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A Statistical Analysis of the Water Levels at Lake Neusiedl

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Abstract

The recent low water levels of Lake Neusiedl have raised concern about the lake's future and have sparked interest on how meteorological variables impact the water level. Data from the last 50 years are used to study the impact of rain and temperature on the cyclical changes of the water levels. Linear and nonlinear regression models are used to describe how rainfall and temperature change the water level, and to assess the future progression of the water level under three scenarios. For average 2022 meteorological conditions the water levels in 2022 may not recover for a dry 2021 autumn, but will recover substantially for a wet ending to the year 2021.

Keywords: Lake Neusiedl, water level, regression model, forecasts.

1. Introduction

Lake Neusiedl is a large steppe lake at the eastern border of Austria. With the increasing public interest in climate issues, the falling water levels of Lake Neusiedl during recent years drew the attention of the public administration, the media, and the population in general. The falling water levels led to headlines in the media proclaiming a "drying out" of the lake. There actually are several periods when the lake had evaporated; the latest such event took place in the mid-19th century when the lake disappeared for several years completely, and the lake area was used for agriculture.

Lake Neusiedl is an important component of the economic health of the region. The lake offers ample opportunities for water sports and attracts large numbers of summer tourists, many of them from nearby Vienna. Tourism induces demand for services of gastronomy, hotel industry and other branches of the regional economy. The lake is also an important factor for the functioning of the region's agriculture. Lake level changes have a great impact on the tourism, agriculture, and related branches of the economy of the whole region. Understanding the development of the lake level and its changes is of major interest to the authorities who are responsible for Lake Neusiedl. Explanatory models that show how relevant factors impact the lake's water level may help develop strategies for stabilizing the lake at a suitable level.

Numerous studies investigate water level variations of lakes, including the North American Great Lakes, Lake Chad, the Salton Sea in the United States, Lake Lisan and the Dead Sea rift, Poyang Lake in China, and Qinghai Lake in Tibet. For a list of references, see Fang, Li, Rubinato, Ma, Zhou, Jia, Yu, and Wang (2019). Their study on the water level of Qinghai Lake, the largest inland saline lake on the Tibetan Plateau, uses data over a period of 57 years to describe and explain the annual trend in the water level. As many other studies on the water level of lakes, their model starts from an annual hydrological water balance equation. This balance equation expresses the yearly water level change as a function of the yearly precipitation onto the lake surface, the yearly evaporation from the lake surface, the yearly surface runoff into the lake, yearly underground runoff from the bottom of the lake, and yearly outflow from the lake through outlet streams. Typically, each component is then modeled using theoretical knowledge from hydrology and the best available data. For some applications, such as the study on Quinghai Lake, good direct data on the runoff of rivers feeding into the lake and evaporation from evaporation pans is available. Other applications, such as the one we describe in our paper, use rainfall and air (and water) temperature as proxies for runoff and evaporation.

Other lake water level studies, such as the ones by Nhu, Shahabi, Nohani, Shirzadi, Al-Ansari, Bahrami, Miraki, Geertsema, and Hoang Nguyen (2020) and Wang and Wang (2020), investigate daily data and use mechanistic machine learning methods to obtain short-term forecasts of lake water levels. Instead of starting from an explanatory model that is supported by theoretical hydrological knowledge, these studies use black-box machine learning methods to predict water levels. Autoregressive integrated moving average models, neural networks, genetic programming, and support vector machine methodology are typically used. These studies extrapolate historical water levels without considering the physical process driven by meteorological conditions.

Our approach follows the hydrology literature on the underlying drivers for water levels (such as rainfall, evaporation, and outflow) and constructs simple interpretable statistical models to explain trends in the water level. It is much closer in spirit to the investigation in Fang et al. (2019).

The interest in the development of the water level of Lake Neusiedl is not new. Formayer (2006), using monthly data from 1932 to 2003, analyses the impact of climate change on the water level. He concludes that a warming in temperature of 2.5 degrees centigrade will result in an evaporation increase of more than 20 %. Soja, Zügner, Knoflacher, Kinner, and Soja (2013) analyse the water balance of the lake and study how it is influenced by weather conditions. Using model-based water level projections for the period 2035–2065, they identify serious risks of hydrological deficits that may lead to water levels even lower than at present.

Ledolter (2008) reports results of a detailed analysis of daily data over a period of more than 30 years. His paper describes and models the effects of meteorological conditions, such as temperature, rainfall, wind speed and wind direction, on the lake level.

The present paper uses daily lake water level data, as well as data on rainfall, air temperature and water temperature, for the 50-year period from 1971 to 2021. Our work provides (1) an analysis of the patterns in monthly and annual average water levels, and (2) models that describe the impact of rainfall, temperature of air and water, and the outflow of water from the lake through a weir that allows the government to control the water level of the lake. The models are used for assessing (1) the impact of rainfall and temperature on the lake water level and (2) scenarios that could explain extreme low lake water levels.

