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alpine lakes network




Alpine Lakes

Survey on climate change

Alpine Space
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Survey on climate change

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REFERENCES FOR LAKE MONITORING AND MODELLING

Past trends

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Ecological model

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Introduction

The lake ecosystems are extremely sensitive to human impacts and climate change (Skjelkvaele and Wright, 1998) and they are characterized by numerous feedback mechanisms between biological processes, external forcings and circulation hydrodynamics, which can be modified by climate change and sometimes contradictory effects (IPCC assessment report, 2001), causing changes in water quality and biodiversity and leading to the possible occurrence of «Catastrophic shifts» in the ecosystem (Scheffer et al. 2001).
A rise in temperature (Mooij et al. 2005; Johnk et al. 2008) can for example facilitate the development of phytoplanktonic bloom due to increased stability of the water column and the dependence of algal growth rate on temperature.

Monitoring and **modelling**, associated to the investigation of the lake evolution (from the point of chemical, physical and biological view), developed during SILMAS at each lake pilot site, provided useful **decision making tools**. Here, summary diagrams and tables of these studies, are provided.

This publication offers a framework of the evolution of the lakes alpine status, in the context of climate change. It is dedicated to the general public better understand how our alpine lake areas have been impacted by climate change, in order to increase environmental awareness. But it contains also detailed technical information helping scientists and decision makers.

Further information and details can be found in the final reports of the Work Package 4 of SILMAS project, available on the project website (http://www.silmas.eu) or on the Alpine Space projects website (http://www.alpine-space.eu).

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The SILMAS project: the activities of Work Package 4

Sustainable Instrument for Lakes Management in Alpine Space (SILMAS) project, co-funded by European Regional Development Fund (ERDF) within the Alpine Space Programme, involved 14 partners of 5 countries (Italy, France, Austria, Slovenia and Germany) leaded by Region Rhône-Alpes (France).
Within SILMAS project, Work Package 4 “Alpine Lakes running changes” (WP4), leaded by ARPA Piemonte (Italy), worked on analysis of effects on climate change on lakes ecosystem, sharing methods and frames of references, and testing models in main types of lakes, to identify likely scenarios in which lakes could be involved.

WP4 was designed as a virtual laboratory producing a dynamic vision of each situation, positioned into identified general trends and related to environmental requirements.
Since lakes are complex dynamic systems, interacting with local environment and connected to the water cycle, WP4 followed first two parallel ways to throw light on lakes evolution factors due to human activities and climatic variability: the biological approach and the physical/chemical approach, specifying lakes bodies and trends by collecting and integration of ecosystem indices, related to climate variability, and characterizing hydrological impacts of climate change on lakes and catchments by applying hydro and thermodynamic models and isotopic analysis.

The biological approach concerns the collection of chemical, physical and biological historical data useful to analysed the trends, the significant ecological events and to observe the ecological effects of climate change on the Alpine lakes. In order to do this, the Regional Agency for Environmental Protection of Piedmont (ARPA) collected a maximum of data on climate change from across Alpine Space. Trough this analysis, it has been possible to produce appropriate practical tools intended to help local decision-makers take the decisions necessary to curb the effects of climate change.

The physical/chemical approach concerns the determination of climate change on lakes and in the catchment areas from a point of view of hydrological and thermodynamic aspects, mixing conditions, residence times. Applying hydrological and thermodynamic models and isotopic analysis delivered data of past and scenarios of future hydrological and mixing conditions.

Through the integration of biological and hydrological data into scenario in relation with main alpine lakes types, it has been possible to describe likely scenarios to be expected from climate change, linked to the main types of lakes encountered in the alpine space. Adjustment strategies have been outlined for stakeholders, according to challenges every networking lake will have to meet, in terms of water resource management and ecosystems preservation or restoration.

The participants and the lakes

The authorities directly involved in Work Package 4 are: for France, Rhône-Alpes Region (project lead partner); for Italy, Piedmont Regional Agency for environmental protection (WP4 lead partner) and Environmental Protection Agency of Trento; for Germany, Institute of Lake Research, State Institute for Environment, Measurements and nature Conservation Baden-Württemberg; for Austria, Regional Government of Carinthia, Competence Centre Environment, Water and Nature Protection and Joanneum Research, Forschungsgesellschaft mbH, Institute of Water, Energy and Sustainability.
Syndicat Mixte du Lac d'Annecy/INRA for France, Regione Lombardia for Lombardy (Italy) and the National Institute of Biology for Slovenia provided data. Within one’s own territory, each project partner selected a series of lakes and provided for each one historical series of chemical, physical and biological data: the data analysis permitted to apply statistical analysis and to provide lakes trends. In particular, the lakes observed are indicated in the following table, and in the map it is possible to consult their geographical position:

Regione/Provincia (Stato)	Nome del lago	
Rhône-Alpes (France)	1	Lake Annecy
Piedmont (Italy)	2	Lake Avigliana Grande
	3	Lake Sirio
	4	Lake Viverone
Baden-Württemberg (Germany)	5	Lake Constance
Trento (Italy)	6	Lake Caldonazzo
	7	Lake Levico
Carinthia (Austria)	8	Lake Ossiacher See
	9	Lake Wörthersee
	10	Lake Klopeiner See

The lakes and climate change

Impacts...

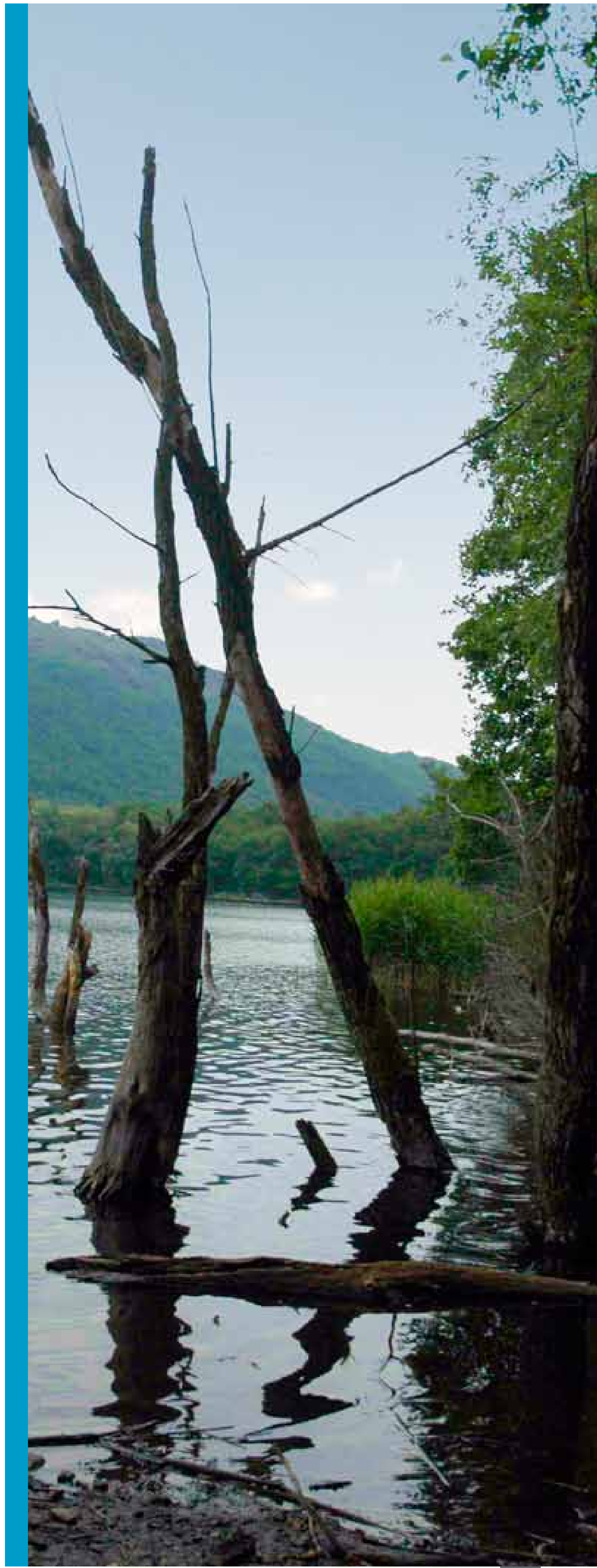
Climate change will alter the hydromorphological conditions of the lakes; the magnitude of change induced by climate change is still relatively small in comparison with the impact of anthropogenic land use, but, in future, climate change will may cause significant change in hydrology and, at the same time, impose land use changes in catchments.
In lakes, hydrological change are expressed in terms of more dynamic fluctuations as well as overall changes in water level and their impacts on eutrophication (Kernan et al., 2010).
Climate warming caused changes in the thermal regime of lake waters and in the course of glacial phenomena in the northern hemisphere (Magnuson et al., 2000) including among others:

- earlier water warming in spring (Gronskaya et al., 2001)
- increase in water temperature both on the surface and at deeper levels in lakes (Endoh et al., 1999)
- lengthening of the period in summer when lake water temperatures exceed 10°C (Jarvet, 2000);
- shortening of periods with ice cover and decrease in its thickness (Todd and Mackay, 2003)

A larger historical survey of rivers and lakes across the whole of the Northern Hemisphere from 1846 to 1995 by Magnuson et al. (2000) revealed significant trends towards earlier break-up and later formation of lake ice providing further evidence for sytematic global warming over the past 150 years.
The timing of lake ice break-up is of ecological importance because the disappearance of ice cover affects the production and the composition of the phytoplankton community and the occurrence of winter fish kills (Weyhenmeyer, 2006).
Even the nutrients cycle in aquatic systems are altered by warmer temperature, as the period of algal bloom that happens 1 month early in the '90 compared to '70 in the large Swedish lakes (Weyhenmeyer, 2001).
The impacts of climate change on lake areas will cause, in turn, impacts on human activities, such as fisheries, water supply, tourism, hydropower, navigation.
Higher water temperatures lead to the progressive reduction of thermal habitats for fish, which will move toward of an habitat more suitable. A reduction in rainfall can lead to water deficit stress, and consequently lead to issues related to water supply in agriculture, navigation and port management.
In addition, extraordinary weather events can cause damage in terms of erosion of soil, carrying nutrients waters and sediments of lakes, damage them. A most extraordinary weather event could also lead to damage forestry located on the shores of lakes, especially in parks or other areas of great natural value.
The lakes in the Alps are used in particular for tourism and recreation; on one hand longer summers will lead to greater use of tourist facilities, from the other hand will have to pay more attention to water quality, and the diffusion of invasive species.

...and adaptation

Adapting to climate change is a process that, as a complement to mitigation process, reduces the consequences of global warming (IPCC, 2007). Many impacts of climate change on lake ecosystem can be effectively addressed through adaptation, in particular short term impacts, while increasing the magnitude of the climate change impact the options for an effective adaptation diminish, while associated costs increase. Adaptation will require technical know-how, funding and substantial businesses, requires coordination between individual actions (e.g., farmers) and public policies (e.g., water management), and requires political will and the presence of adequate institutional structures (e.g., risk management).
Adaptation of a lake ecosystem to climate change can be either natural (resilience) or there may be options for adapting human activities. Among them there are those named «hard», i.e. infrastructure and technology, characterized by long times and more investments, and those named «soft», that is non-structural systems based on optimization of resource management and risk prevention. For example the adaptation options for water supply from one hand could be the water reuse, the water transport, the building of dams and water storage (hard adaptation), and from the other hand the demand management and the changing dam operational rules (soft adaptation).
In general adaptation can be efficient to reduce (some) climate change impacts.
But adaptation is not an easy task: in several economic sectors, climate change should already be included in decision-making frameworks, especially where infrastructures are being constructed.
Because of uncertainty, inadequate adaptation strategy can worsen the situation. Innovative strategies that improve robustness to climate change situation could be proposed. Soft adaptation strategies are often better able to manage uncertainty than hard adaptation strategies. Actually, soft adaptation strategies should be considered very seriously and be the topic of more research, as, responding to needs of local authority, imply environmental benefits, even on a large scale, creating significant synergies with the environmental sustainability policies. These forms of adaptation, if on the one hand are more easily achievable, require the formation of an active social and cultural context, together with the capacity of governance.



Guide to consult lake sheets

In lake sheets, you can find a series of information about the lake, its own evolution and climatic scenarios for the area interested by the lake. The aggregate information resulting from the statistical analysis applied to collected data.
Therefore, for further information, refer to the other detailed publications or to specific publications published by competent authorities.

Lakes are in geographical location order, from west to east.
Each sheet contains following sections:

The lake

This section includes a short description of the lakes, main morphometric and hydrologic data featuring the lake (Identity card) and its catchment basin.

Catchment area: river basin surface expressed in square km. In case of reservoirs and if data are available, the connected basin area is indicated next to natural basin dimensions.
Lake area: lake surface expressed in square km.
Maximal depth: maximal lake depth expressed in m.
Average depth: average lake depth expressed in m and calculated as the lake volume divided by its surface area.
Volume: lake volume expressed in millions of cubic meters.
Average altitude: lake average altitude expressed in meters above sea level.
Residence time: the average length of time that water stays in a lake.
Fill up time: the time to fill the empty lake.
Trophic state of the lake: the degree of fertility of a lake.
The images shows the location of the lake in the whole alpine space and the position of monitoring point in the lake and of the meteorological station, both used for the analysis of climate change in the lake area.

Climate Driven Scenarios

Scenarios for precipitation and temperature from 2001 to 2050 (reference period: 1961 – 2000) in the area interested by the lake, calculated using the E-obs dataset and the Multimodel SuperEnsemble Technique (Air temperature scenarios) and the Probabilistic Multimodel SuperEnsemble Dressing (Precipitation scenarios).

Past trends

Information about the main past trend climate driven (air temperature and precipitation) and the main past trend of water temperature lake parameter, showing linear regression lines and their gradients in winter (mean of December, January and February months) and in summer (mean of June, July and August months), except for water temperature parameter of Trentino and Austrian lakes, for which this analysis has been made using monthly data.

Ecological Model

The responses of phytoplankton and zooplankton communities to anthropogenic pressures frequently provide the most visible indication of a long term change in water quality. The plankton community is well buffered against the sudden fluctuations of temperature, but can be sensible to the seasonal changes on long-times. In order to understand better the phytoplankton sensitivity to climate change, two models have been applied: a homogeneus and a two layer lake ecosystem model. The models are applied to the following lakes: Lake Annecy, Lake Viverone, Lake Sirio, Lake Avigliana Grande, Lake Caldonazzo, Lake Levico and Lake Wörthersee.

Hydrodynamic model

For a better understanding of the climate change induced shifts of physical properties in an Alpine lake a hydrodynamic, one-dimensional, and vertical model was applied to alpine lakes. First, the model was calibrated with measured meteorological data and the respective water temperature measurements. This guaranteed a close to reality mathematic lake description and a necessary condition for projections of possible future lake physics. In a second step, the model was forced by various climate scenarios. Air temperature, air humidity, wind speed, and cloud cover were changed to get an idea of the lakes sensitivity to a climate change. The results show a high sensitivity of circulation patterns in a lake. This model has been applied to Lake Viverone, Lake Constance and Lake Wörthersee.

Hydrological modelling and isotope investigations

The water balance of lakes and the residence time of lake water are very sensitive to changes of the meteorological parameters air temperature and precipitation.
Semi-distributed conceptual rainfall-runoff models have been used at 3 Carinthian lakes with the aim

to simulate past changes and develop scenarios of the lake volume renewal depending on land use and climatic conditions and of the lake evaporation.
The application of environmental isotopes gives the unique possibility to get direct insights into water dynamics and circulation behaviour of lakes. The environmental stable isotopes Oxygen-18 and Deuterium have been used to deliver information about the origin of water, mixing and evaporation processes in the lakes. Furthermore they support the modelling activities by the detection of losses from lakes to springs or inflows from groundwater.
The radioactive isotope Tritium as remnant in precipitation from the atmospheric bomb tests in the 60ies and 70ies of the last century in combination with its decay to Helium was used to determine the mean residence time of lake water in the deepest parts. The results gave a mean residence time of 9.5 years for Wörthersee, 1.5 years for Ossiacher See and 6.8 years for Klopeiner See (lakes to which this survey has been applied). The hydrological model in combination with isotope investigations represents a very useful tool to estimate changes of the lake water renewal and fill up time as consequence of environmental (climate, land use) changes and to understand better the circulation behaviour in lakes.

Change in water temperature and water circulation

Detailed investigation on surface water temperature and development of temperature stratification, applied to Austrian lakes (Wörthersee, Klopeiner See, Ossiacher See).

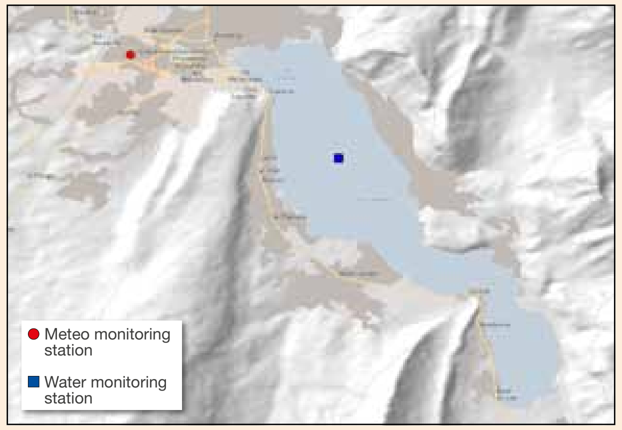
Lake Annecy

The lake

Lake Annecy (Haute-Savoie, 74) is the second French largest natural lake. In the late 1950s, as a result of the constantly increasing pressure of human activity, Lake Annecy, along with many other sub-alpine lakes, experienced the early stages of eutrophication. However, in 1962, local representatives decided to start the construction of a vast network of drains to divert waste water away from the catchment basin. The polluted water was treated and discharged downstream from the lake. The nutrient enrichment period was therefore relatively limited and the lake is now considered to be oligotrophic. It is very clear, its water contains good oxygen levels and there is a good variety and balance of the various biological groups (phytoplankton, zooplankton, fish). In fact, the water quality is so good that the water can be used as drinking water for most of the surrounding towns (30,000 m^3 are pumped out every day).

