water diversions for drinking water purposes according equations [2] and [3] for the validation period 1978–1990 (GURTZ et al. 1997). To arrive at the mean daily balance during the investigation period, an average lake inflow from the catchments Q_{basin} of 31.3 mio m^3 (362.5 m^3/s), a mean lake precipitation rate P_{lake} of 1.4 mio m^3 (15.9 m^3/s), a mean lake evaporation E_{lake} of 0.9 mio m^3 (10.4 m^3/s) and a mean diversion of drinking water Q_{export} of 0.3 mio m^3 (3.9 m^3/s) were used. Of the average annual total water input into the lake, 4.2% originated from precipitation on the lake's surface. From there are evaporating 2.7%, 1% are exported as drinking water and 96.3% run off into the Seerhein River. The sum of the lake evaporation and the drinking water diversion corresponds approximately in average to the precipitation on the lake surface.

Generally, the model calculations for this period scarcely deviate from the balanced data. A minimal difference (<1%) between the calculated (12.057 km^3) and the balanced yearly average (11.956 km^3) total water input confirms the validity of the model. Also the monthly averages (Fig. 2) are similar. Among the positive and negative differences between the model calculated and the balanced results especially the positive deviations in July and August are evident.

The calculated and measured lake outflows of the Seerhein River were compared for the time period between 1985 and 1990, since the most recent discharge measurements available began in 1984 (GURTZ et al.

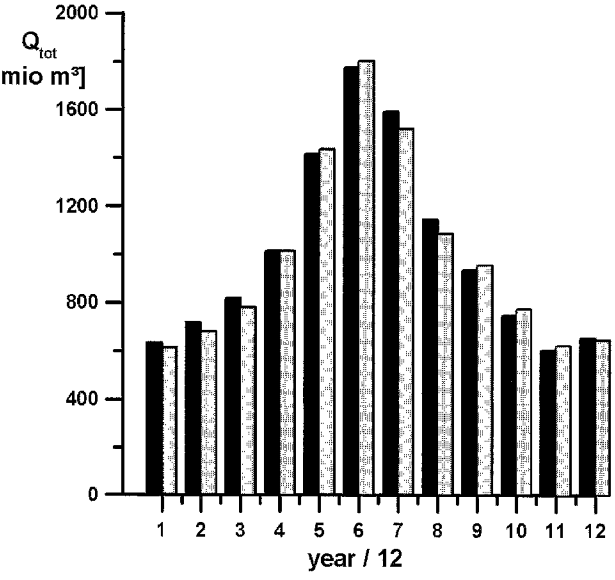

Fig. 2. Means of total water inputs to Upper Lake Constance for the validation period from 1978 to 1990 (based on time-equivalent twelfths of the year: model calculated = black; balanced from measurements = grey).

1997). A daily mean outflow of 29.4 mio m^3 (340 m^3/s) was calculated and compared to the mean measured outflow of 30.1 mio m^3 (349 m^3/s). The difference reflects a variance of 2%. Previous outflow observations and investigations (TH. LUTZ, in KIEFER 1972) arrived at remarkably similar results. Nevertheless, during lowest water situations, values up to 60% higher were now measured. Changes in the methodology as well as alterations of the Seerhein River morphology possibly offer explanations for this difference. The discharges during the low water period between November to February are poorly supported by measurements. Processing of low water level values is sensitive to the use of data rounded off to the nearest centimeter. When analysing specific days, the fact that the water level at the gauge station can be influenced by wind driven oscillations on the lake surface must be taken into account. However, since these restrictions pertain to minimal outflow quantities, they bear little relevance to the water budget.

Water budget and lake water inputs are calculated with aid of this model depending on the relation between fluctuations of the lake water levels and changes in the lake volume respectively. However, increasing high water levels cause an increase in water retention within the ground water storages near the shore. After the yearly highwater period the ground water inflow to the lake increases during phases of decreasing water levels (July/August; Fig. 2). Up to now these processes cannot be proved by measurements [2]. Therefore, temporary seasonal differences between the measured and simulated inflows occur. However, the effect of these short-term processes is small in respect to the long-term annual water inputs.

No morphological changes relevant to discharge of the Seerhein River have been known since the 1940s. Water budget calculations using the present model configuration prior to this time may lead to inaccurate results due to possible alterations in discharge conditions.