2. The data

The Hydrology Office of the state of Burgenland (Hydrographischer Dienst Burgenland) provided the following data:

- Lake water levels: the average water level (representing the overall level of the lake) and water levels at various measurement stations including the one at Neusiedl am See. Measurements are in meters above the Adriatic Sea level.

- Rainfall: precipitation (in mm of rainfall) at eight measurement stations surrounding the lake (Pöttsching, Steinbrunn, Margarethen, Donnerskirchen, Oggau, Rust, Podersdorf, Apleton). The average of daily measurements from these eight stations is taken as measure of the overall daily precipitation.
- Air temperature (in degree C): for January 1971 until December 2004, the Austrian Central Institute for Meteorology and Geodynamics provided daily data for its station at Neusiedl am See; for January 2005 until July 2021, the average of daily measurements from two stations (Illmitz, Mörbisch) is taken as measure of the overall daily temperature.
- Water temperature (in degree C), measured at the station Neusiedl am See.
- Water outflow (millions of m^3) through the Einser Kanal.

Daily data are available for the period January 1971 until August 2021. Water temperature recordings start in January of 1976.

3. Descriptive data analysis

The focus of the analysis is on the lake water level and its progression over time. A topic of special interest is about lake water level trends towards extreme low levels. The average depth of the lake is about 1 meter. The lake has totally dried up several times in history, most recently in 1866. A partial disappearance of the lake took place in the summer of 1949 and lasted a few weeks. The drying-up of the lake has major environmental effects: the regional climate lacks the humidifying and temperature buffering effect of a large body of water, and winds transport large amounts of salty dust into the surrounding area. At present the lake is a magnet for tourists who come for sailing and windsurfing, a sector of the regional economy that is of growing importance. Low lake levels, not to mention a complete dry lake, would severely affect tourism, agriculture, land and property prices, and the regional economy. These facts explain the strong interest in the lake water level.

Rainfall and temperature are main drivers of the lake water level. Heavy rainfalls change the lake level, at least over a short period. In 1965 the water level increased 35 cm within just a single month. Similarly, a period of drought in 2003 reduced the lake water level by 30 cm. Temperature has a strong effect on evaporation; the warmer the water of the lake (and the temperature of the air), the higher the evaporation.

3.1. Lake levels

This section describes the lake water level and its progression over the studied observation period. The lake water level is influenced by (a) the water evaporation which, in turn, is affected by the temperature of air and water and (b) the precipitation which also affects the water inflow from small rivers and wells that feed the lake.

Einser Kanal

The outflow through the Einser Kanal is intended to prevent extreme high lake water levels and floods and to stabilize the lake water level at a more constant level. The Einser Kanal was designed such that a lake level of 116 m above the Adriatic Sea would correspond to a 100-year flood event. However, no specific details could be found. Weir Operating Regulations (Wehrbetriebsordnung (2011)) have been developed and are in use since 2011:

- from November until January, the weir is opened for an outflow of 5 m^3/s (m^3 per second) if the lake water level is above 115,70 meters

- from February until August, the target lake water level is increased to 115,80 m; in case of a higher lake water level, an outflow of 4 m^3/s (February), 2 m^3/s (March and April), 4 m^3/s (May until July) and 5 m^3/s is (August) is allowed
- in September and October, the target lake level is reduced to 115,70 m and an outflow of 5 m^3/s is allowed.

The Österreichisch-Ungarische Gewässerkommission, a board of experts and stakeholders from public administration, agriculture, tourism, and other interested parties, monitors the lake water level; it may increase the outflow up to 15 m^3/s.

Lake Neusiedl covers an area of 315 km^2. Thus, an increase of 1 million m^3 water results in an increase of 0,3175 cm in the lake level. To drain 5 cm of water from the lake, the weir must be fully open for 12 days.

Low and high lake levels

Figure 1 shows the time series graph of the monthly averages of the lake water level: Both the actual observed water levels and the levels that are augmented with the outflow through the Einser Kanal are shown. The latter levels were calculated by adding to the actual level the height that corresponds to the known outflow through the Einser Kanal, by multiplying the outflow volume (in million m^3) by 0,3175 cm. The range of the observed levels without adjustment extends from a low level of 115,08 m to a high level of 115,93 m above the Adriatic Sea level. The 5th and 95th percentiles are 115,23 m and 115,76 m. For the augmented levels with added outflow through the Einser Kanal, the maximum (115,97 m) and the 95th percentile (115,78 m) are only slightly higher. The added outflow through the Einser Kanal does not change the pattern of the lake level in any substantial way; its only effect are truncated maxima of the actual lake level. The correlation coefficient between the actual levels and the augmented levels amounts to 0,997.

Of special interest are times with low lake water levels. For eight years, the minimum *daily* lake level was below 115,2 m above the Adriatic Sea: In 2003, the minimum lake level was 115,05 m; in all years between 2002 until 2005, the minimum lake level was below 115,2; this was also the case in 1978, 1984, 1990, and 2020 (115,18 m). A look at the minimum average monthly lake levels shows the following results: for five years (1978, 1990, and 2002 to 2004) the average *monthly* level was below 115,20 m. For five additional years, the minimum monthly level was between 115,20 m and 115,25 m; last year (2020), the minimum average monthly level was 115,21 m.