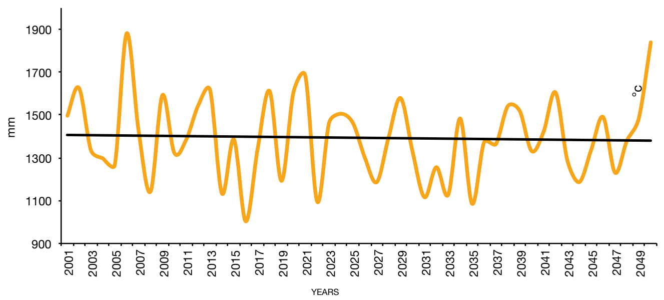
Identity Card

Catchment area	270	km^2
Lake area	27	km^2
Maximal depth	65	m
Average depth	41	m
Volume	1124,5	$m^3 \times 10^6$
Average altitude	447	m a.s.l.
Residence time	3,8	years
Inflow	-	m^3/y
Outflow	8	m^3/y
Trophic state of the lake	Oligotrophic	

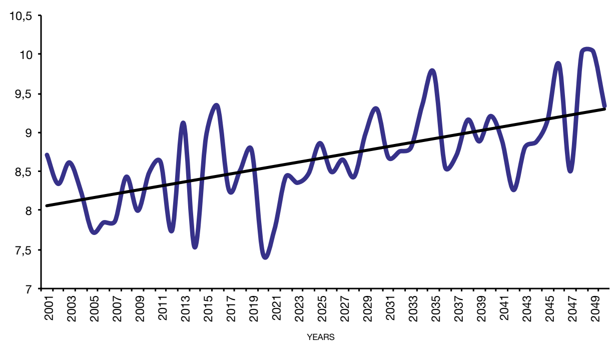


Climate driven scenarios 2001 - 2050

Precipitation



Temperature

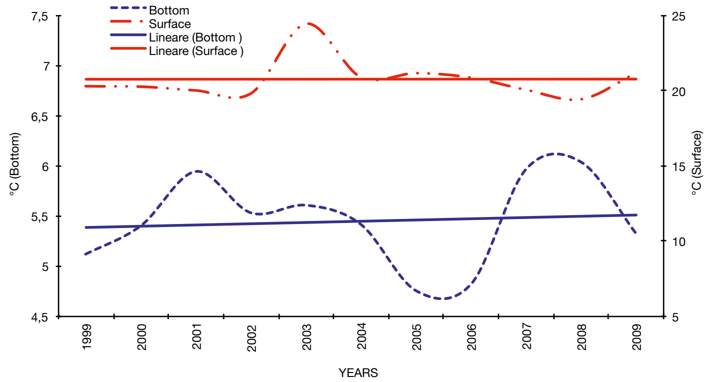


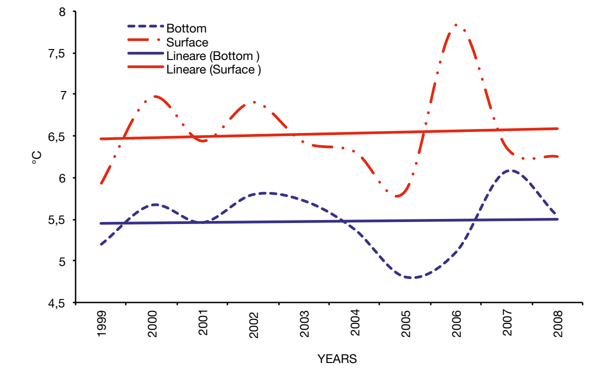
	2020	2030	2040	2050
Precipitation scenarios (mm)	- 116	- 73,2	- 118	- 27
Air temperature scenarios (°C)	+ 0,14	+ 0,51	+ 0,92	+ 1,25

Past trend

Water temperature

Summer (JJA) **Winter (DJF)**

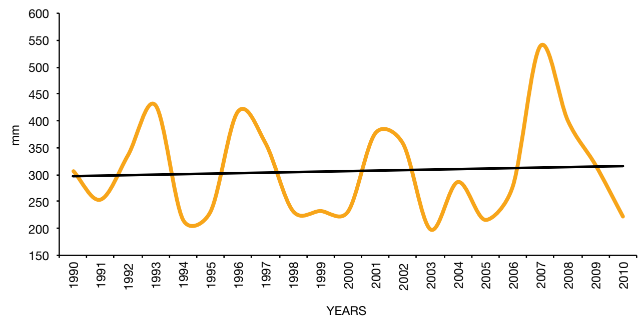


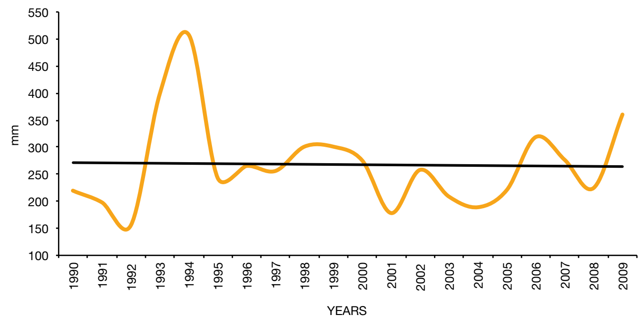


	Period: 1999 - 2010	
	Rate: °C per decade	
	JJA	DJF
Surface	+ 0.009	+ 0,13
Bottom	+ 0,12	+ 0,05

Precipitation

Summer (JJA) **Winter (DJF)**

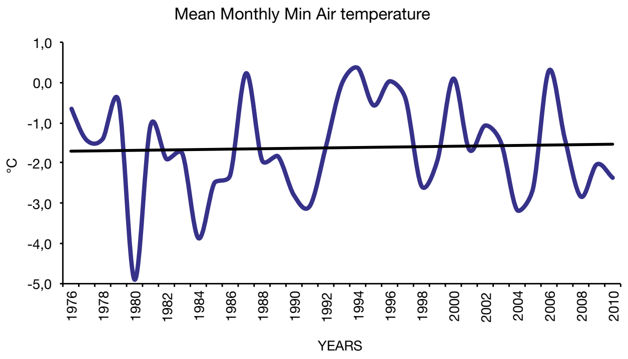


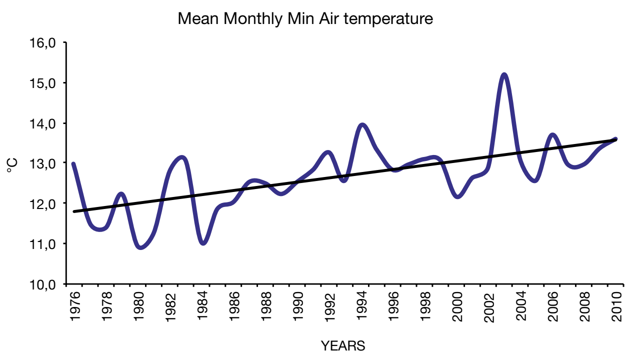


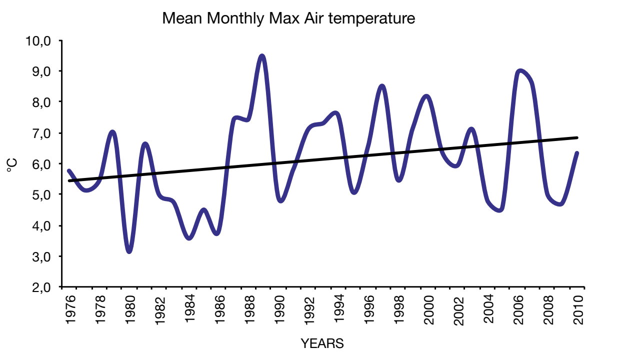
Period: 1999 - 2010	
Cran – Gevrier Station	
Rate: mm per decade	
JJA	DJF
+ 9,4	- 3,80

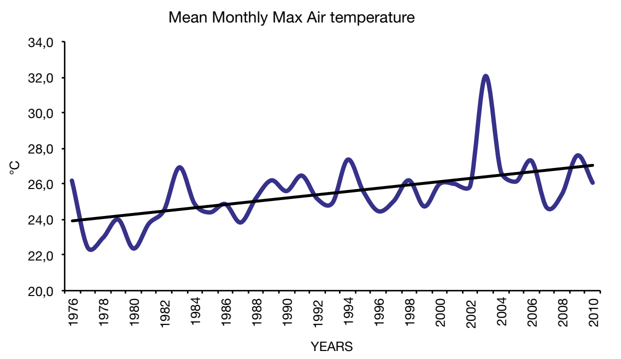
Air temperature

Summer (JJA) | **Winter (DJF)**







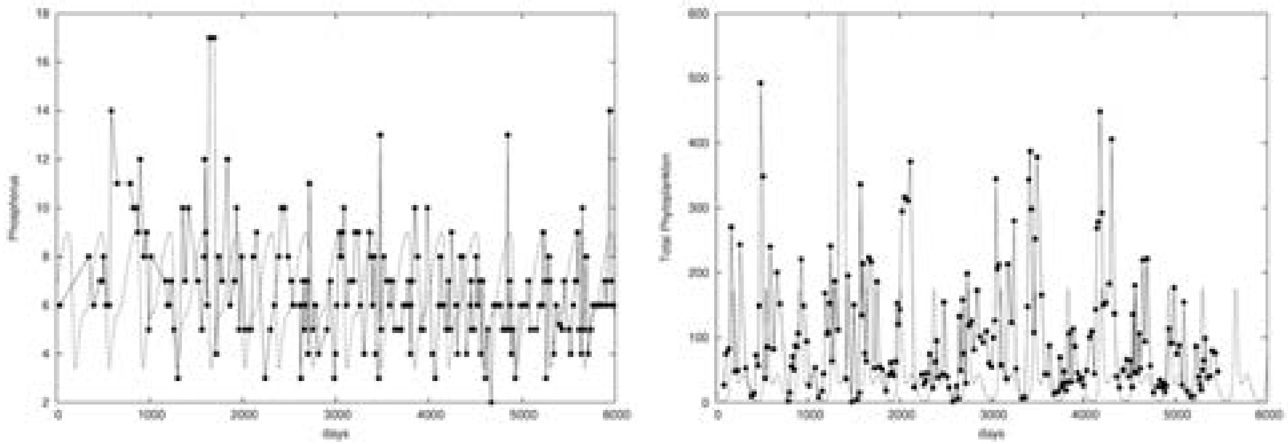


	Period: 1976 - 2010 **Cran – Gevrier Station**	
	Rate: °C per decade	
	JJA	DJF
Min Air Temperature (°C)	+ 0,5	+ 0,05
Max Air Temperature (°C)	+ 0,9	+ 0,40

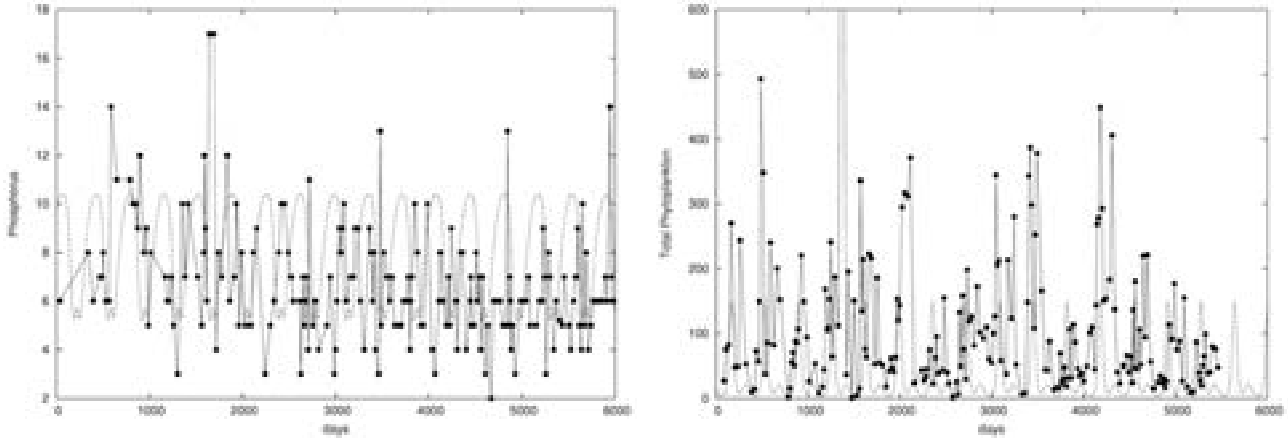
Source:
SILA INRA, for lake monitoring data
Meteo-France - SILA, for meteorogical data

Ecological model

Homogeneous model



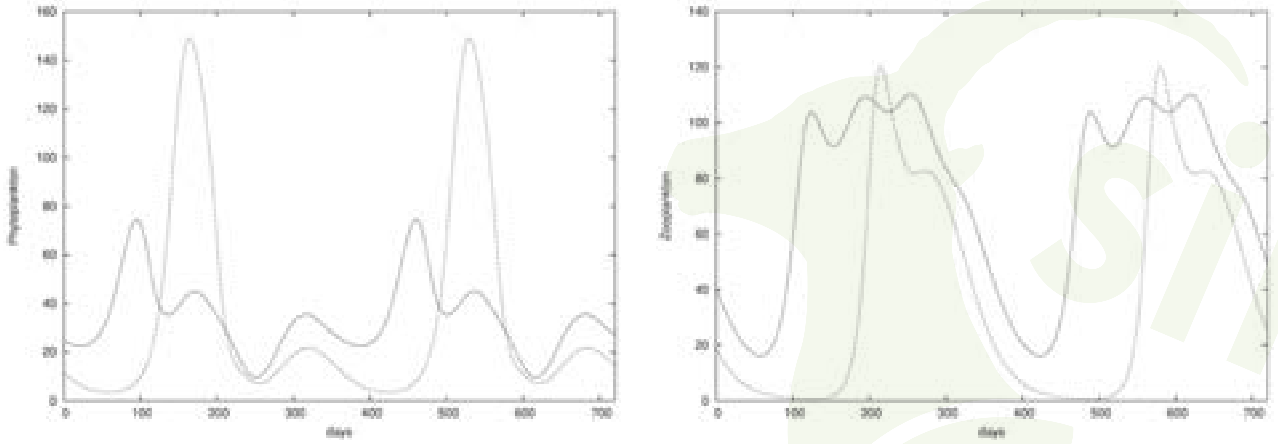
Two layer model



Total phosphorus concentration in µg-P/L from measurements at a depth of 10 meters (solid points and connecting line) from the homogeneous model (upper panel, dashed line) and from the two-layer model (lower panel, dashed line).

Comparison between measured total phytoplankton concentration (solid points and connecting line) and the phytoplankton concentration produced by the homogeneous model (upper panel, dashed line) and from the two layer model (lower panel, dashed line). Concentrations are in µg-C/L assuming a carbon-to-biomass ratio R=0.2.

Effects of temperature and environmental changes



Left panel: comparison between the two-layer model phytoplankton concentration in the upper layer for faster winter turbulent exchange between the two layers, μ_0=0.2 day^{-1}, and warmer summer and winter conditions (+ 3 °C) (solid line) and current conditions (dashed line).
Right panel: the same for zooplankton concentration. Concentrations are in µg-C/L.
Warmer conditions and more intense winter turbulent exchange lead to a decrease in the maximum phytoplankton concentration at the bloom and to higher concentrations in the inter-bloom period, while the zooplankton concentration is almost unaffected in the peak and it is increased in the inter-bloom periods.
In addition, there is a significant increase in the fish compartments.

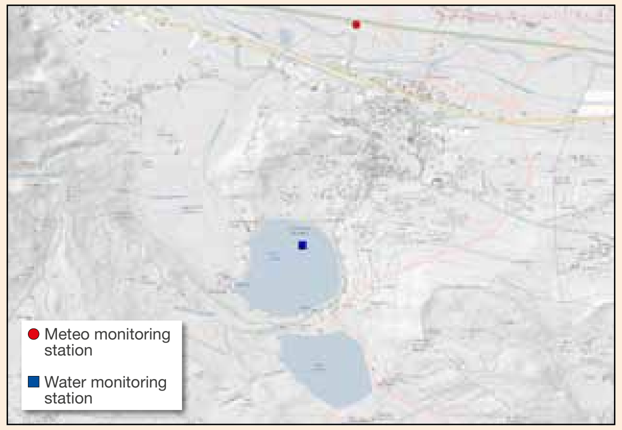
Lake Avigliana Grande

The lake

Lake Avigliana Grande is located within the Parco Naturale Laghi di Avigliana. Tourism has significantly developed in the area around the lakes - an area that is remarkably interesting for historical and naturalistic reasons: north-west of the lake, there is Mareschi area, the most wester Italian wetland.

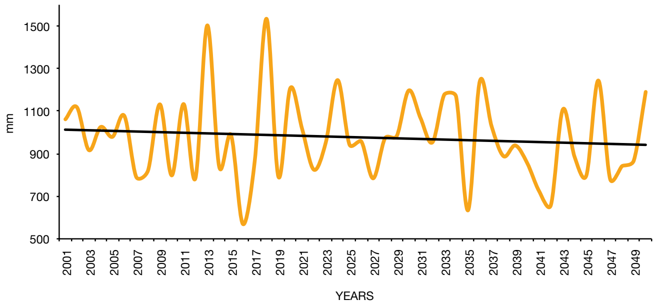
Identity Card

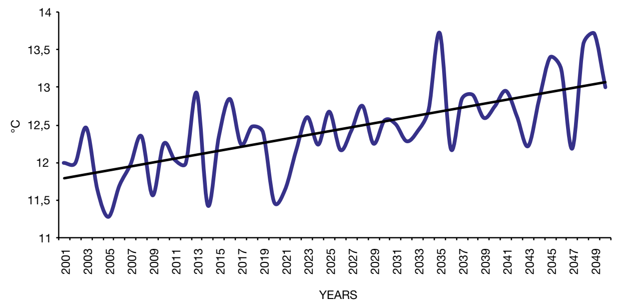
Catchment area	11,5	km²
Lake area	0,89	km²
Maximal depth	26	m
Average depth	19,5	m
Volume	17,2	m³ x 10^6
Average altitude	346	m a.s.l.
Residence time	2,3	years
Inflow	-	m³/y
Outflow	-	m³/y
Trophic state of the lake	Eutrophic	



Climate driven scenarios 2001 - 2050

Precipitation **Temperature**



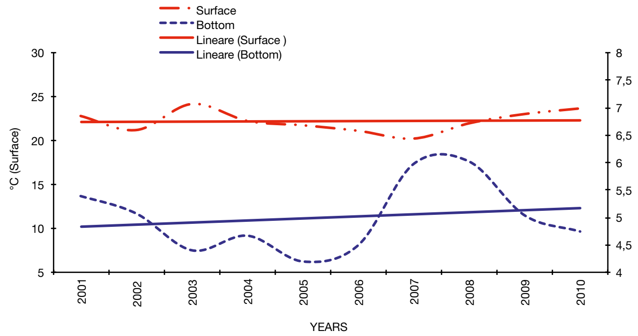


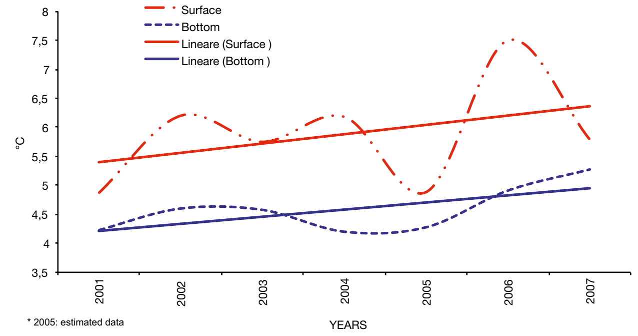
	2020	2030	2040	2050
Precipitation scenarios (mm)	+ 31,6	+ 11,7	- 4	- 70
Air temperature scenarios (°C)	+ 0,42	+ 0,6	+ 0,96	+ 1,3

Past trend

Water temperature

Summer (JJA) **Winter (DJF)**

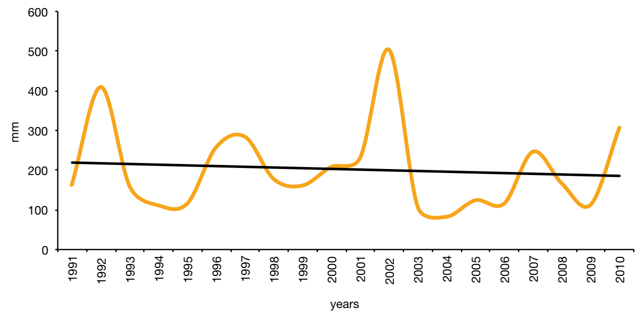


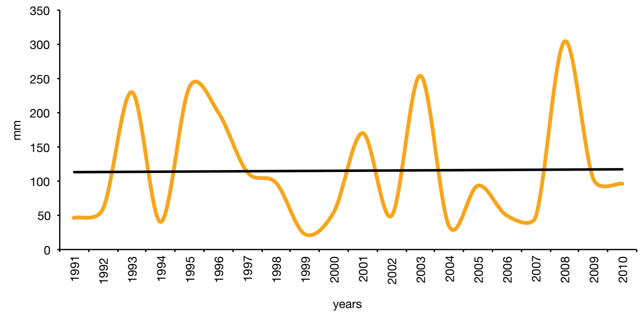


	Period: 2001 - 2010	
	Rate: °C per year	
	JJA	DJF
Surface	+ 0.02	+ 0,16
Bottom	+ 0,03	+ 0,12