Model application

In a first step, the model approach discussed in this study has been implemented to produce long-term simulations determining the annual total water input to Upper Lake Constance for the period of 1941 through 2000 on a daily basis (Fig. 3). A mean of 12.033 km^3/a was calculated for the entire period. The smallest annual input was recorded for the year 1949 with 7.855 km^3 and the largest was recorded for the year 1970 with 15.97 km^3. The 11-year moving average of the inputs displays a slight increase from the first half of this period until 1970 and reflects a slight decrease from 1970 onward. During the period from 1941 to 1970, the annual mean amount of input measured 12.330 km^3 and the second period up to 2000 boasts 11.737 km^3.

In a second step, the model was used to simulate daily water inputs of the Upper Lake for flood year 1999. In the winter of 1998/99 prior to the flooding of 1999, intensive snowfall and extensively over-average snow storage occurred regionally. The first flood event was caused by extensive snow melt which was brought about by moderate temperatures during February and March. In early May, extensive melting caused lake inflows with daily precipitation equivalents of approximately between 15 and 20 mm. Extraordinary weather situations resulted in extreme rainfall and in an intensification of the snow melt also in higher altitudes for the period from May 11th to May 15th (GREBNER & ROESCH 1999). Rainfall amounts with up to 130 mm during 48 hours took place in the Alpine Rhine River basin in northern alpine Switzerland and the bordering Austrian and German drainage basins of Upper Lake Constance. Finally the synergetic effect of all these processes caused the largest flood event of Upper Lake Constance in the 20th century (Figs. 4 and 5). At May 13th the daily total input came up to 200 mio m^3. In 1999 the highest water levels during May were registrated (LFU B-W)

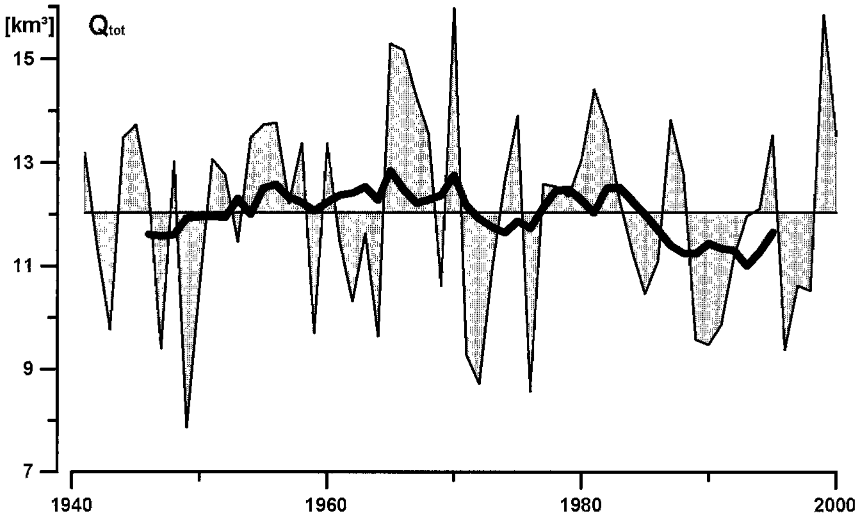

Fig. 3. Annual total water inputs Q_{tot} to Upper Lake Constance for the period 1941–2000 overlapping the mean value and 11-years moving average.

since the beginning of the regular observations. The strong melting period in the alpine region still extended to June followed by a moderate period to September. Further floods were caused by strong precipitation events in autumn. From February up to July and later on from September to the end of the year the daily inputs quasi continuously (with the exception of few days) exceeded the long-term mean daily values (Fig. 5). Some of the daily peak values of the floods in February, May, June and October were of higher amount than the other for these days calculated total water inputs of the whole time period. Finally the total water input of 15.85 km^3 in 1999 was the second largest within the whole investigation period.

Conclusions

The sequence of the long-term calculated total water inputs to the lake is influenced by the various climatic conditions which prevail during given years. Using the 11 year moving average, possible effects of the oscillation of the sunspots can be eliminated. The direct influence of long-term climatic change processes still cannot be detected. Possible reasons for the decrease of the annual water input during the last years could also be the increased use of irrigation water in agriculture, as well as water losses connected to various other human water use such as additional retention in reservoirs of water power stations. In favour of better based statements con-