A look at the maximum observed average monthly water levels shows five years with maximum levels above 115,80 m. Such high-water levels were observed in 1996 (115,93 m) and for years 2009 to 2010 and 2013 to 2014 when the maximum average monthly lake level was between 155,81 m and 115,84 m. Adding the water adjustment of the Einser Kanal, there are six years with maximum average monthly lake levels above 115,80 m: 1996 (115,97 m), and 2009-2010 and 2013-2015 with maximum average monthly water levels between 155,86 m and 115,89 m.

Lake water level cycles

Figure 1 shows two types of cycles:

- annual seasonality of the lake water level, with the maximum level in spring and the minimum level in late fall
- less regular trend cycles which became more pronounced after 1990, with long phases of rising and falling levels

For annual cycles, *daily* lake water levels vary within a range of 0,301 m on average. The yearly range of lake levels exceeded 0,4 m in five years. The largest yearly range was observed

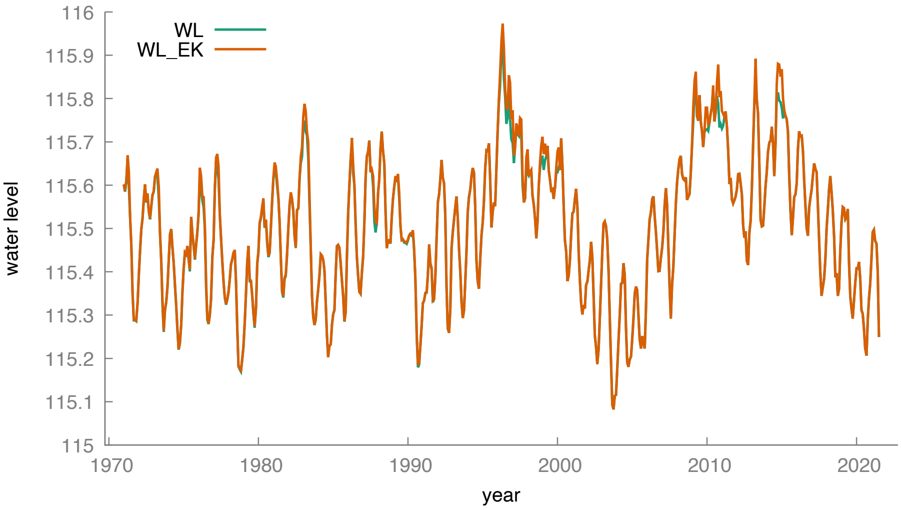

Figure 1: Average monthly lake water level for January 1971 until August 2021; actual levels (WL, green line) and levels with added outflow (WL_EK, red line)

for 1983 with 0,513 m; the other four years with such extreme ranges were 1971, 1973, 1992, and 2003. In all these years, a dry summer caused a substantial decrease in the water level.

Figure 1 indicates cyclic changes beyond the annual seasonality of lake water levels. However, these changes appear not to follow a specific pattern; cycles with lengths of a few years in the period from 1971 until 1990 are followed by two distinct longer cycles, covering the periods from 1992 until 2003 and from 2003 until 2020. Questions how these cycles can be explained and how such cycles may develop in the future have become of great interest in recent years. Possible explanations include a change in the equilibrium of the lake and the widely discussed climate change. How this may affect the lake level are the subject of articles in the Austrian and Hungarian media.

It is worth noting that both the actual monthly averages of the water level and of the water level with added outflow can be assumed stationary time series. By the Augmented Dickey-Fuller test (Dickey and Fuller (1979)), the unit root null-hypothesis of non-stationarity is rejected ($p < 0,01$) for both time series of monthly averages. This suggests that the time series have fixed means and that there is no evidence of long-term trends.

3.2. Precipitation

Rainfall is the dominant source of water entering the lake: About 80 % of the water is supplied through precipitation and about 20 % through small rivers like the Wulka and other sources like wells and local sewers. When explaining the changes in the lake water level, precipitation has to be taken into account.

Figure 2 shows the time series graph of the annual averages of rainfall, together with the annual averages of the observed unadjusted lake water levels. Daily precipitation, measured in mm of rainfall, is obtained by averaging the rainfalls from at eight stations around the lake. Figure 2 shows that rainfall varies substantially from year to year. Between 1971 and 2020, the mean of the annual rainfall averages was 556 mm, and it ranged from 353 mm to 833 mm; the 5th and 95th percentiles were 392 mm and 715 mm. The time series of precipitation in Figure 2 does not exhibit strong long-term trends. Both the wettest year (2014) and two especially dry years (2003 and 2011) occurred within the last 20 years.

Figure 2 illustrates an impact of precipitation on the lake water level and suggests a plausible positive correlation. The correlation coefficient between annual averages of rainfall and actual water level amounts to 0,38; the correlation with the augmented levels is 0,35.