Precipitation

Summer (JJA) **Winter (DJF)**

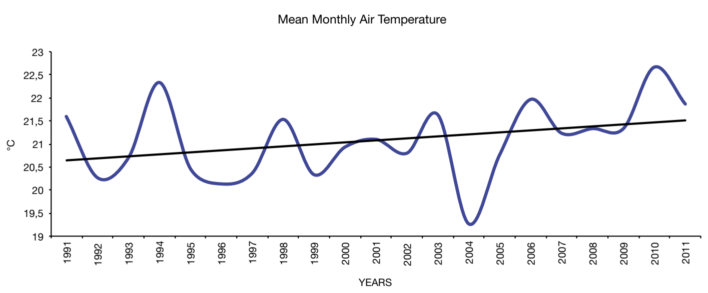


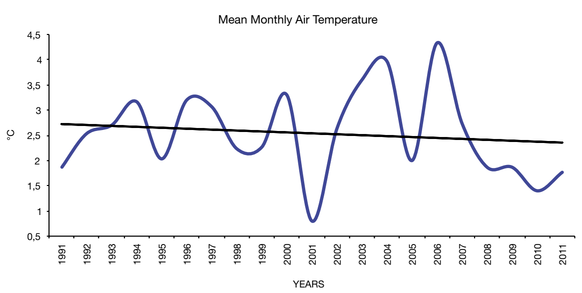


Period: 1991 - 2011	
Avigliana Station	
Rate: °C per decade	
JJA	DJF
+ 17,64	- 2,18

Air temperature

Summer (JJA) **Winter (DJF)**





Period: 1991 - 2011

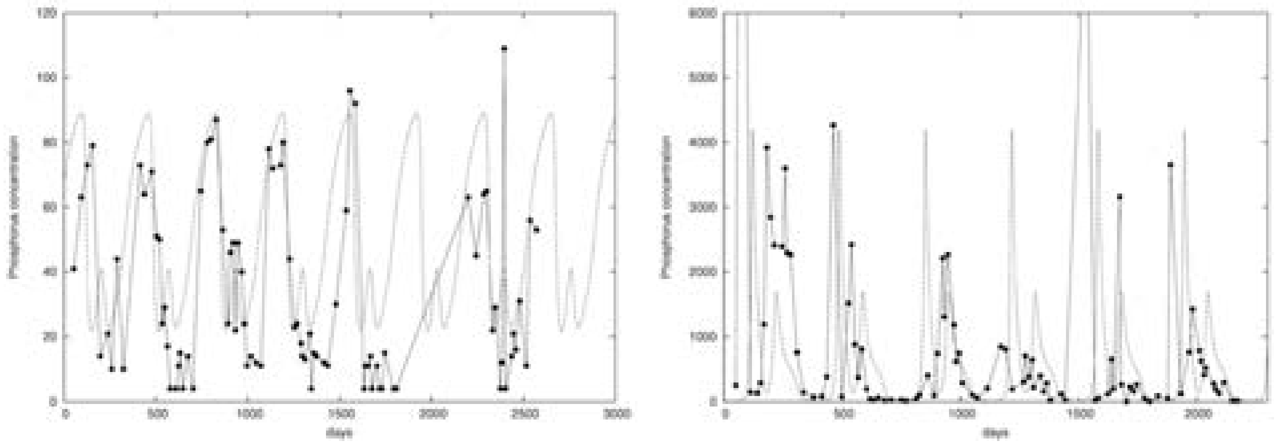
Avigliana Station

Rate: °C per decade

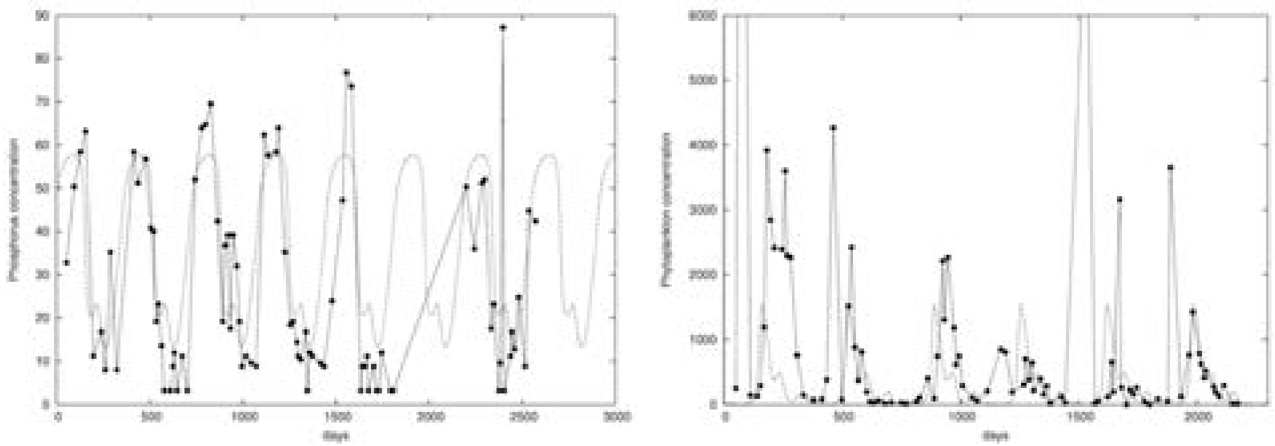
JJA	DJF
- 0,18	+ 0,43

Ecological model

Homogeneous model



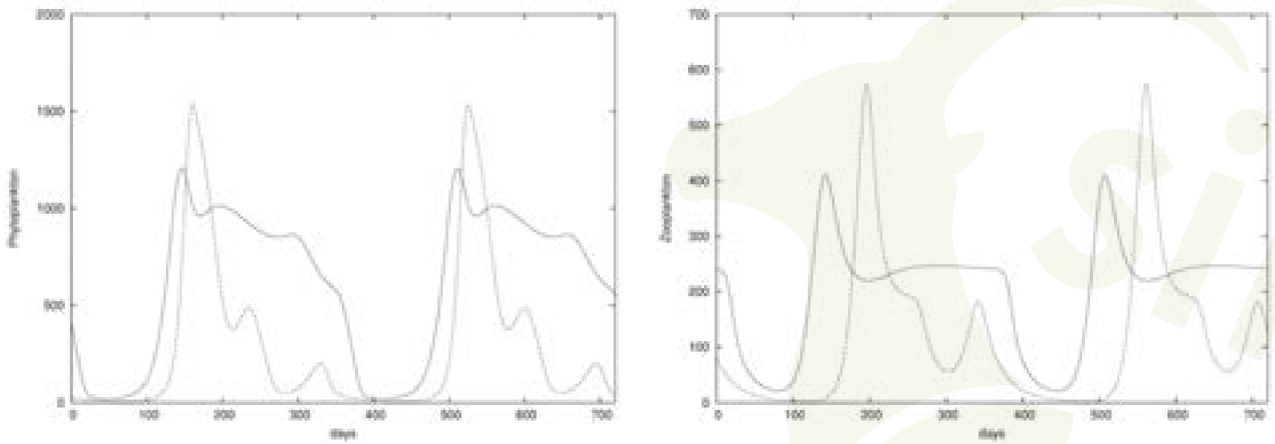
Two layer model



Total phosphorus concentration in µg-P/L from measurements at a depth of 10 meters (solid points and connecting line) and from the homogeneous model (upper panel, dashed line) and from the two-layer model (lower panel, dashed line).

Measured *chlorophycea* concentrations (solid points and connecting line) and phytoplankton concentration produced by the homogeneous model (upper panel, dashed line) and by the two-layer model (lower panel, dashed line). Concentrations are in µg-C/L using a carbon-to-biomass ratio R=0.2 and assuming cells with size 10 µm.

Effects of temperature and environmental changes



Left panel: comparison between the two-layer model phytoplankton concentration in the upper layer for faster winter turbulent exchange between the two layers, μ_0=0.2 day^{-1}, and warmer summer and winter conditions (+ 3 °C) (solid line) and current conditions (dashed line). Right panel: the same for zooplankton concentration. Concentrations are in µg-C/L.
Warmer conditions and more intense winter turbulent exchange lead to a very slight anticipation of the bloom, with a smaller maximum concentration but with a significantly longer period of high phytoplankton concentrations.

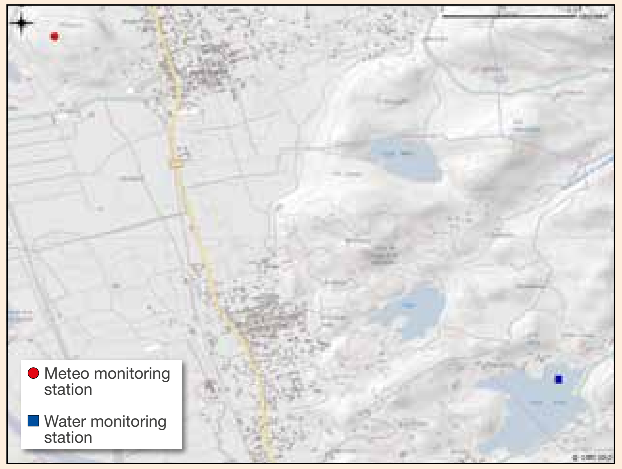
Lake Sirio

The lake

The Lake Sirio is located within the SIC (Site of Community Importance) «Lakes d'Ivrea,» in the Alpine biogeographical region straddling the towns of Chiaverano and Ivrea, in northern part of the moraine Amphitheatre of Ivrea on left bank of the river basin of Baltea. The beauty of the place is the main peculiarity of the lake: it is nestled on a hillside modeled in the Pleistocene from Glacier Balteo whose left lateral moraine, Serra.

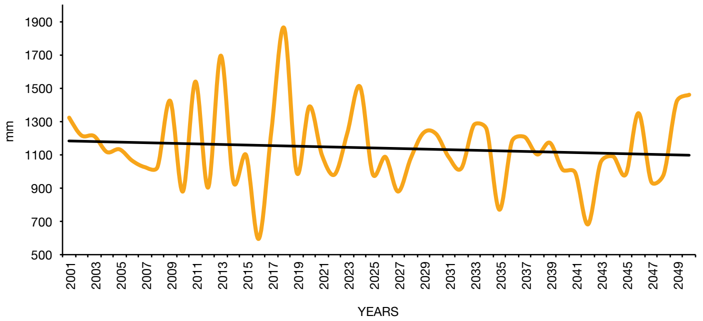
Identity Card

Catchment area	1,4	km²
Lake area	0,29	km²
Maximal depth	43,5	m
Average depth	18	m
Volume	5,24	m³ x 10^6
Average altitude	266	m a.s.l.
Residence time	5,7	years
Inflow	-	m³/y
Outflow	-	m³/y
Trophic state of the lake	meso-eutrophic	

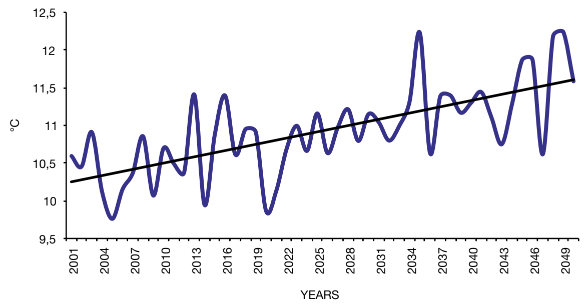


Climate driven scenarios 2001 - 2050

Precipitation



Temperature

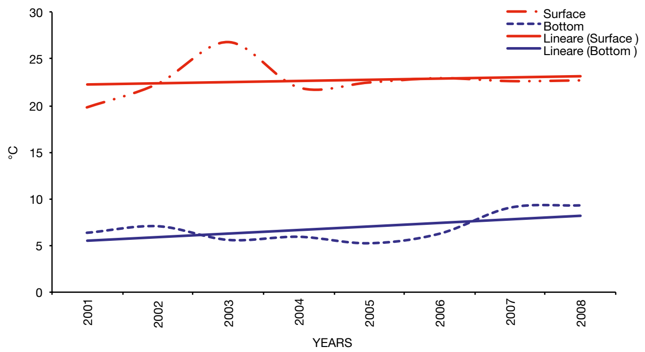


	2020	2030	2040	2050
Precipitation scenarios (mm)	+ 77,6	- 34,2	- 85,2	- 85
Air temperature scenarios (°C)	+ 0,38	+ 0,63	+ 1,04	+ 1,35

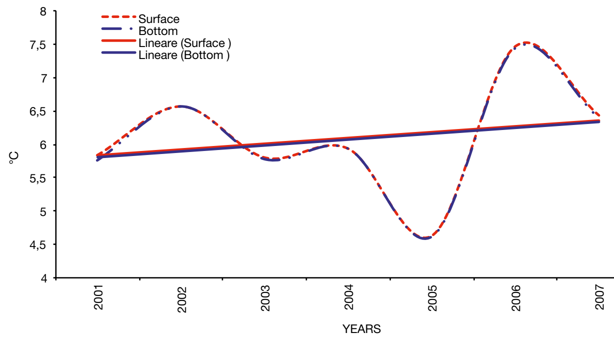
Past trend

Water temperature

Summer (JJA)



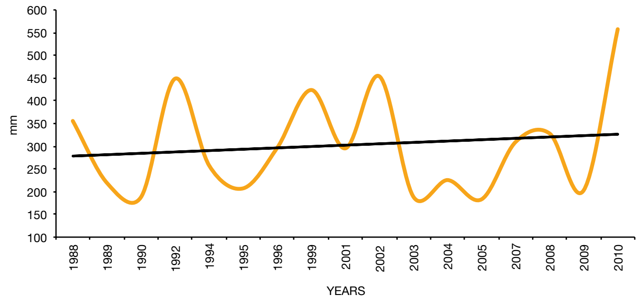
Winter (DJF)



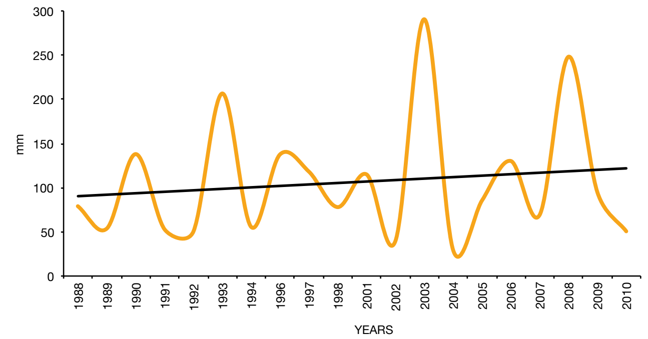
	Period: 2001 - 2007	
	Rate: °C per year	
	JJA	DJF
Surface	+ 0.12	+ 0,08
Bottom	+ 0,03	+ 0,08

Precipitation

Summer (JJA)



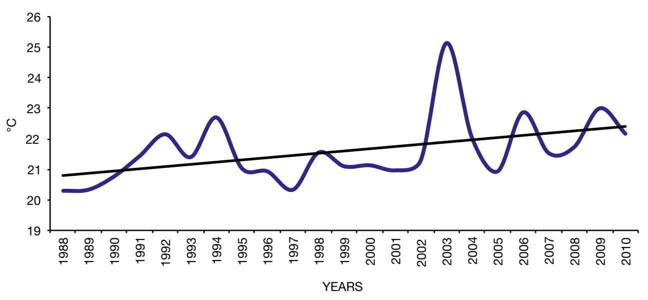
Winter (DJF)



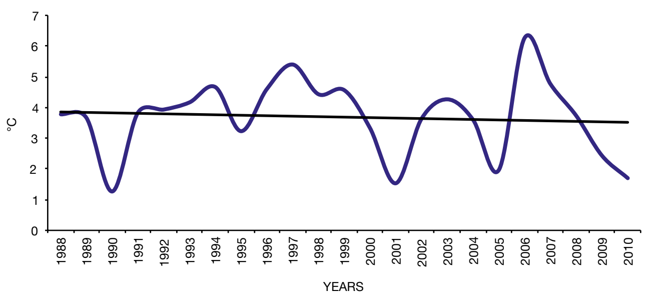
Period: 1988 - 2010	
Borgofranco d'Ivrea station	
Rate: mm per decade	
JJA	DJF
+ 30,0	+ 16,5

Air temperature

Summer (JJA)



Winter (DJF)

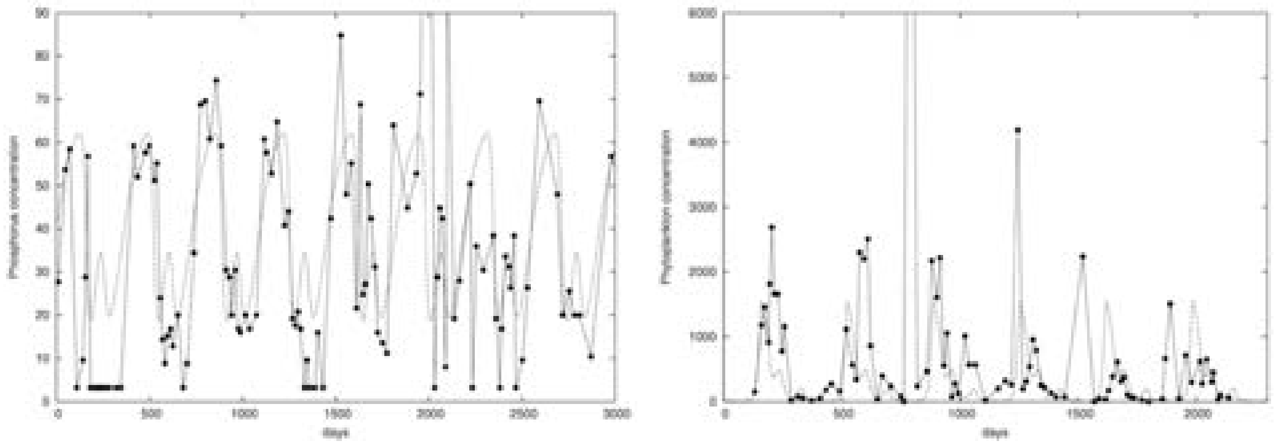


Period: 1991 - 2011

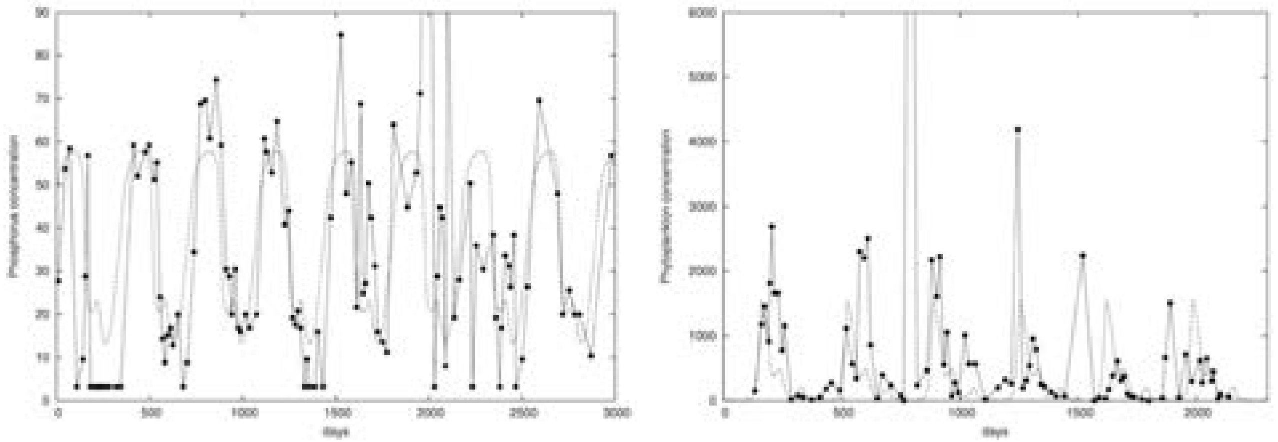
Borgofranco d'Ivrea station	
Rate: °C per decade	
JJA	DJF
+ 0,73	- 0,15

Ecological model

Homogeneous model



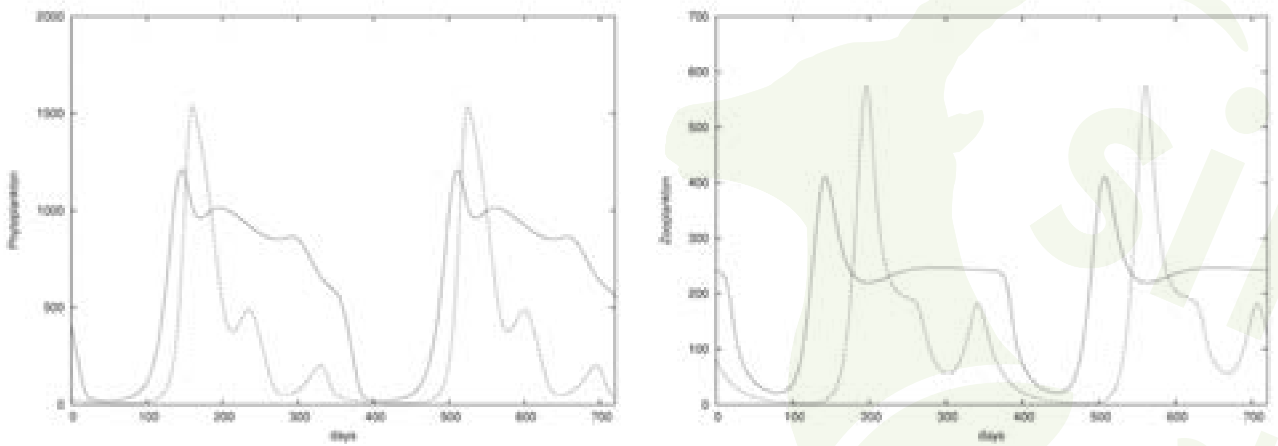
Two layer model



Total phosphorus concentration in μg-P/L from measurements at a depth of 10 meters (solid points and connecting line) and from the homogeneous model (upper panel, dashed line) and from the two-layer model (lower panel, dashed line).