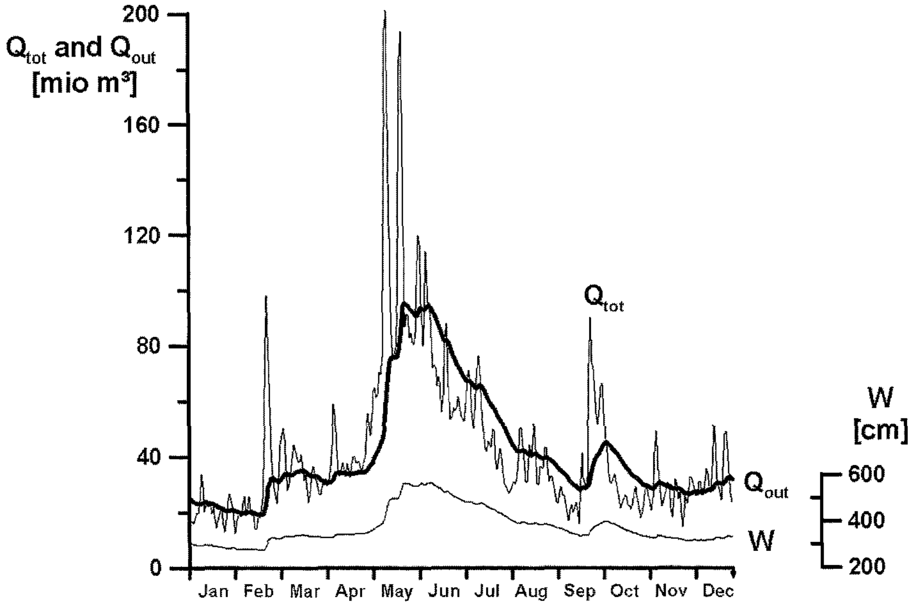

Fig. 4. Daily total water inputs Q_{tot} to Upper Lake Constance, water levels W and outflows Q_{out} at Constance in 1999.

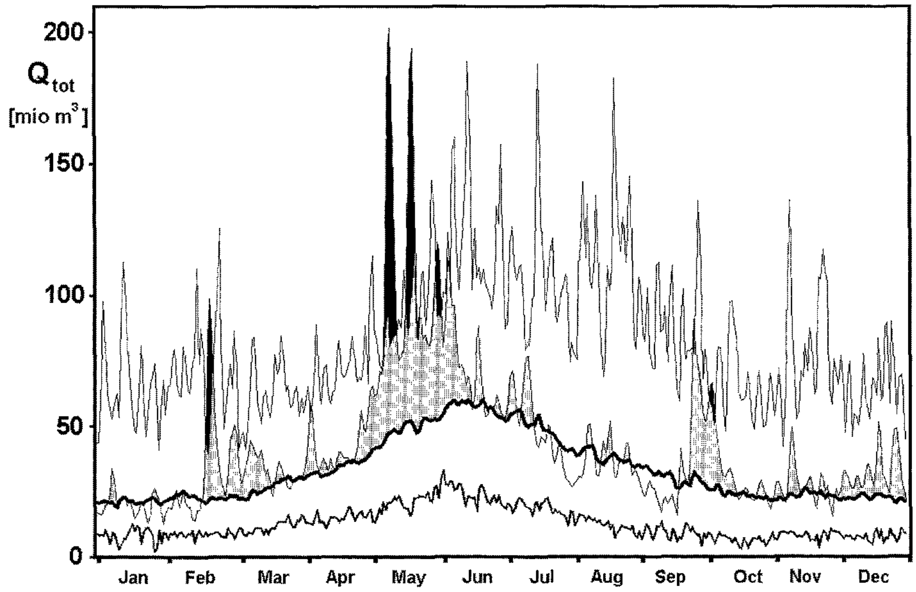

Fig. 5. Daily total water inputs Q_{tot} to Upper Lake Constance for the period 1941–2000: lower line = minima; thick line = mean; upper line = maxima. The daily inputs during 1999 are compared to the mean values, with overlappings: white = values below the mean values 1941–2000; grey = values exceeding the mean values 1941–2000; black = values of 1999 exceeding all other maxima since 1941.

cerning changes of the inflow regime, the investigation must be extended for a longer time period. Moreover, the outlet profiles of Upper and Lower Lake Constance respective to their discharge capacity do not remain stable over time. This could explain a very gradual decrease of the lake water level. Therefore, the relation between lake water level and outflow has to be confirmed by repeated measurements in the future, which can lead to a temporal changing of different model parameters.

The model described in this paper provides a quick assessment of the short-term water balance with satisfying precision. In practice, it was also used to predict the evolution of flood events at Lake Constance. Furthermore by the help of the model the total sum off all water inputs into the lake can be checked and possible changes in the behaviour of the lake outflow can be predicted.

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