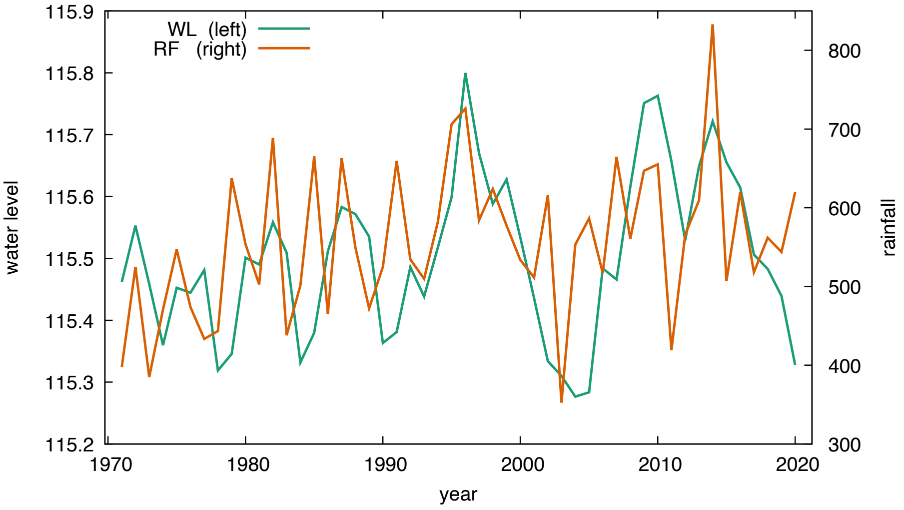

Figure 2: Average annual rainfall (RF) and actual lake levels (WL) for the period 1971 to 2020

3.3. Temperature of air and water

For the evaporation of lake water, the temperature of the water and the temperature of the air are crucial: The higher the temperature, the more evaporation which, in turn, reduces the water level. Temperature is a potential candidate for explaining the changes in lake water levels.

Figure 3 shows the time series graphs of the annual averages of the air temperature for the lake area and of the temperature of the water of the lake, both measured in Celsius degrees (°C). The correlation coefficient between the annual averages of the air and water temperature is 0,914. Monthly averages of air temperature vary between −6,0 °C and 24,8 °C, with mean of 11,1 °C and 5th and 95th percentiles of −0,8 °C and 22,4 °C. Monthly averages of water temperature range from 0,2 to 25,3 °C, with mean of 22,6 °C and 5th and 95th percentiles of 1,1 °C and 23,4 °C. The correlation coefficient between monthly averages of the air and water temperature is 0,989.

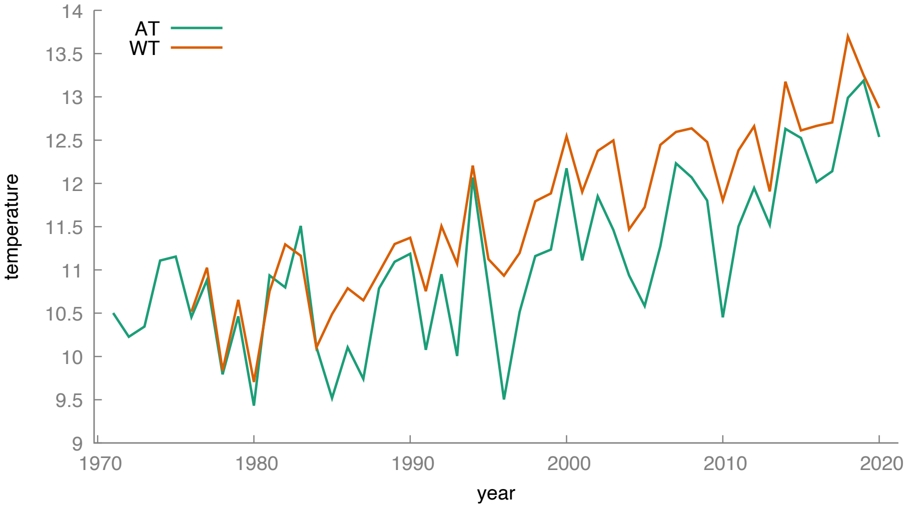

Figure 3: Average annual air temperature in the lake area for the period 1971 to 2020 (green line) and of the water temperature of the lake for the period 1976 to 2020 (red line)

Figure 3 shows that over the last 50 years temperatures of air and water have increased considerably. For air temperature, the average of the annual changes from 1976 to 2020 is 0,047 °C, resulting in an estimated 45-year increase of 2,08 °C. For water temperature, the estimated 45-year increase amounts to 2,35 °C.

The increase of the temperature variables certainly causes a higher evaporation rate of the water of Lake Neusiedl. However, the steady increase in temperature over the whole observation period cannot be used to explain the cyclic changes of the lake level seen in Figures 1 and 2.

3.4. Summary and conclusions

The descriptive analysis can be summarized as follows:

Lake water level

The annual seasonality brings high lake levels in spring and low levels in late fall; on average, water levels change by 30 cm within a year; the maximum change of 51 cm was observed in 1983 and changes larger than 40 cm happened in four other years.

Monthly averages of the lake level range from 115,08 m to 115,93 m above the Adriatic Sea level. The 5th and 95th percentiles are 115,23 m and 115,76 m.