Measured *chlorophycea* concentrations (solid points and connecting line) and phytoplankton concentration produced by the homogeneous model (upper panel, dashed line) and by the two-layer model (lower panel, dashed line). Concentrations are in μg-C/L assuming a carbon-to-biomass ratio R=0.2. The concentration was derived from the number concentration assuming an equivalent cell radius of 10 μm.

Effects of temperature and environmental changes



Left panel: comparison between the two-layer model phytoplankton concentration in the upper layer for faster winter turbulent exchange between the two layers, μ_0=0.2 day^{-1}, and warmer summer and winter conditions (+ 3 °C) (solid line) and current conditions (dashed line). Right panel: the same for zooplankton concentration. Concentrations are in μg-C/L.
Warmer conditions and more intense winter turbulent exchange lead to a very slight anticipation of the bloom, with a smaller maximum concentration but with a significantly longer period of high phytoplankton concentrations.

Lake Viverone

The lake

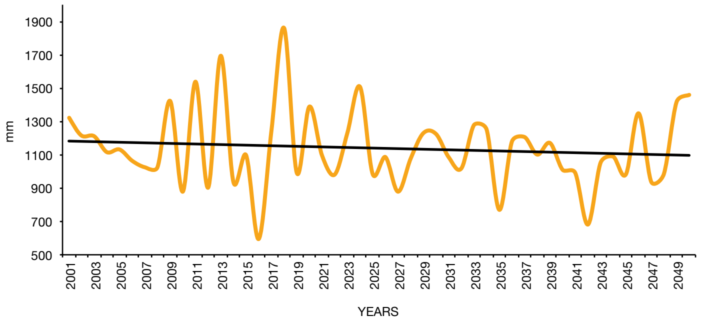
The Lake Viverone (or d'Azeglio) is a lake of glacial origin, situated between the provinces of Turin and Vercelli, Piedmont region (Italy), south east of the town of Ivrea. It is third largest lake in the Piedmont Region.

Identity Card

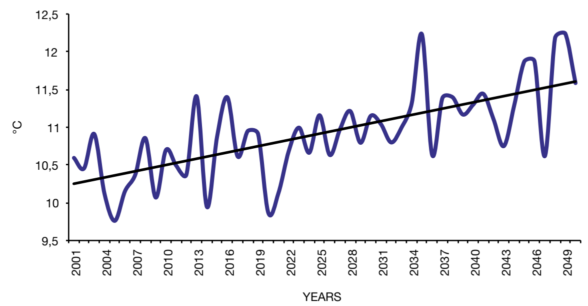
Catchment area	49,3	km²
Lake area	5,3	km²
Maximal depth	49	m
Average depth	27	m
Volume	149	m³ x 10^6
Average altitude	449	m a.s.l.
Residence time	3,6	years
Inflow	-	m³/y
Outflow	-	m³/y
Trophic state of the lake	Eutrophic	

Climate driven scenarios 2001 - 2050

Precipitation



Temperature

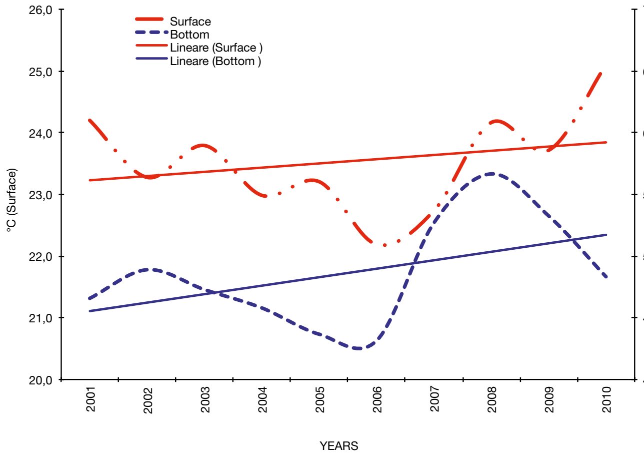


	2020	2030	2040	2050
Precipitation scenarios (mm)	+ 77,6	- 34,2	- 85,2	- 85
Air temperature scenarios (°C)	+ 0,38	+ 0,63	+ 1,04	+ 1,35

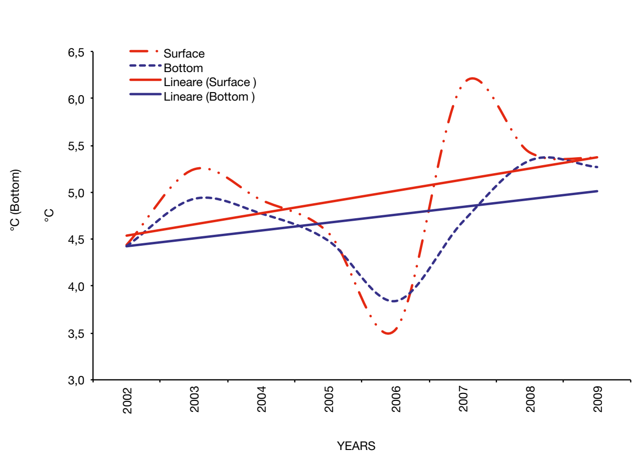
Past trend

Water temperature

Summer (JJA)



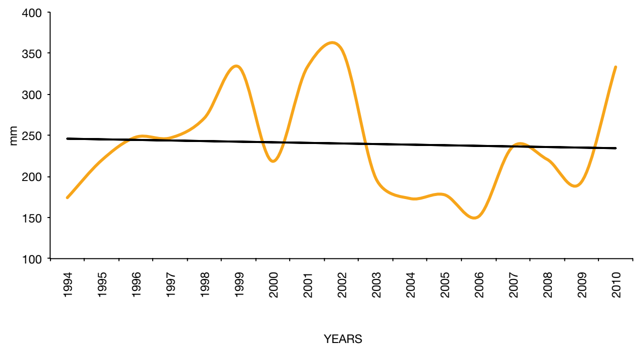
Winter (DJF)



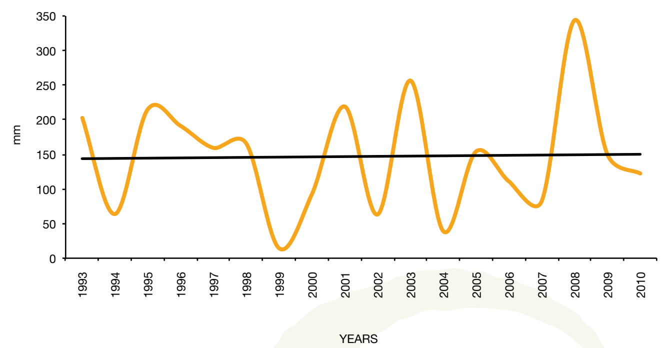
	Period: 2001 - 2007	
	Rate: °C per year	
	JJA	DJF
Surface	+ 0.67	+ 0,68
Bottom	+ 0,11	+ 0,08

Precipitation

Summer (JJA)



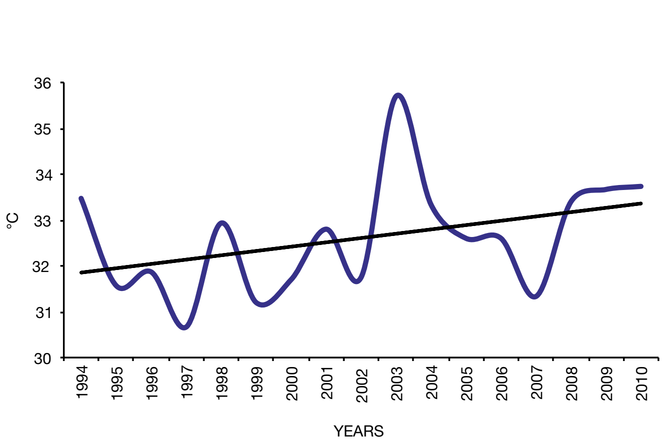
Winter (DJF)



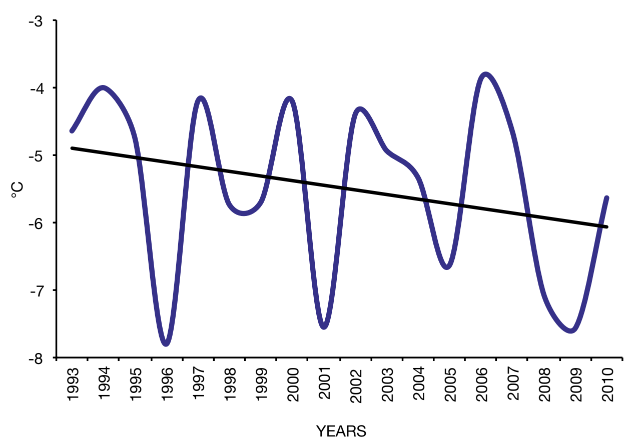
Period: 1988 - 2010	
Piverone station	
Rate: mm per decade	
JJA	DJF
- 7,25	+ 3,74

Air temperature

Summer (JJA)



Winter (DJF)



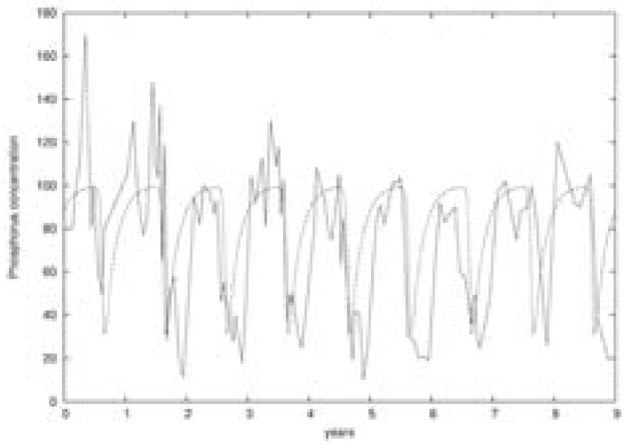
Period: 1991 - 2011

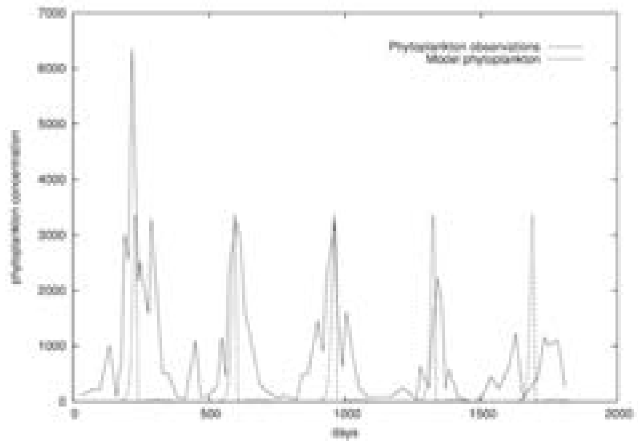
Piverone station

Rate: °C per decade	
JJA	DJF
+ 0,66	- 0,51

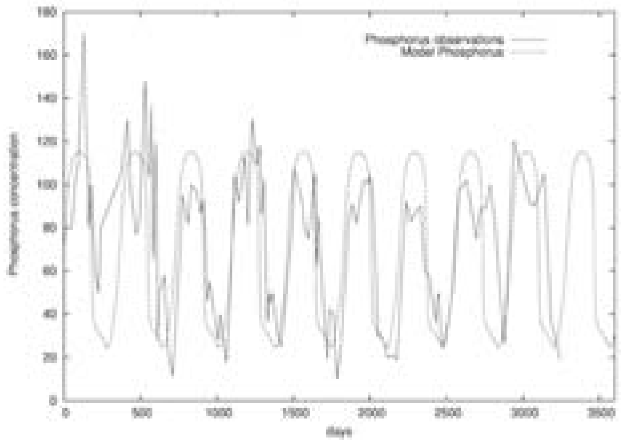
Ecological model

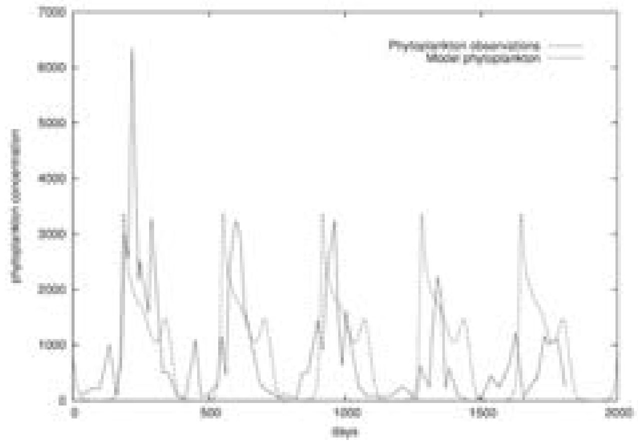
Homogeneous model





Two layer model

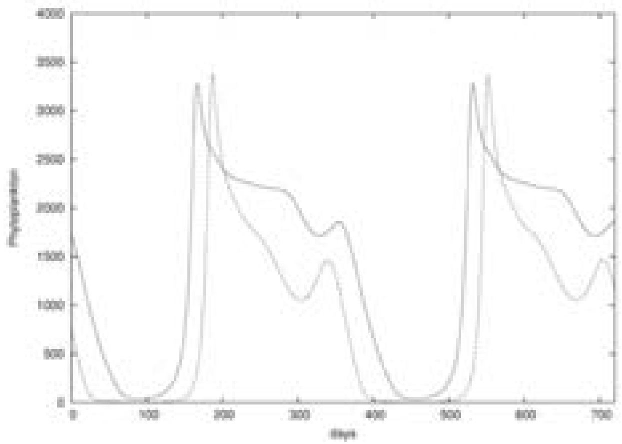


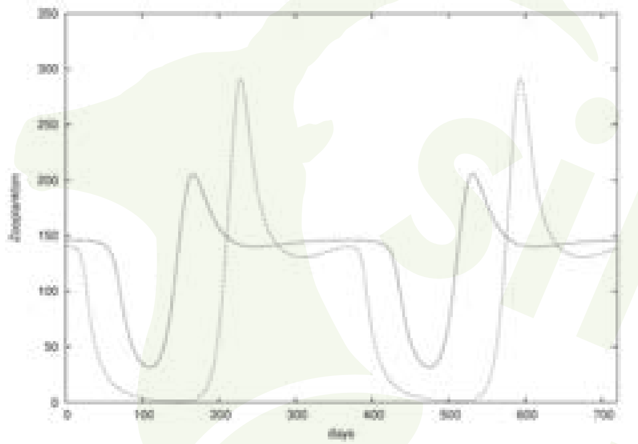


Total Phosphorus concentration in µg-P/L from measurements at a depth of 10 meters in Lake Viverone (solid line) and from the homogeneous model (dashed line, upper panel) and from the two layer model (dashed line, lower panel).

Comparison between measured *chlorophycea* concentrations (solid line), assuming cells with approximate equivalent radius of 15 µm, and the phytoplankton concentration produced by the homogeneous model (dashed line, upper panel) and by the two-layer model (dasched line, lower panel). Concentrations are in µg-C/L assuming a carbon-to-biomass ratio R=0.2.

Effects of temperature and environmental changes



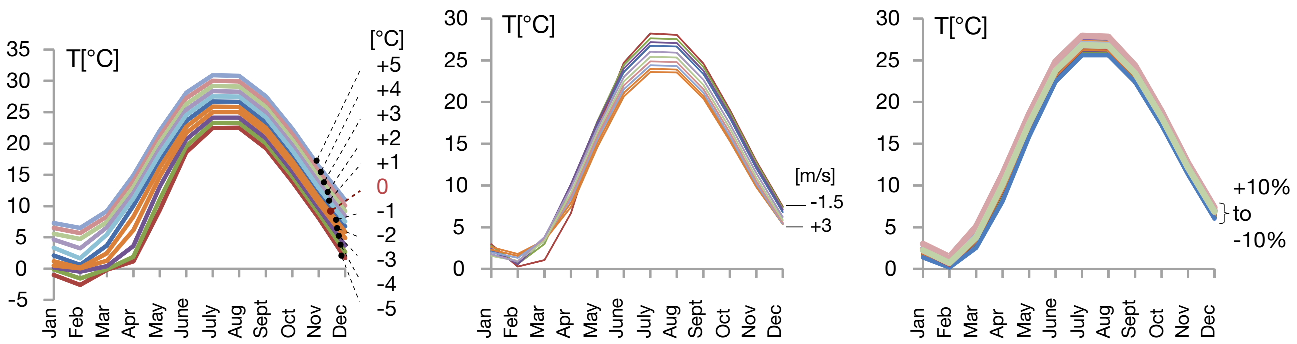


Comparison between the two-layer model dynamics for warmer conditions (solid lines) and model dynamics for current conditions (dashed lines). Left panel: phytoplankton concentrations in the upper layer; right panel: zooplankton concentration. All concentrations are expressed in µg-C/L.
Warmer conditions lead to an anticipation of the phytoplankton and of the zooplankton blooms, and a net increase of the phytoplankton biomass. Interestingly, a similar result is obtained also when increasing only the winter temperature and, to slightly lesser extent, only the summer temperature.