Extreme high-water levels of 115,8 m and higher are prevented by the outflow through the Einser Kanal.

Trend cycles beyond the annual seasonality show no regular pattern, neither in their duration nor in their extreme water levels. After about 1990, these cycles became more pronounced, with long phases of raising and falling levels. Prominent cycles in the observation period were

- the 1974-1978 cycle starting from a lake level 115,21 m (September 1974)
- the 1978-1984 cycle starting from 115,18 m (November 1978)
- the 1984-1990 cycle starting from 115,20 m (September 1984)
- the 1990-2004 cycle starting from 115,17 m (October 1990)
- the present cycle starting from 115,08 (October 2003) and ending with 115,15 (September 2021) with a break-in in 2012. At present, it is not known whether its decreasing phase will continue.

Table 1 summarizes relevant information about cycles. The average rainfall is higher in upswing phases than in downswing phases; exception is the 2012 – 2020 cycle with decreasing water levels despite massive rainfalls. The average air temperature is higher in the downswing phases, again with one exception.

Table 1: Relevant information about cycles, separated for the upswing and downswing phases: The change of water level (Δ WL), the duration in years, and the averages of rainfall (RF) and air temperature (AT); the last row shows averages over the six cycles

	peak	upswing phase				downswing phase			
	year	Δ WL	years	RF	AT	Δ WL	years	RF	AT
1974-1978	1977	0,085	4	510,53	10,80	-0,126	2	428,45	10,34
1978-1984	1982	0,240	5	595,74	10,41	-0,049	3	438,20	11,51
1984-1990	1987	0,074	4	573,73	9,87	-0,220	4	515,50	11,02
1990-2004	1996	0,436	7	619,75	10,57	-0,523	9	524,06	11,31
2004-2012	2010	0,486	7	605,21	11,40	-0,234	3	492,55	11,72
2012-2020	2014	0,120	3	565,85	11,95	-0,321	7	600,55	12,57
		0,240	5,0	578,47	10,83	-0,246	4,7	501,55	11,41

Minimum average monthly lake levels below 115,20 m are observed in the years 1978, 1990, and 2002 to 2004. Days with extreme low lake levels like 115,2 m or less were observed in several years (1978, 1984, 1990, 2002-2005, and 2020). No systematic pattern or trend for these occurrences is recognizable.

Empirical evidence shows that both the actual monthly averages of the lake water level and of the augmented lake water level with added outflow are stationary time series.

Precipitation

Rainfall is the dominant source of water for the lake. Hence, rainfall is a potential candidate for explaining the variation in the lake water levels over time.

The mean of the annual rainfall averages was 556 mm; the annual averages range from 353 mm to 833 mm, with percentiles for 5th and 95th percentiles of 392 mm and 715 mm, respectively.

An impact of precipitation on the lake water level is evident from Table 1 that indicates high rainfalls in years of raised water levels and vice versa. The correlation coefficient between annual averages of rainfall and actual water level amounts to 0,38; the correlation with the augmented levels is 0,35.

Empirical evidence shows that the time series of monthly averages of rainfall is also stationary, with no increasing and decreasing long-term trends.

Air and water temperature

Because of evaporation of lake water, the temperature of the water and hence the temperature of the air are crucial. Temperature is a potential candidate for explaining the changes in the lake level.

Monthly averages of air temperature vary between −6,0 °C and 24,8 °C, with mean of 11,1 °C and 5th and 95th percentiles of −0,8 °C and 22,4 °C, respectively. Monthly averages of water temperature range from 0,2 °C to 25,3 °C, with mean of 22,6 °C, and 5th and 95th percentiles of 1,1 °C and 23,4 °C, respectively.

Temperature of air and water exhibit a steady increase over the studied 50-year period. In the period 1976 until 2020, the air temperature increased by 2,08 °C and the water temperature increased even more by 2,35 °C.

The impact of temperature on the lake level is not evident in the graph of water levels, and the steady increase in temperature does not explain the cyclic changes in the lake levels. However, Table 1 indicates that the upswing and downswing phases of the cycles are accompanied by low and high air temperatures, respectively.

Impact on the lake water level

The cyclic changes in monthly water levels have a seasonal component and, beyond that, an irregular/cyclical component with phases that can last for several years. These irregular cycles have become more pronounced after 1990, with longer phases of raising and falling levels and larger extreme (higher highs and lower lows) lake levels. The very low water levels fall into this period. During the late months of 2003 and in January 2004 monthly water levels were at low of around 115,1 m. Such low levels had never been observed before. The current very low water levels in 2021 approach the low levels of the year 2004.

Falling water levels of Lake Neusiedl are of great concern. Media headlines proclaim the danger having the lake dry out within the coming years.

However, the present analysis does not show that during the observation period lake water levels decreased steadily, following a steady downward trend. Visually, effects of precipitation but not of temperature can be recognized that can explain the variability in the lake levels over time; the effects of precipitation and of temperature on the water level are indicated by Table 1 for the upswing and downswing phases of the irregular cycles. Nevertheless, whenever the cyclical changes of the water level resulted in very low values, a new cycle started with increasing lake levels.

The low lake levels in late 2003 caused serious concerns and led to discussions at the highest level and international conferences about developing measures for preventing the drying out of the lake. However, these low water levels were followed by many years of high lake levels. Between 2009 and 2015, the Einser Kanal had to be used nearly every year to drain substantial amounts of water from the lake to prevent high water damages.

4. Statistical modeling results

For determining the impact of precipitation and temperature on the development of the water level of the Lake Neusiedl, monthly water levels are modelled as functions of precipitation and temperature. The models will be used for assessing the impact of these factors on the lake water levels under a number of scenarios.

4.1. Impact on the lake water level

Models that explain the water level as functions of the explanatory variables, rainfall and air and water temperature, are shown below. Because of the high collinearity between air and water temperature (0,989 for monthly observations) and because of the relationship between temperature and rainfall, model specifications with different functional forms and different regressor variables and associated lag structures fit the data equally well. The models discussed here are selected on their explanatory power and their interpretability.

The dependent variable for the models is the monthly average water level (WL) of the lake; see Figure 1. Regressors are the average monthly rainfall (RF) and the average monthly temperatures of air (AT) and lake water (WT). All subsequent models are estimated with the open-source software GNU Regression, Econometrics and Time-series Library (Gretl (2021)). Model 1 is based on the linear regression

$$\mathrm{WL}_t = \alpha + \beta_0\mathrm{WL}_{t-1} + \beta_1\mathrm{RF}_t + \beta_2\mathrm{RF}_{t-1} + \beta_3\mathrm{AT}_t + \beta_4\mathrm{AT}_{t-1} + \epsilon_t \qquad (1)$$

with white noise ϵ_t. The model is estimated using the data of the whole observation period 1971 to 2021. Table 2 shows results from the standard output of Gretl.

Table 2: Results from fitting Model 1 to the data

Model 1: OLS, using observations 1971:02-2021:07 ($T = 606$) Dependent variable: WL				
	coefficient	std. error	t-ratio	p-value
const	-0,03758	0,00260	-14,44	<0,0001
RF	0,00061	3,67e-05	16,58	<0,0001
RF(-1)	0,00078	3,54e-05	21,93	<0,0001
AT	-0,00049	0,00019	-2,56	0,0109
AT(-1)	-0,00194	0,00020	-9,76	<0,0001
WLad(-1)	0,95981	0,00909	105,60	<0,0001

The p-values of the estimates indicate a strong impact of all regressors:

- the water level in the previous month (WL(-1)) has a large influence on the current water level;
- precipitation increases the water level: the rainfall of both the current and the preceding month increase the actual water level; the coefficient 0,00055 of RF indicates that 1 cm

of rainfall in the current month increases the water level by 5,5 mm with 95 % confidence interval ± 0,71 mm; in a month with the average rainfall of 4,63 cm, the water level rises by about 25,6 ± 3,29 mm; the average amount of rain during two consecutive months increases the water level by 58,8 ± 14,4 mm;

- air temperature reduces the water level: the higher the temperature in the current and the preceding month, the larger the reduction in the water level; the coefficients of AT indicate that increasing the temperature by 1 °C in both the current and preceding month reduces the water level by a combined 6,63 ± 0,31 mm.

Extensions of the model with higher lags of the regressors RF and AT as well as interaction terms do not change the results. Replacing the air temperature AT by water temperature WT (which shortens the observation period by five years as WT is only available from 1976) does not alter the conclusions.

Several modifications of Model 1 with regular and seasonal moving average components were also considered. While these models were able to reduce the autocorrelations in the residuals, the fit of the models was only modestly improved and the conclusions about the impact of precipitation and temperature were not changed.

Model 1 indicates that the current water level is highly determined by the water level of the preceding month (with its influence reduced by about 3,5 %), by the rainfall in the current and preceding months (increase of about 6 cm given an average rain) and by the evaporation in the current and preceding months (about 1,7 cm given an air temperature of 25 °C).

As an alternative, models such as the nonlinear regression model in equation (2) shown below were fitted to the monthly average water level (WL). Results are similar, with good residual diagnostics indicating little serial correlation in the residuals.

$$\mathrm{WL}_t = \alpha(\mathrm{WL}_{t-1} + \beta_1 \mathrm{RF}_t)/(1 + \beta_2 \mathrm{AT}_t + \beta_3 \mathrm{AT}_t^2) + \epsilon_t \tag{2}$$

Table 3 shows results from the non-linear least squares estimation in Gretl.