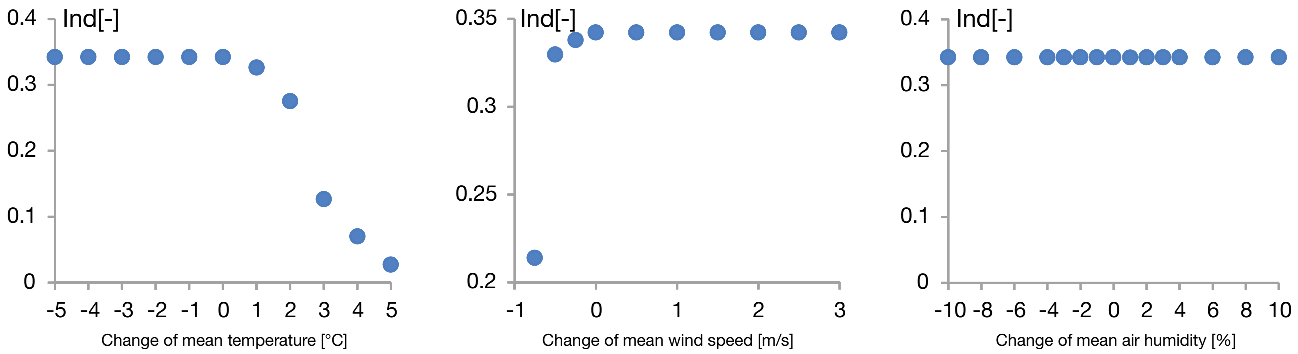
Thermodynamic model

Temperatur scenarios			Wind speed scenarios			Air humidity scenarios			
Changes of the mean air temperature in [°C]:			Changes of the mean wind speed in [m/s]:			Changes of the mean air humidity in % of rF:			
0	4	- 3	- 0.75	0.5	2.5	- 10	- 3	1	6
1	5	- 4	- 0.5	1	3	- 8	- 2	2	8
2	- 1	- 5	- 0.25	1.5	3.5	- 6	- 1	3	10
3	- 2		0	2		- 4	0	4	

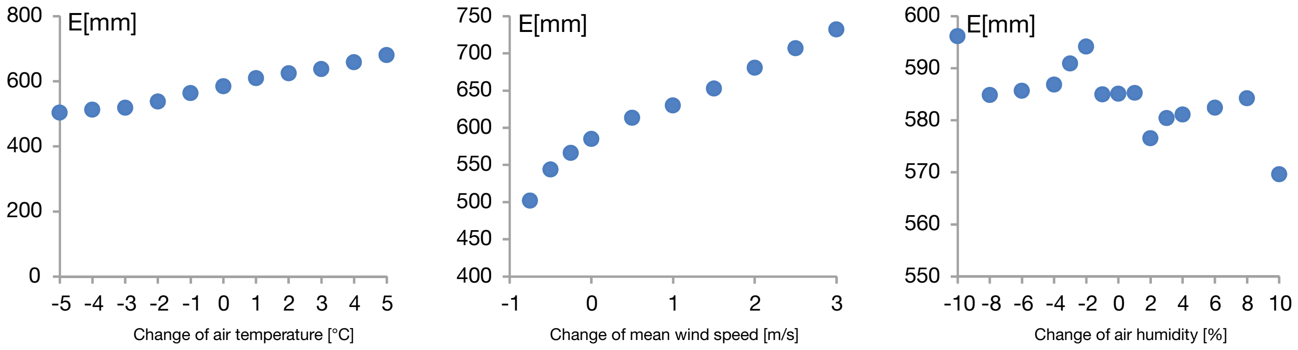
Surface water temperature



Mean mixing index(1)



Evaporation



If the mean air temperature increases the surface water increases approximately with the same amount. Increasing temperature leads to a decline of circulation intensity. Lower air temperatures have no effect onto the mixing. But a decline in mean wind speed results in a less mixing intensity.The higher the wind speed the higher is the amount of evaporation. A Change in the mean air humidity has fewer effects to evaporation from the lake's surface.

(1) This mixing index describes the vertical circulation and mixing intensity in winter/spring. The higher the index, the more intensive is the mixing. 0 means no exchange between surface and bottom water layers. Maximum at Lake Viverone: 0.34.

Lake Constance

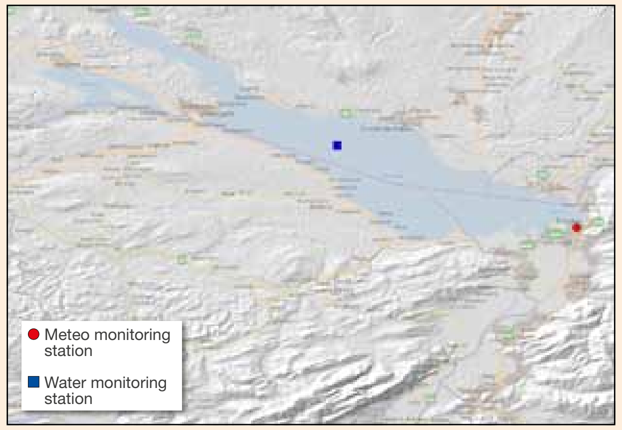
The lake

Lake Constance is a typical glacier formed perialpine oligotrophic lake. It consists of two separate basins. The outflow of the large and deep Upper Lake drains at Konstanz into the smaller and more shallow Lower Lake. Most of the hydrological catchment area of

Lake Constance is situated in the Alpine region, resulting in high water levels in summer (due to snow melting) and low water levels in winter. Lake Constance provides more than 4 million people with drinking water and is most attractive for tourism.

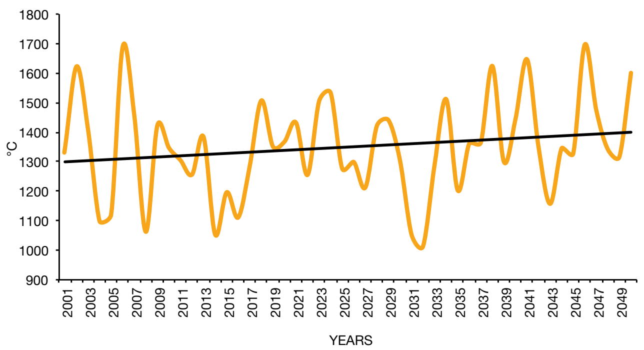
Identity Card

Catchment area	11487	km²
Lake area	535	km²
Maximal depth	254	m
Average depth	90	m
Volume	48,4	m³ x 10⁶
Average altitude	395	m a.s.l.
Residence time	4,5	years
Inflow	-	m³/y
Outflow	-	m³/y
Trophic state of the lake	Oligotrophic	

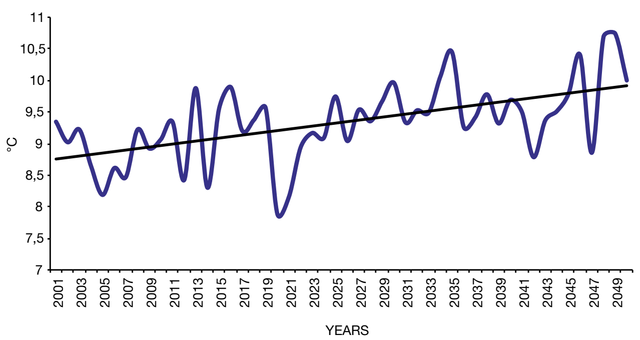


Climate driven scenarios 2001 - 2050

Precipitation



Temperature

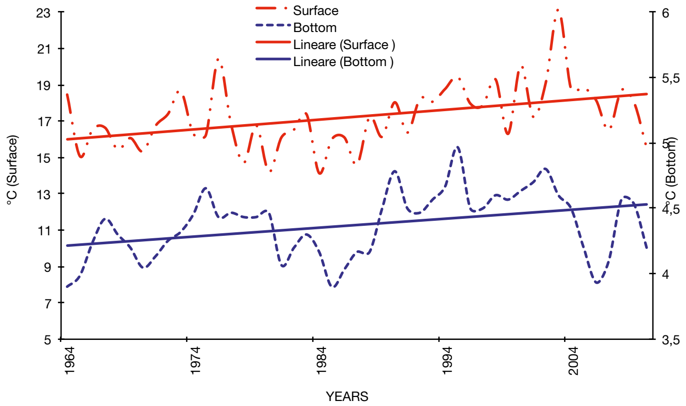


	2020	2030	2040	2050
Precipitation scenarios (mm)	- 94,4	+ 15,3	+ 13,2	+ 102
Air temperature scenarios (°C)	+ 0,28	+ 0,6	+ 0,96	+ 1,15

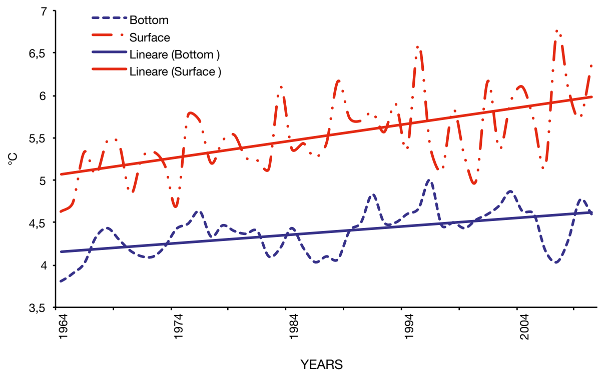
Past trend

Water temperature

Summer (JJA)



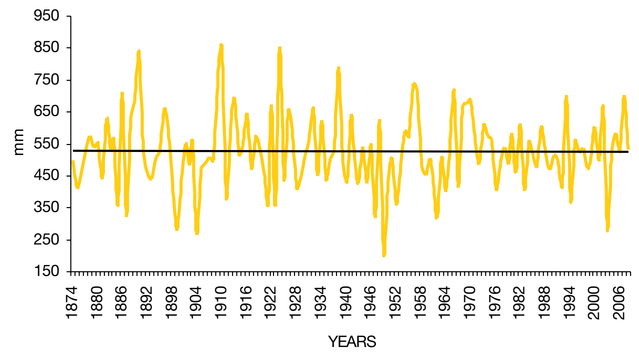
Winter (DJF)



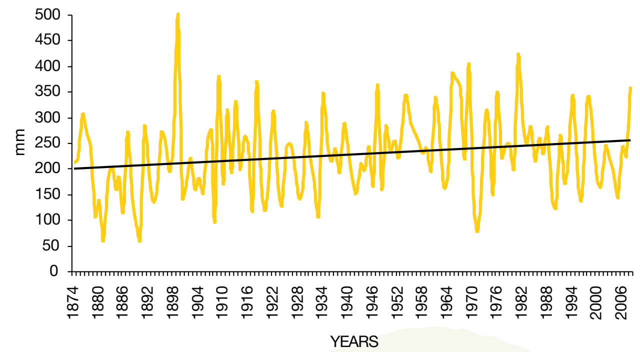
	Period: 2001 - 2007	
	Rate: °C per year	
	JJA	DJF
Surface	+ 0.54	+ 0,19
Bottom	+ 0,06	+ 0,10

Precipitation

Summer (JJA)



Winter (DJF)

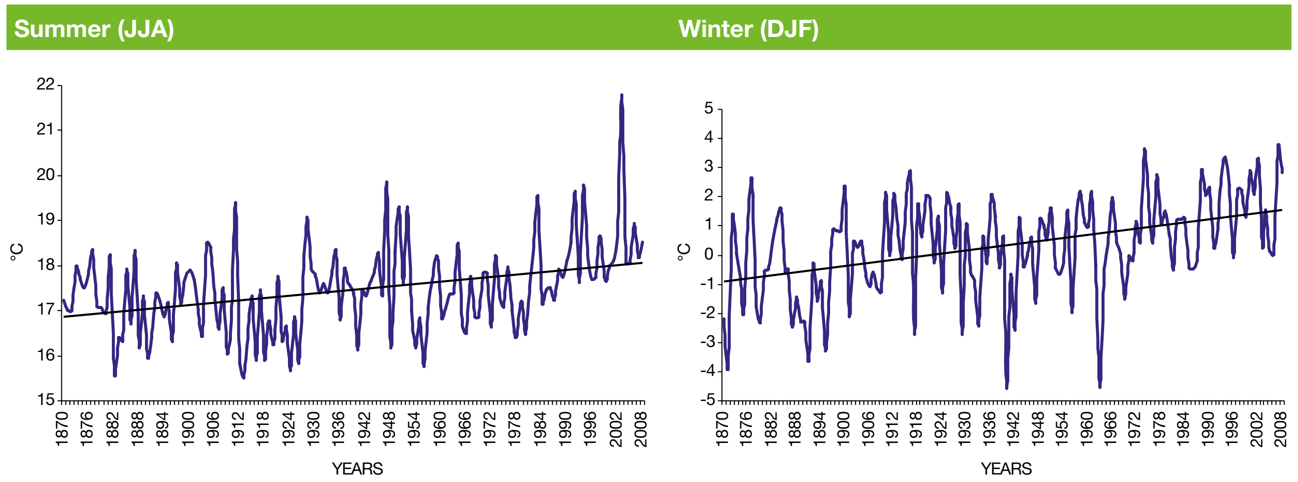


Period: 1874 - 2008

Histalp project – Bregenz station

Rate: mm per decade	
JJA	DJF
- 0,15	+ 4,20

Air temperature

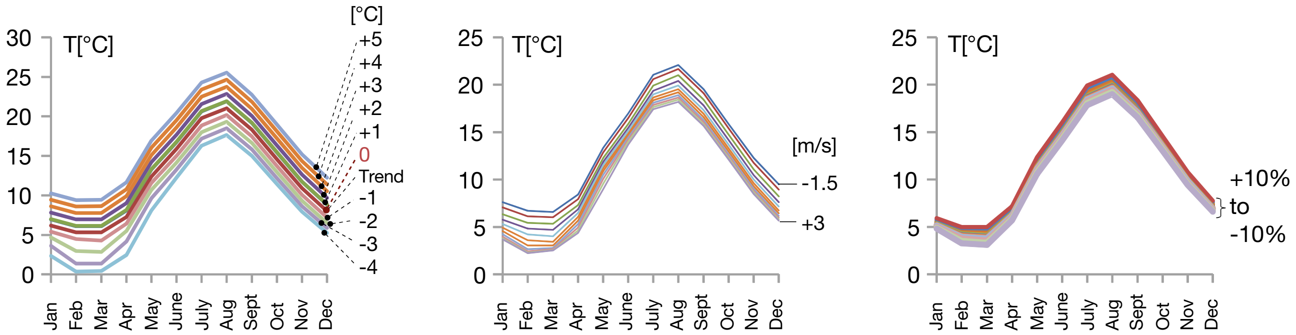


Period: 1870 - 2008	
Histalp project – Bregenz station	
Rate: °C per decade	
JJA	DJF
+ 0,08	- 0,18

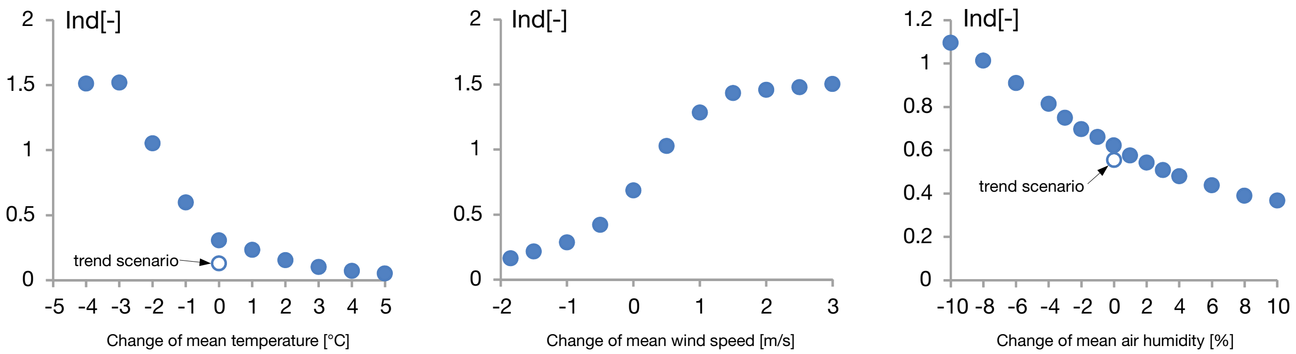
Thermodynamic model

Temperatur scenarios			Wind speed scenarios			Air humidity scenarios			
Changes of the mean air temperature in [°C]:			Changes of the mean wind speed in [m/s]:			Changes of the mean air humidity in % of rF:			
Trend(1)	3	- 2	- 1.5	0.5	2.5	- 10	- 3	1	6
0	4	- 3	- 1.0	1.0	3.0	- 8	- 2	2	8
1	5	- 4	- 0.5	1.5		- 6	- 1	3	10
2	- 1		0	2.0		- 4	0	4	Trend(2)

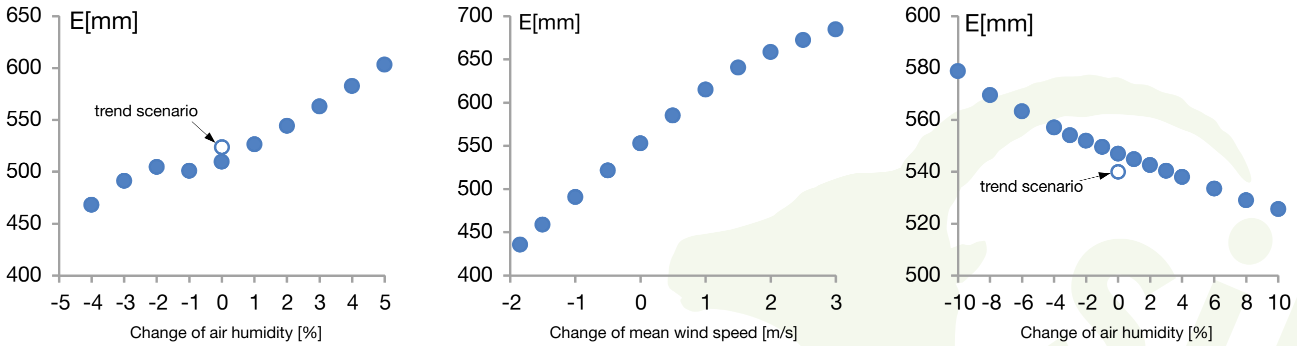
Surface water temperature



Mean mixing index(3)



Evaporation



If the mean air temperature increases the surface water increases approximately with the same amount. Increasing temperature and/or lower wind speeds lead to a decline of circulation intensity. Lower air temperatures increase the circulation intensity. The higher the wind speed and/or the dryer the air, the higher is the amount of evaporation.

(1) The Trend scenario for the air temperature is a linear continuation of the trend that was observed in the past decades.
(2) The air humidity scenario for the air humidity is a continuation of the increasing amplitude in the winter/summer changes
(3) This mixing index describes the vertical circulation and mixing intensity in winter/spring. The higher the index, the more intensive is the mixing. 0 means no exchange between surface and bottom water layers. Maximum at Lake Constance: 1.54.