Table 3: Results from fitting Model 1 to the data

Model 2: NLS, using observations 1971:02-2021:07 ($T = 606$) $\mathrm{WL} = \alpha(\mathrm{WL}_{t-1} + \beta_1 \mathrm{RF}_t)/(1 + \beta_2 \mathrm{AT}_t + \beta_3 \mathrm{AT}_t^2)$				
	coefficient	std. error	t-ratio	p-value
α	1,00022	2,7391e-05	36516	<0,0001
β_1	0,00051	4,7747e-05	10,66	<0,0001
β_2	1,5064e-05	5,1507e-06	2,925	<0,0036
β_3	1,4175e-06	2,2680e-07	6,250	0,0001

The model displays the expected impact of the regressors on the water level:

- the water level is determined by that of the previous month (WL(-1)) plus 0,00051 times the rainfall in the actual period; 1 cm of rainfall increases the water level by 5,1 mm;
- air temperature reduces the water level: the higher the temperature the smaller is the denominator of the model; at a temperature of 10, 20, and 30 °C the average water level (115,5 m) is reduced by 4, 13, and 26 cm, respectively, illustrating the fact that evaporation proceeds more quickly at higher temperatures.

A modified model with a linear function of AT in the denominator of equation (2) shows similar reductions of the water level of 7, 14, and 21 cm for temperatures 10, 20, and 30 °C. The correlogram of the residuals shown in Figure 4 suggests modest deviations from white noise.

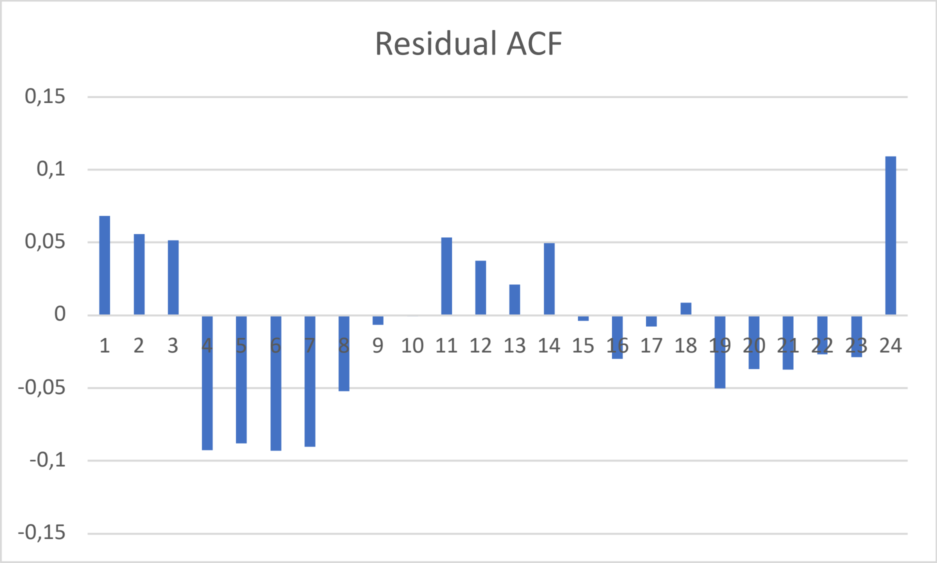

Figure 4: Autocorrelation function (ACF) of the residuals of Model 2 for lags up to 24; with standard error $1/\sqrt{T} = 0{,}0406$ (number of observations $T = 606$), 95 % confidence limits are ± 0,080

4.2. Scenario forecasts of the lake water level

The increasingly lower water levels during recent years raises questions about the future path of the lake water level. Questions of interest concern (1) the recovery of the water level in a record dry year like 2021 and (2) its future path during a phase of falling water levels.

Data are available until July 2021. Forecasts are obtained from Model 1 of the previous section, assuming three scenarios for precipitation and temperature for August to December 2021:

A. they are given by their monthly averages from 2016 to 2020,

B. they are as in the extremely dry year 2003,

C. they are as in the record wet year 2014.

For year 2022 it is assumed that precipitation and air temperature follow the monthly averages from years 2016 to 2020.

The average annual amount of rain in the period 2016 to 2020 was 573 mm, a value not far from 557 mm, the average annual rain during the whole 50-year study period. The year 2011 was one of the driest during the 50-year period we study: Both the annual rain (352,7 mm) and the rainfall in autumn (September to December: 92,0 mm) were among the smallest. In 2014, the annual rain total was 833,0 mm, the maximum rainfall over the studied 50-year period, with very wet summer and autumn.

Figure 5 shows the water level since 2017 and our scenario forecasts for August to December 2022.

What can be expected for the dry year 2021?

The steady decrease of the lake water level since 2014 and the public discussion of a possible drying out in the near future raises the question how low the water level may fall in a year like the current year 2021. Figure 6 shows the development of the water level since 2017 including our forecasts for August to December 2021. The forecasts are estimated for the following three scenarios for precipitation and air temperature that govern the remaining months of 2021.

In 2003, the amount of rain in autumn (August to December) was the smallest during the whole 50-year period we study (143,8 mm). 2003 was also the year with smallest annual rain (352,7 mm). In 2014, the annual rain was 833,0 mm, with 375,4 mm in autumn; both are maximum rainfalls over the studied 50-year period. The average annual amount of rain in the period 2016 to 2020 was 573 mm, a value not far from 557 mm, the average annual rain during the whole 50-year study period.

The respective average annual air temperature in the periods of the three scenarios were 12,5 °C, 11,4 °C and 12,6 °C. The corresponding average temperature during the autumn (August to December) season were 21,3 °C, 21,1 °C and 18,8°C.

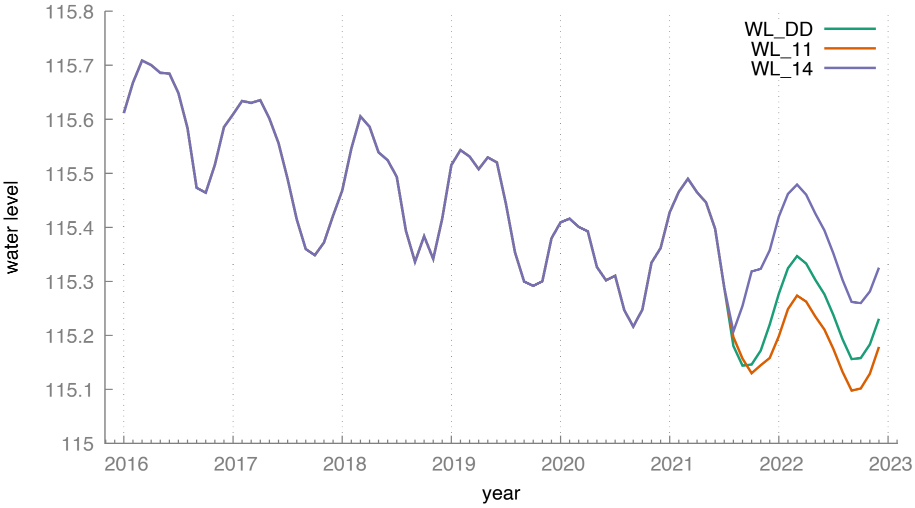

Figure 5: Water level since 2016 and forecasts for August 2021 to December 2022: (1)WL_DD (scenario A) with precipitation and temperature as their average values between 2016 to 2020; (2) WL_11 (scenario B) as in the extreme dry year 2011 and (3), WL_14 (scenario C) as in the record wet year 2014 for August to December 2021

For none of the three scenarios, the predicted water levels for August to December 2021 fall below 115,13 m. For October, the predicted water levels under scenarios A and B are as low as 115,15 and 115,13 m, but recover for December to 115,22 m and 115,16 m. Under scenario C, the predicted water level increases steadily and reaches 115,36 m in December. The standard errors are 0,04 for October and 0,05 for December for all scenarios.

The analysis shows that conditions like those of the last 5 years will keep the water level in autumn at low levels, with even lower readings for an extremely dry autumn. A wet autumn, on the other hand, will increase the water level substantially.

What can be expected for coming years?

An even more interesting question is how water levels will respond after a year with low water levels such as the ones in 2021. Predictions are calculated for 2022, under scenarios A through C for the remaining months of 2021 and the additional assumption that precipitation and air temperature follow the monthly averages from the years 2016 to 2020.

Figure 5 shows that meteorological conditions as experienced during the recent five years keeps the water level in the usual range. In the case that the year 2021 ends with a rather dry autumn like in 2003, the water level can be expected to drop still further to a minimum of 115,10 m. But, for a wet ending to the year 2021 like the one we had in 2014, there will be a substantial recovery of the water level, with an expected minimum in autumn of 2022 at about 155,25. The standard errors are 0,07 in June and 0,08 in December 2022 for all scenarios.

5. Concluding remarks

Trends in the water levels of Lake Neusiedl over a 50-year period were studied. The objectives were to (1) understand the impact of meteorological variables on the water level and (2) to predict future water levels under several scenarios. The interest was triggered by the falling water levels during recent years and the extreme low water level in 2021.

The data analysis shows that the current water level is determined by the water level of the preceding month and is increased by rainfall and reduced by temperature (evaporation) in the current and preceding months.

The annual amount of rain follows a stable pattern with fixed mean and without long-term trend. Temperatures of air and lake water have increased over the study period; air temperature increased by about 2 °C.Water levels change, apart from their obvious annual seasonality, in cycles that typically last several years. Rising and falling phases of these cycles have become longer, and higher maxima have been recorded during the last 30 years.

Rain is the major source of water for Lake Neusiedl, and its impact on the water level is one focus of the analysis. The model for the monthly average water levels indicates that in a month with average rainfall of 4,6 cm, water level increases by about 2,6 cm; the increase due to rain in the preceding month is slightly higher. Temperature in the current and preceding months affects the water level.

Forecasts are used to illustrate the future progression of the lake water level. The question how low the water level may fall in 2021 was investigated for three scenarios, assuming that the remaining months reflect meteorological conditions of (1) a year with average 2016-2020 conditions, (2) an extremely dry year, and (3) a record wet year. In none of these scenarios, the predicted water level falls below 115,13 m. By December 2021 the water level has recovered under all scenarios, to 115,16 m for the dry year scenario and to 115,36 m for the wet year scenario.

The water levels in 2022 are influenced by (1) the water level at the end of year 2021 and (2) the meteorological conditions during 2022. For average 2022 meteorological conditions the water levels in 2022 may not recover for a dry 2021 autumn but will recover substantially for a wet ending to the year 2021.

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