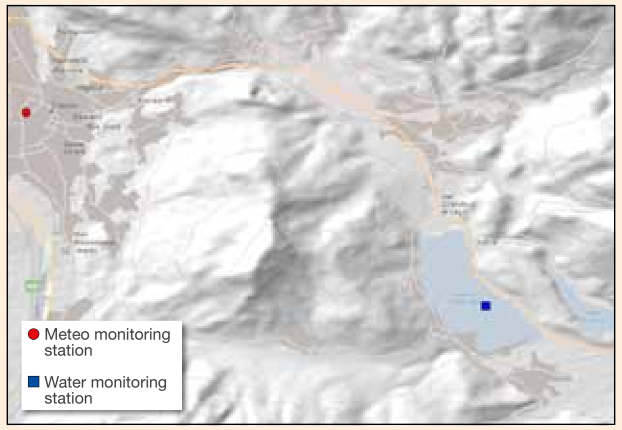
Lake Caldonazzo

The lake

Lake Caldonazzo is the largest lake entirely within the provincial boundary of Trentino. Lake Caldonazzo constitutes a tourist attraction with its various beaches (Caldonazzo, Calceranica, S.Cristoforo, etc..) and its pleasant landscape: in the background it is possible to admire the peaks of the Brenta Dolomites. Situated in Valsugana, far only 15 Km from Trento, it is almost entirely encircled by mountains; the Tenna hill separates it from the near lake Levico. Lake Caldonazzo originated from a blockage. The perennial tributary of the lake are Rio Màndola, two or three brooks which get down from the Mountain Marzola and others of less flow from the Tenna hill. A big spring is born in the north-eastern part of the lake, at an altitude of 463 meters; it can be considered as the source of the lake. There are a few artificial tributaries. One gets into the lake at San Cristoforo, another comes from the Fersina, and the Merdàr brook, deviated by man. In the eastern part of the lake there is only an emissary that gives origine to the Brenta river together with the emissary of the lake Levico.

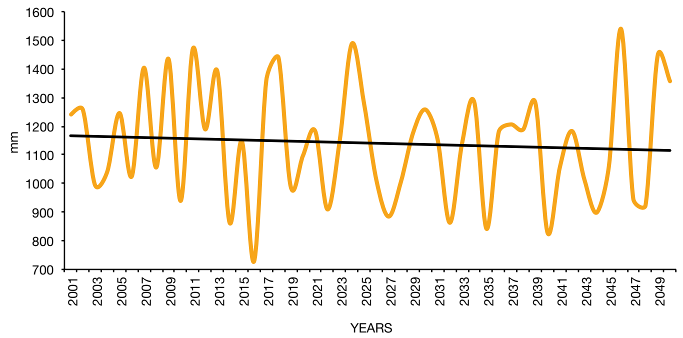
Identity Card

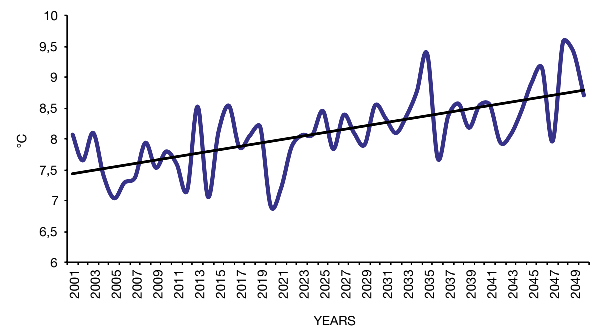
Catchment area	49,3	km²
Lake area	5,3	km²
Maximal depth	49	m
Average depth	27	m
Volume	149	$m^3 \times 10^6$
Average altitude	449	m a.s.l.
Residence time	3,6	years
Inflow	-	m³/y
Outflow	-	m³/y
Trophic state of the lake	mesotrophic	



Climate driven scenarios 2001 - 2050

Precipitation | **Temperature**



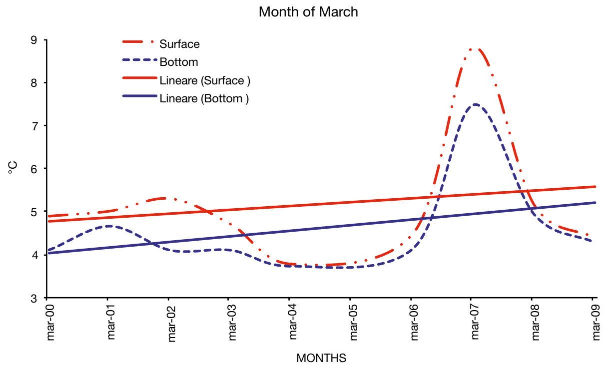


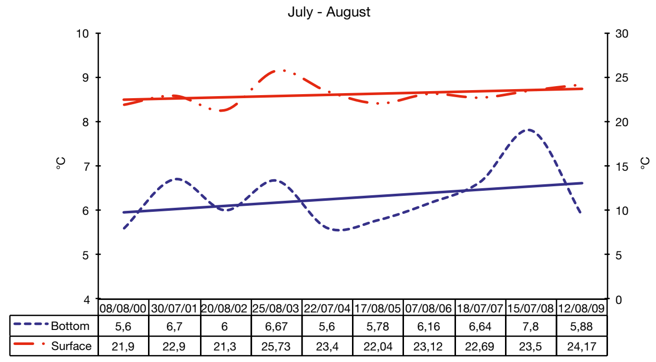
	2020	2030	2040	2050
Precipitation scenarios (mm)	- 51,6	- 66,6	- 102,4	- 52
Air temperature scenarios (°C)	+ 0,24	+ 0,63	+ 1,04	+ 1,35

Past trend

Water temperature

Month of March (mean) | **July - August**

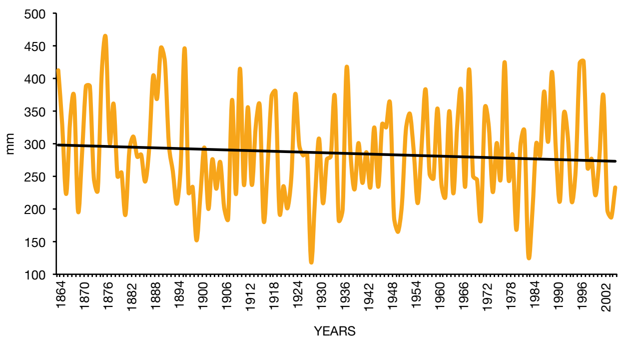


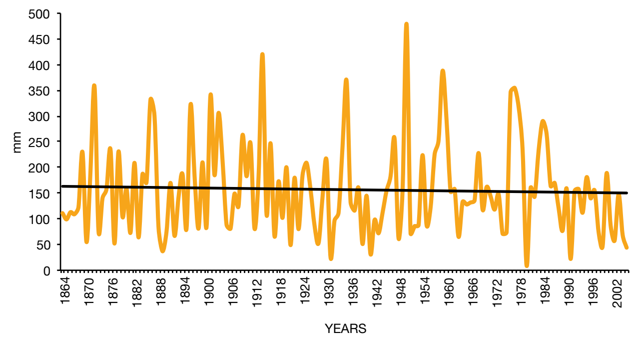


	Period: 2000 - 2009	
	Rate: °C per month	
	Month of March	July - August
Surface	+ 0,007	+ 0,13
Bottom	+ 0,01	+ 0,07

Precipitation

Summer (JJA)	Winter (DJF)





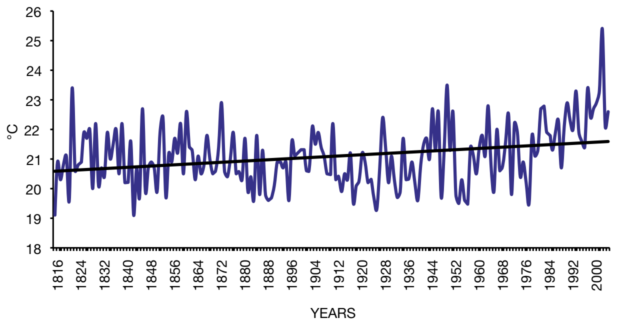
Period: 1991 - 2011

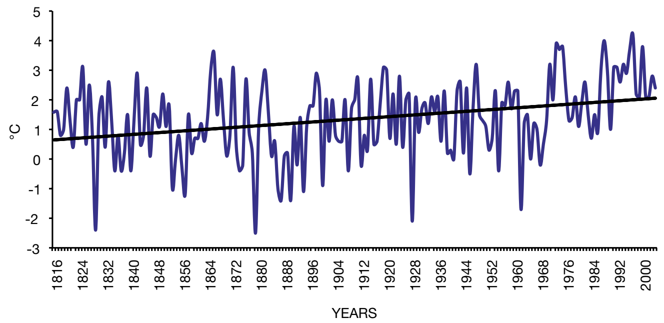
Histalp project Trento station

Rate: mm per decade	
JJA	DJF
- 1,75	- 0,92

Air temperature

Summer (JJA)	Winter (DJF)





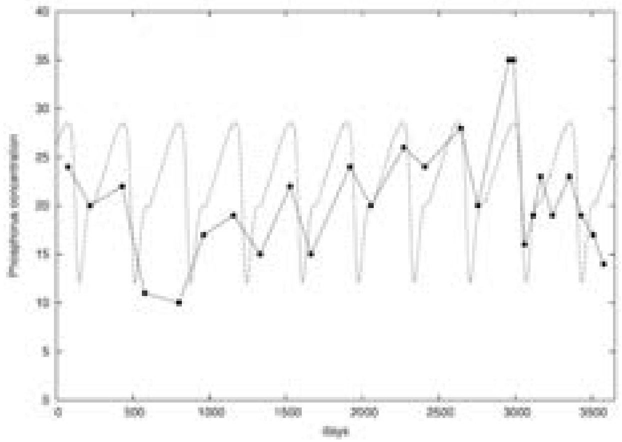
Period: 1870 - 2008

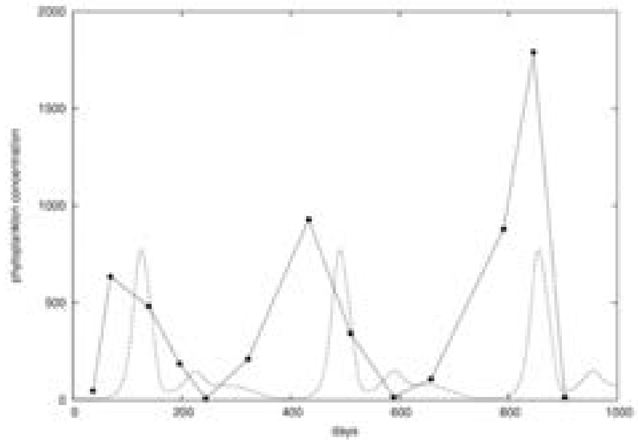
Histalp project Trento station

Rate: °C per decade	
JJA	DJF
+ 0,05	+ 0,07

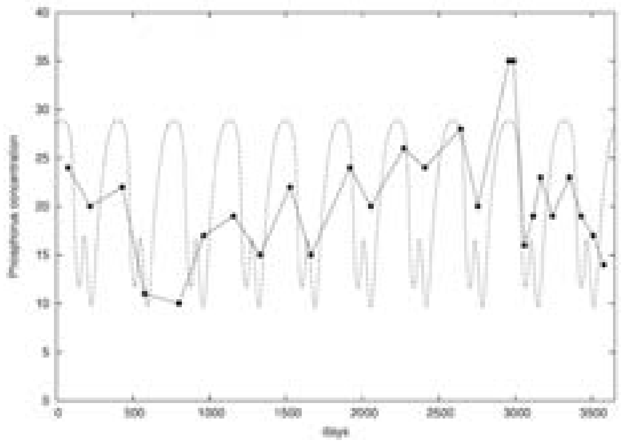
Ecological model

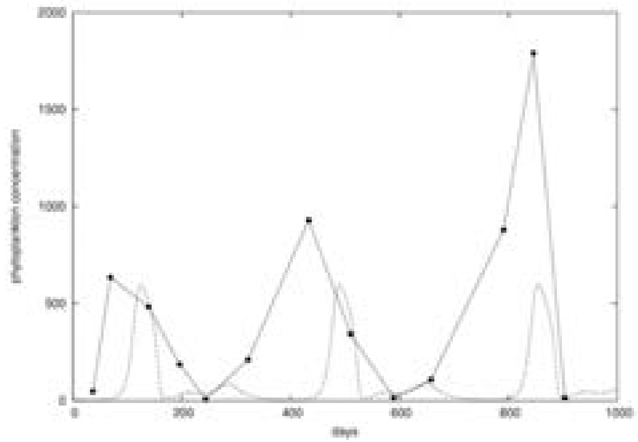
Homogeneous model





Two layer model





Total phosphorus concentration in µg-P/L from measurements at a depth of 10 meters (solid points and connecting line) and from the homogeneous model (upper panel, dashed line) and from the two-layer model (lower panel, dashed line).

Measured *chlorophycea* concentrations (solid points and connecting line) and phytoplankton concentration produced by the homogeneous model (upper panel, dashed line) and by the two-layer model (lower panel, dashed line). Concentrations are in µg-C/L assuming a carbon-to-biomass ratio R=0.2.

Effects of temperature and environmental changes

Since the model parameters are the same as those used for Lake Levico, also for Lake Caldonazzo we find the same dependence of the model dynamics on temperature and parameter changes as discussed for Lake Levico.

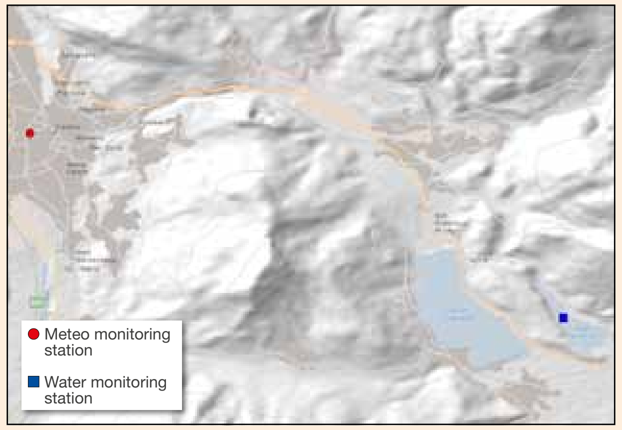
Lake Levico

The lake

Lake Levico, situated in Valsugana (20 Km. from Trento), is near the Lake Caldonazzo and separated from it by the Tenna hill.
The landscape around the lake is fascinating: it is closed in by the wooded slopes of the surrounding mountains and the majority of the banks are natural.
The lake presents a fjord-shape; its tributary are the "Roggia', which collects the water of the Rio Vignola, and the Rio Maggiore. The waters of Lake Levico feeds, together with those of Lake Caldonazzo, the river Brenta which flows into Adriatic near Venetia.
The Lake Levico forming, owing to the blockage of the alluvial cone of Rio Maggiore and Rio Vignola, dates back to 270 A.C. This date is given by the carbon-14 dating of a oak trunk found, still erect, on the lake bottom. The only town near the lake is Levico Terme, famous for its lake and the spawhich waters are rich in iron and arsenic minerals and have many therapeutic effects. It is a resort with a prestigious tourist tradition.

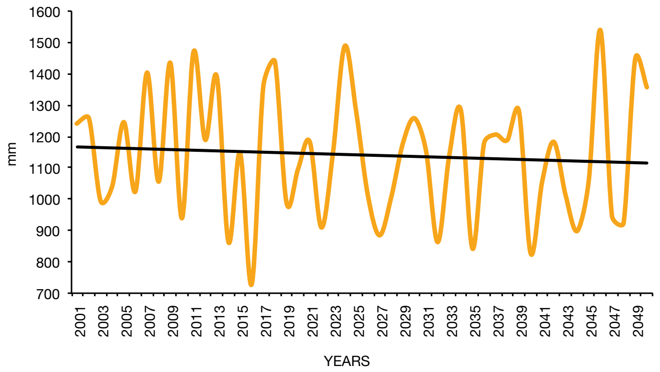
Identity Card

Catchment area	22	km²
Lake area	1,1	km²
Maximal depth	38	m
Average depth	11	m
Volume	13	m³ x 10⁶
Average altitude	440	m a.s.l.
Residence time	1,1	years
Inflow	-	m³/y
Outflow	-	m³/y
Trophic state of the lake	mesotrophic	

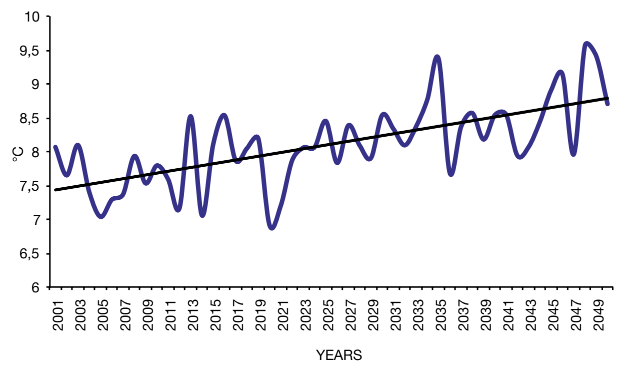


Climate driven scenarios 2001 - 2050

Precipitation



Temperature

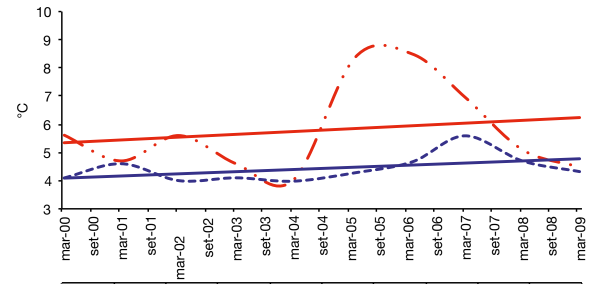


	2020	2030	2040	2050
Precipitation scenarios (mm)	- 51,6	+ 66,6	- 102,4	- 52
Air temperature scenarios (°C)	+ 0,24	+ 0,63	+ 1,04	+ 1,35

Past trend

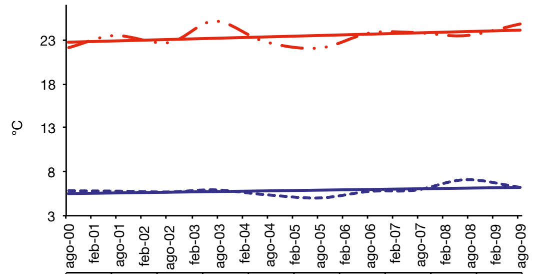
Water temperature

March - April



	15/03/00	06/03/01	12/03/02	03/03/03	08/03/04	04/04/05	18/04/06	28/03/07	10/03/08	09/03/09
Surface	5,6	4,7	5,6	4,6	4,02	8,38	8,49	6,96	5,1	4,48
Bottom	4,1	4,6	4	4,1	3,98	4,28	4,67	5,59	4,7	4,32

July - August

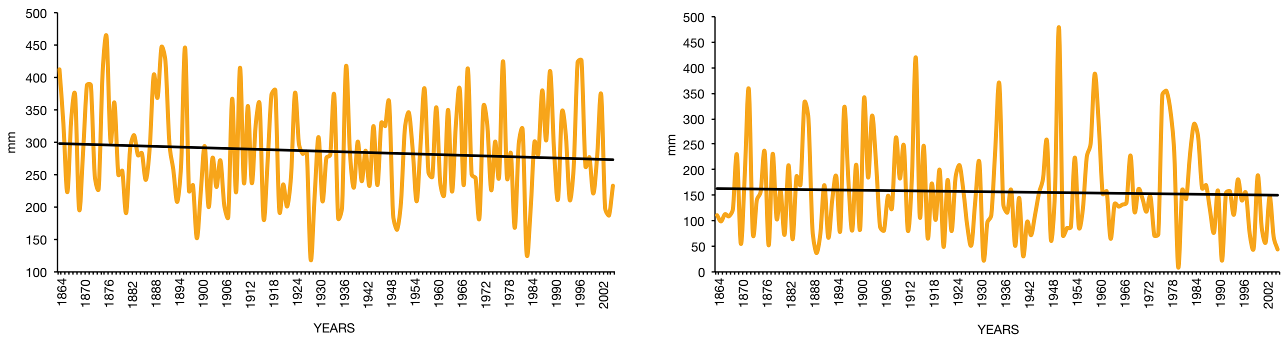


	08/08/00	30/07/01	20/08/02	28/07/03	22/07/04	17/08/05	07/08/06	18/07/07	15/07/08	12/08/09
Surface (0,12 °C)	22,1	23,5	22,7	25,149	22,8	22,08	23,79	23,84	23,5	24,82
Bottom (0,06 °C)	5,8	5,8	5,7	5,94	5,4	5,02	5,77	5,91	7,1	6,22

	Period: 2000 - 2009	
	Rate: °C per month	
	March - April	July - August
Surface	+ 0,006	+ 0,008
Bottom	+ 0,012	+ 0,01

Precipitation

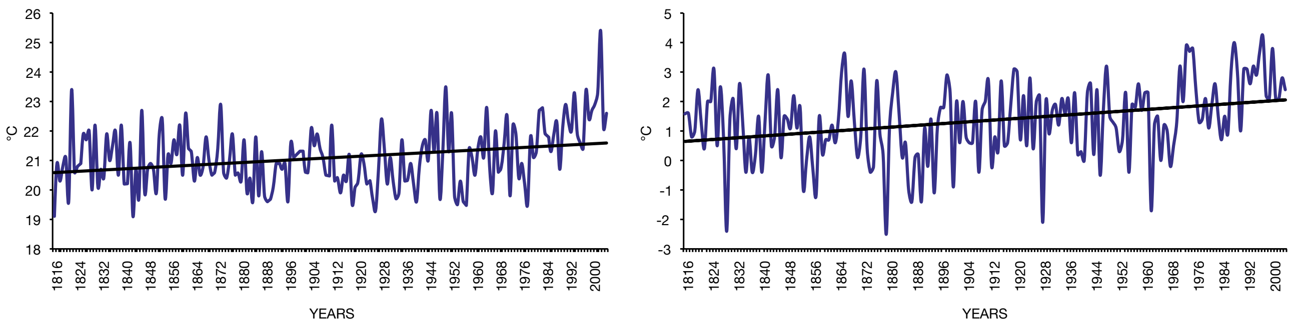
Summer (JJA) **Winter (DJF)**



Period: 1991 - 2011	
Histalp project Trento station	
Rate: mm per decade	
JJA	DJF
- 1,75	- 0,92

Air temperature

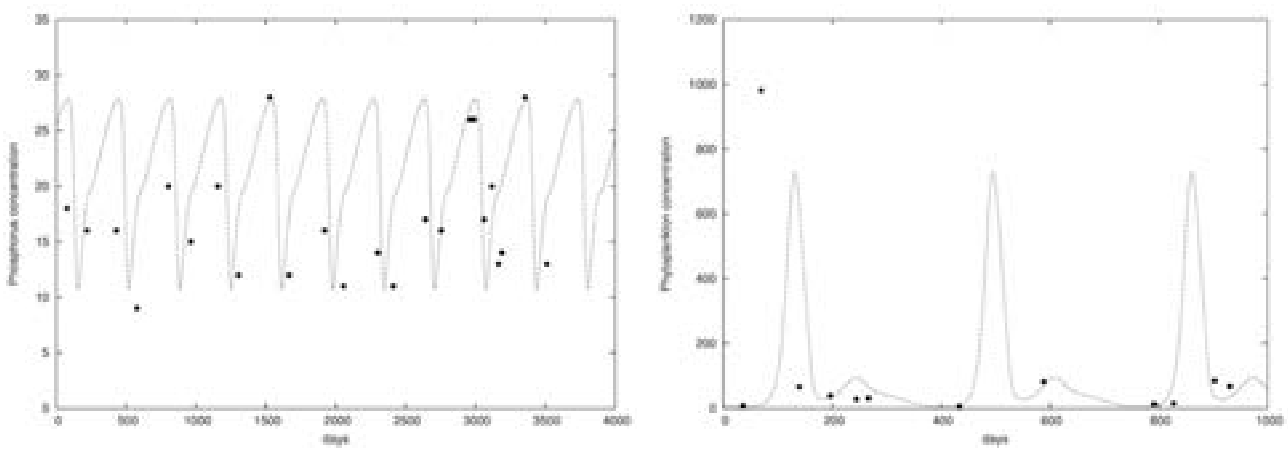
Summer (JJA) **Winter (DJF)**



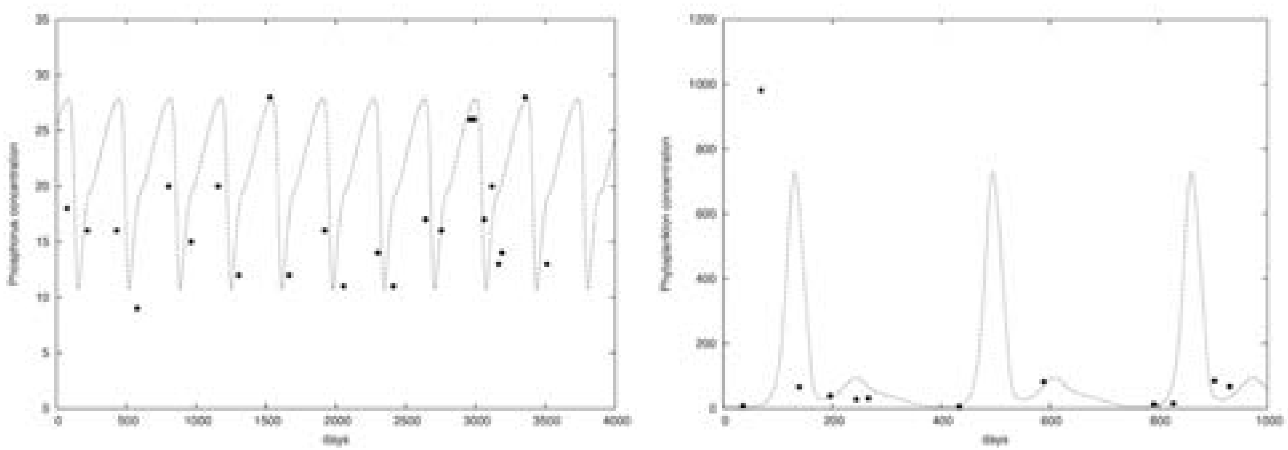
Period: 1816 - 2005	
Histalp project Trento station	
Rate: °C per decade	
JJA	DJF
+ 0,05	+ 0,07

Ecological model

Homogeneous model



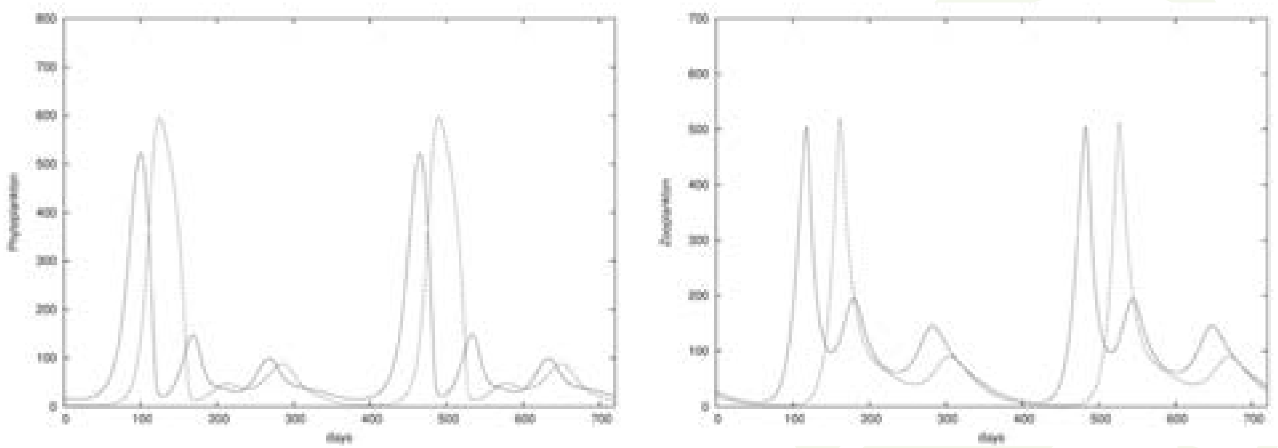
Two layer model



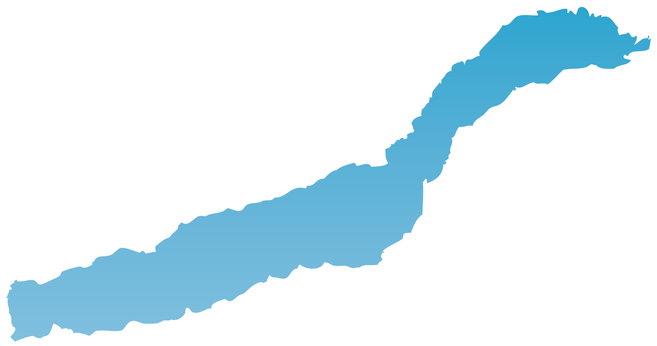
Total phosphorus concentration in µg-P/L from measurements at a depth of 10 meters (solid points and connecting line) and from the homogeneous model (upper panel, dashed line) and from the two-layer model (lower panel, dashed line).

Measured *chlorophycea* concentrations (solid points and connecting line) and phytoplankton concentration produced by the homogeneous model (upper panel, dashed line) and by the two-layer model (lower panel, dashed line). Concentrations are in µg-C/L assuming a carbon-to-biomass ratio R=0.2. The concentration was derived from the cell number concentration assuming an equivalent radius of 10 µm.

Effects of temperature and environmental changes



Left panel: comparison between the two-layer model phytoplankton concentration in the upper layer for faster winter turbulent exchange between the two layers, μ_0=0.2 day^{-1}, and warmer summer and winter conditions (+3 °C) (solid line) and current conditions (dashed line). Right panel: the same for zooplankton concentration
Warmer conditions and more intense winter turbulent exchange lead to anticipation of the phytoplankton and zooplankton blooms, with a slightly smaller maximum concentration for phytoplankton.



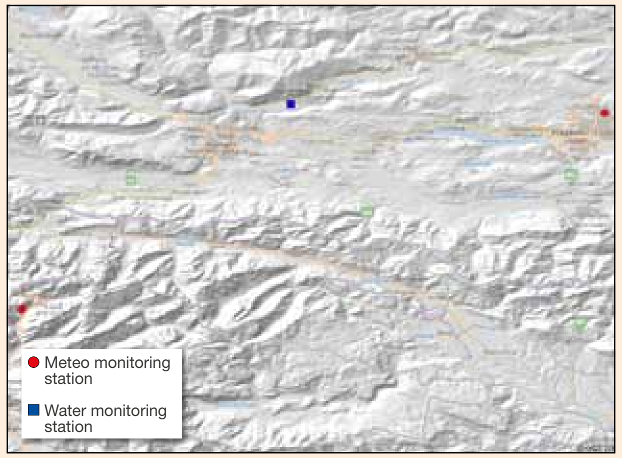
Lake Ossiacher See

The lake

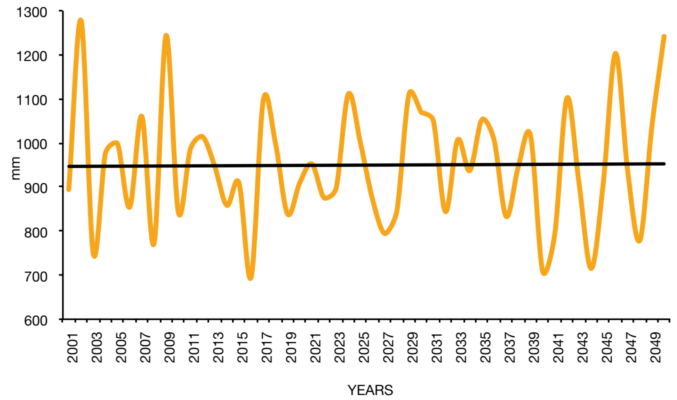
Lake Ossiacher See is the third largest Lake of the southern Austrian province Carinthia. The (holomictic: circulation of the whole water body) lake is divided by a swell into two basins. The maximum depth of the smaller eastern part (3,9 km²) is 10 m and of the larger western part (6,9 km²) is 52 m. The main tributary is the River Tiebel, that enters the lake at the east end runs through a swampy area (6 km²) – Bleistättter Moor. In the past the moor was drained for agricultural purposes. The development of tourism in the catchment area of Lake Ossiacher See showed an increase from 100 000 overnight stays a year in the 1950s to 2 Mill. over the past years. This led to a massive increase of domestic sewage lake influx and as a consequence the Lake showed eutrophication phenomena. The first available data are from 1931. Since 1970 a continous monitoring program exists. In addition the lake was a target of the Lake Restoration Project from 1974 to 1978. After great investments in collecting and deviating the sewage from the lake, a re- oligotrophication process started and today the lake is classified between oligo- and mesotrophic. During summer the temperature of the lake can reach more than 25 °C.

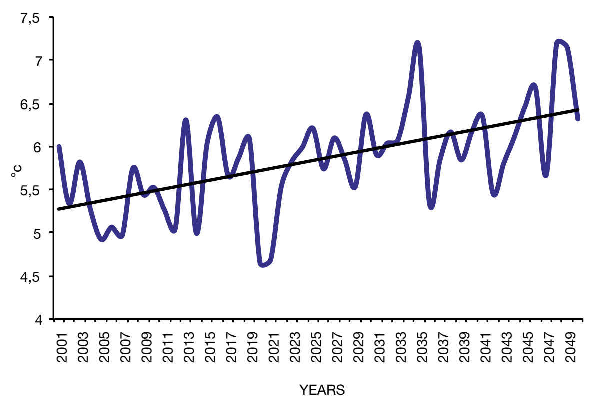
Identity Card

Catchment area	154	km²
Lake area	10,8	km²
Maximal depth	52,6	m
Average depth	19,9	m
Volume	203	m³ x 10⁶
Average altitude	501	m a.s.l.
Mean fill up time	2,2	years
Mean residence time of deep lake water	-	m³/y
Mean annual inflow 1971-2010	-	m³/y
Mean annual out flow 1971-2010		
Trophic state of the lake	weakly mesotrophic	



Climate driven scenarios 2001 - 2050

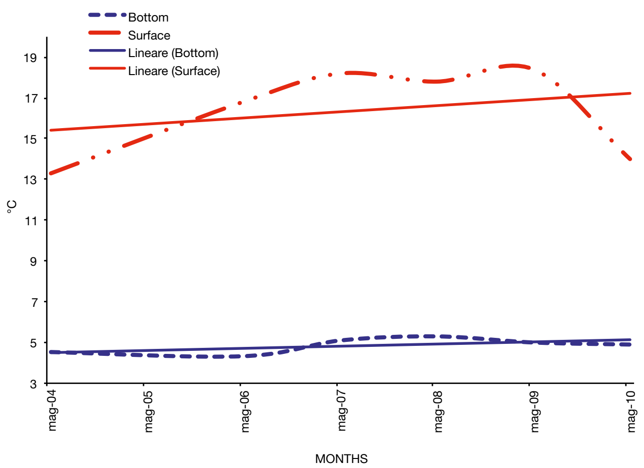


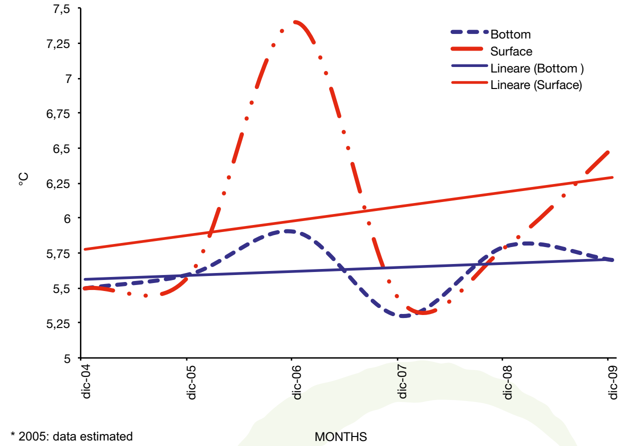


	2020	2030	2040	2050
Precipitation scenarios (mm)	- 86,4	- 20,1	- 29,6	+ 5,5
Air temperature scenarios (°C)	+ 0,46	+ 0,42	+ 0,76	+ 1,1

Past trend

Water temperature

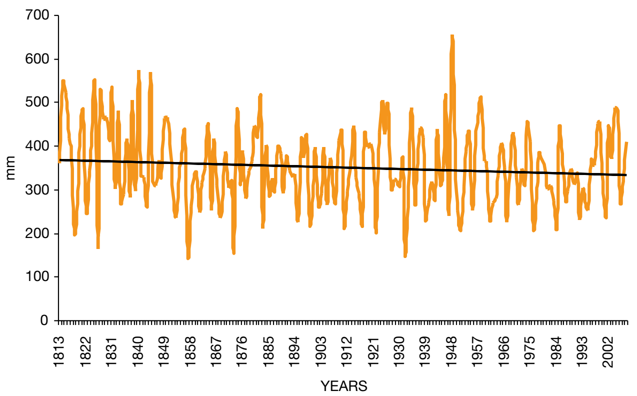


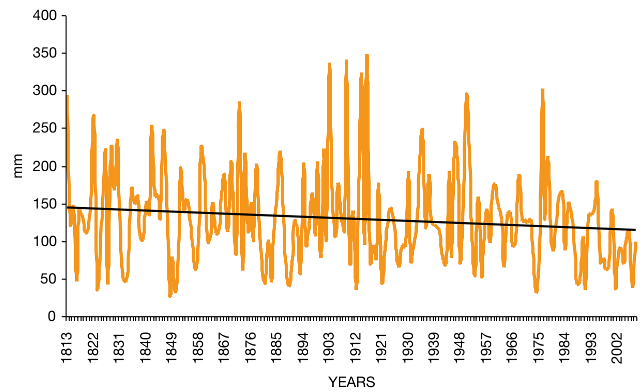


	Period: 2004 - 2009	
	Rate: °C per month	
	Month of May	Month of December
Surface	+ 0,008	+ 0,025
Bottom	+ 0,002	+ 0,008

Precipitation

Summer (JJA) | **Winter (DJF)**





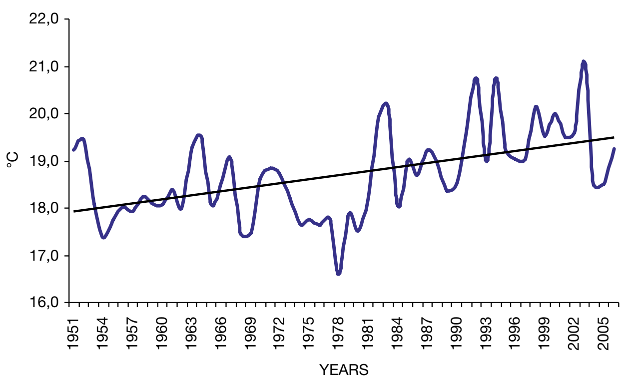
Period: 1813 - 2011

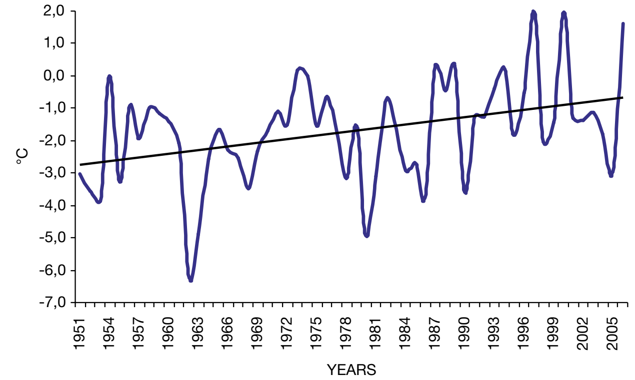
Histalp Project –– Klaghenfurt - Flugafen station

Rate: mm per decade	
JJA	DJF
- 1,8	- 1,5

Air temperature

Summer (JJA) | **Winter (DJF)**



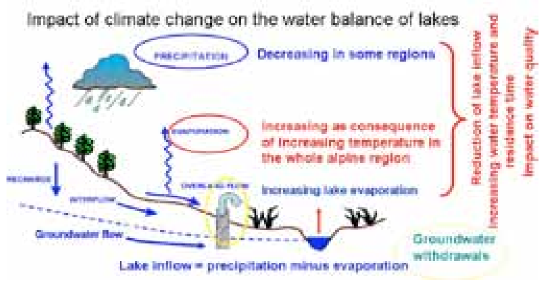


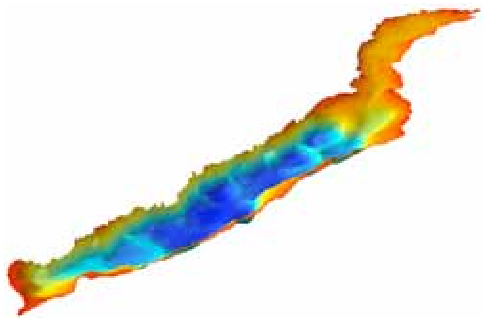
Period: 1951 – 2005

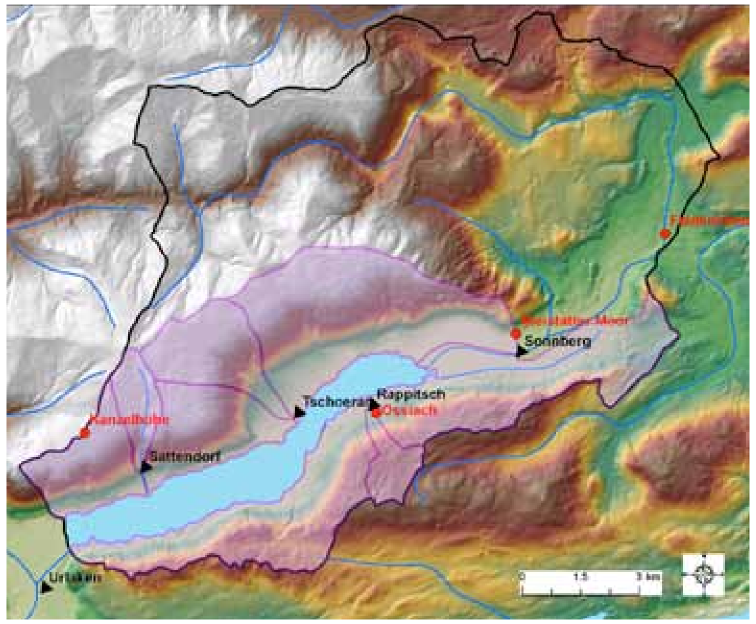
Ossiach station

Rate: °C per decade	
JJA	DJF
+ 0,28	+ 0,38

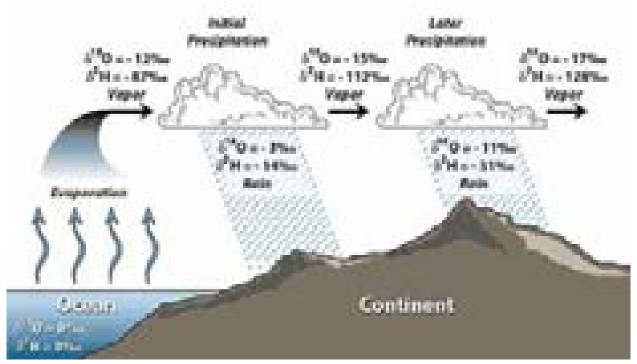
Hydrological modelling and isotope investigations



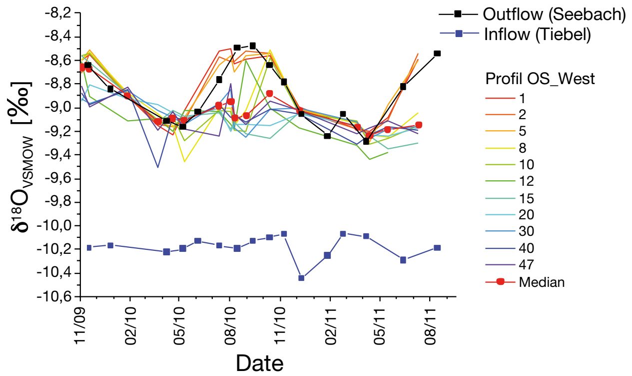




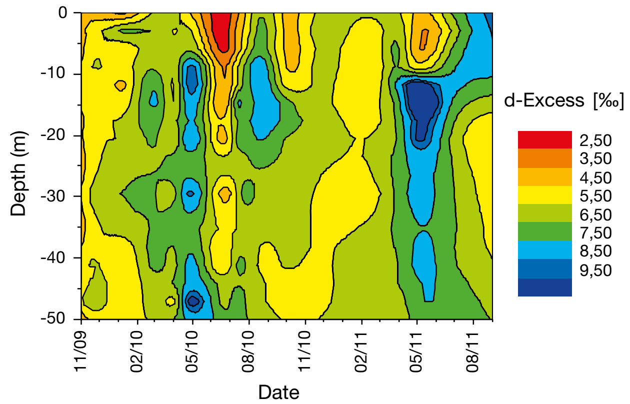
Investigation of the actual circulation and evaporation processes using environmental isotopes



Mean residence time in the deepest part: 1.5 years



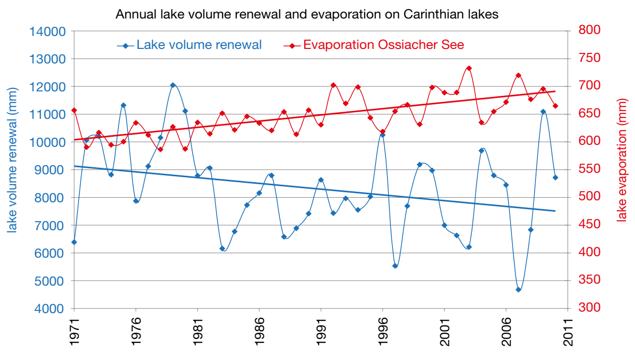
Isotpoic composition of in and outflow as tracer for water movement



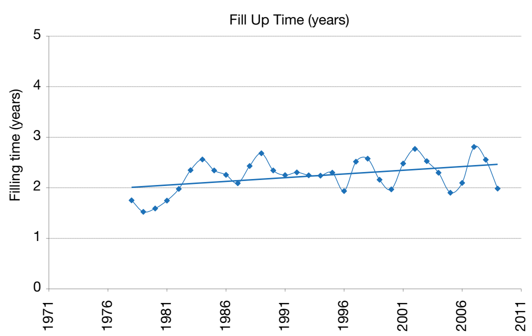
Actual circulation behaviour (Deuterium excess)

Past water balance changes and trends

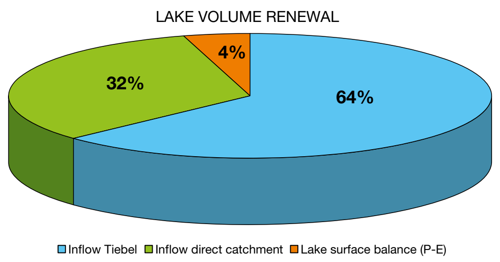
Trends of lake water renewal and evaporation

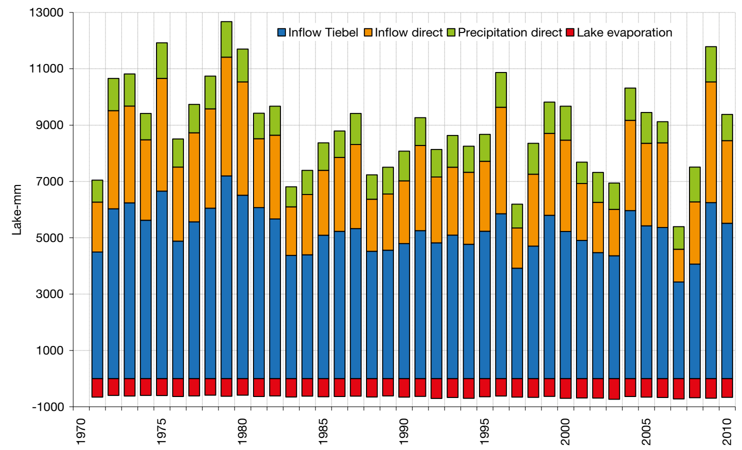


Trend of the filling time

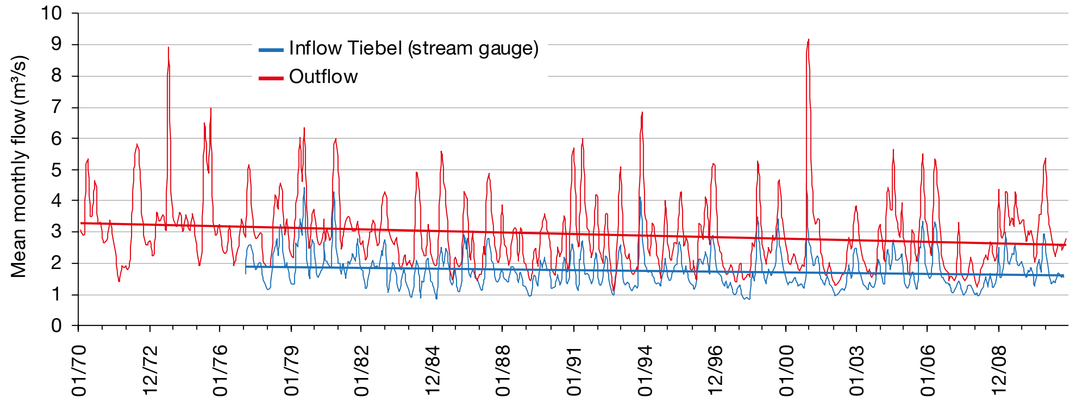


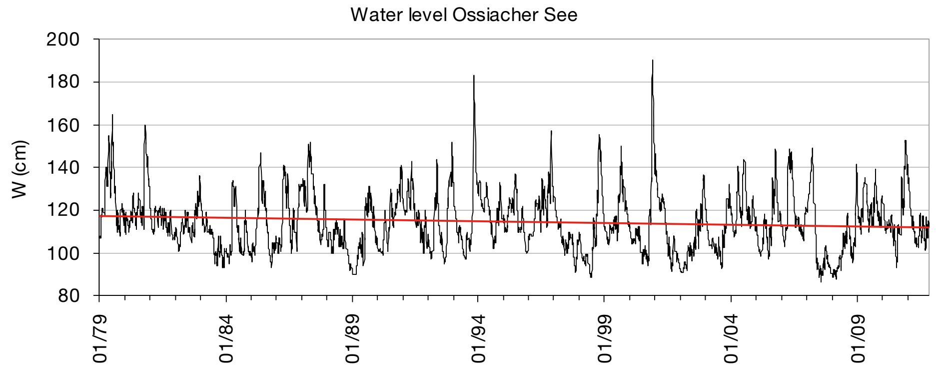
Annual lake water components





Trends of inflow, outflow and water level





What could happen in the future?

Due to the not definable catchment area of the main inflow a simulation of scenarios was not possible.	Similar changes as at Wörthersee can be expected

The lake is characterized by a relatively fast circulation, the catchment is more dominant for the water balance as the lake itself.

A semi-distributed conceptual rainfall-runoff model has been used with the aim to simulate past changes and develop scenarios of the lake volume renewal depending on land use and climatic conditions and of the lake evaporation. The graphs show significant changes in the water balance (decrease of the lake volume renewal and water level, increase of the lake evaporation) and consequently an increasing fill up time.

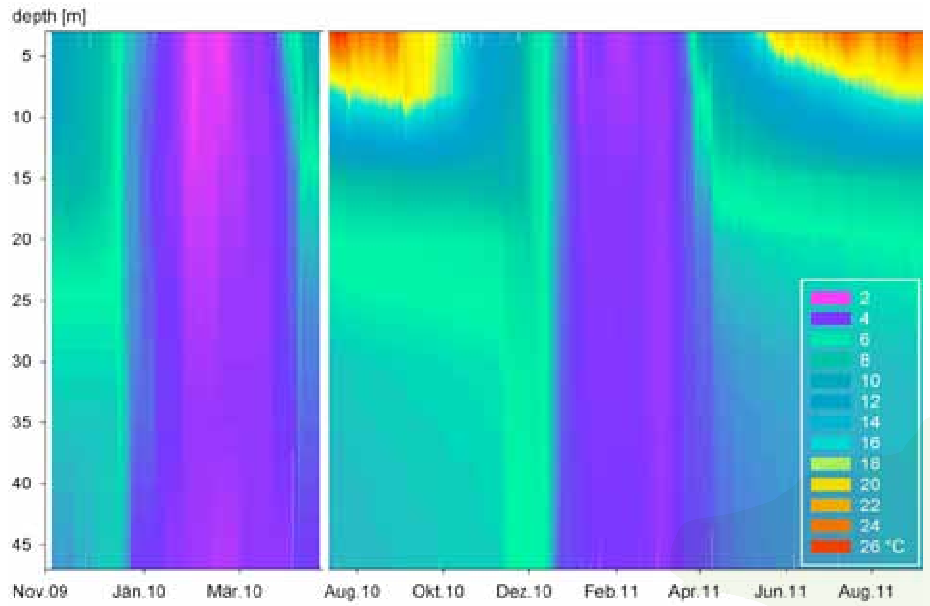
The past development shows, that the lake water balance is very sensitive to changes in the air temperature and precipitation. Therefore similar changes as simulated for the lake Wörthersee can be expected with percentual reductions of the lake water renewal of approx. 12 to 23%. Furthermore land use changes in the catchment of the lake can have important additional impacts.

Change in water temperature and water circulation

Medium water temperature at surface

	January	April	August	November
Ossiacher See: 1990 - 2010	+ 0,4 °C	+ 1,6 °C	– 0,8 °C	+ 0,4 °C

Development of temperature stratification



There is a clear increase in surface water temperature in January , April and November due to global warming - later cooling in winter and earlier warming in spring. In summer there is a decrease in water temperature due to higher evaporation (cooling effect on water surface).

Lake Ossiacher See is a holomictic (totally mixing) lake. The water body is circulating down to the bottom of the lake. The figure shows that in mixing period the cold water from the surface is transported down to the bottom of the lake so the temperature is lower than 4 °C.

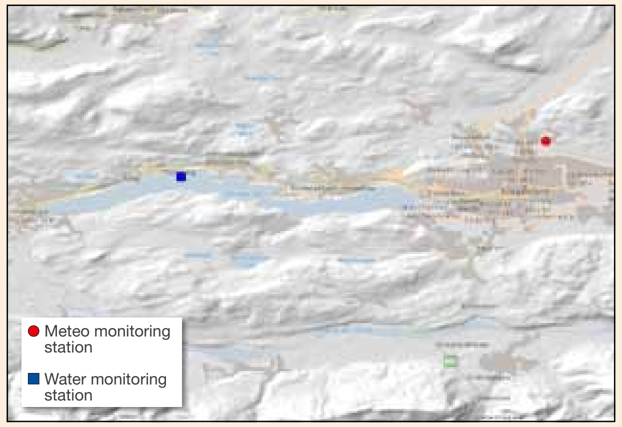
Lake Wörthersee

The lake

Lake is the largest natural and meromictic lake of the southern Austrian province Carinthia.
A meromictic lake is characterized by the lack of oxygen and the highest nutrient in the deepest water, which must be taken into account when assessing the water quality. In the late 1950s and early 1960s the increasing pressure of human activities caused the development of algal blooms, a signal for eutrophication. At this time local representatives took action, and in 1963 the construction work for a waste water system started. In 1968 the sewage plant that collects the waste water from the catchment area of Lake Wörthersee went on line. Since that time the water quality of lake Wörthersee turned better and is now considered to be between oligo- and mesotrophic. Now a clear lake with good oxygen content, rich on various biological groups (phytoplankton, zooplankton and fish) will invite visitors to have a bath during summer.

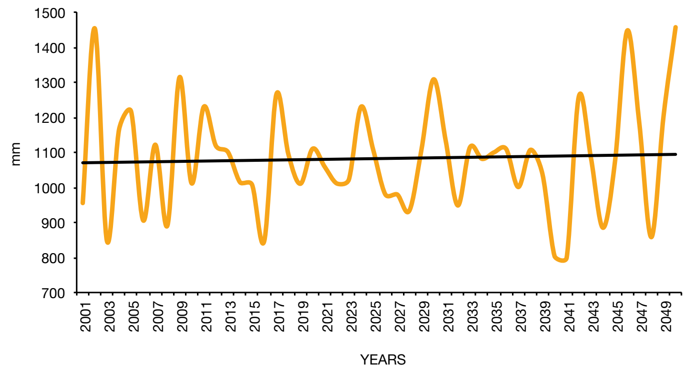
Identity Card

Catchment area	137	km²
Lake area	19,4	km²
Maximal depth	85,2	m
Average depth	41,9	m
Volume	1001	m³ x 10⁶
Average altitude	439	m a.s.l.
Mean fill up time	15,0	years
Mean residence time of deep lake water	9,5	m³/y
Mean annual inflow 1971-2010	3108	m³/y
Mean annual out flow 1971-2010	3504	
Trophic state of the lake	between oligo- and mesotrophic	

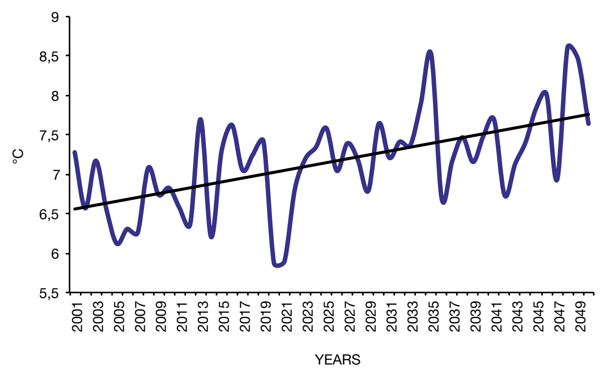


Climate driven scenarios 2001 - 2050

Precipitation



Temperature

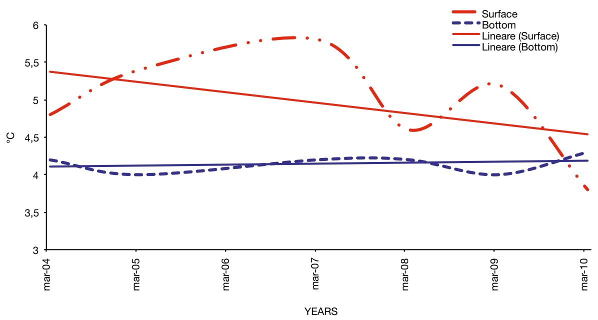


	2020	2030	2040	2050
Precipitation scenarios (mm)	- 42,6	- 21,3	- 63,6	+ 24
Air temperature scenarios (°C)	+ 0,32	+ 0,6	+ 0,92	+ 1,2

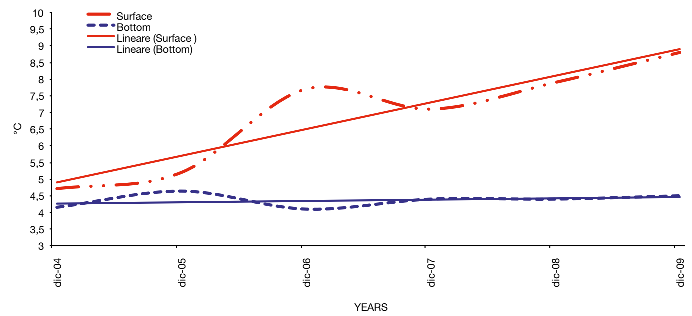
Past trend

Water temperature

Month of March



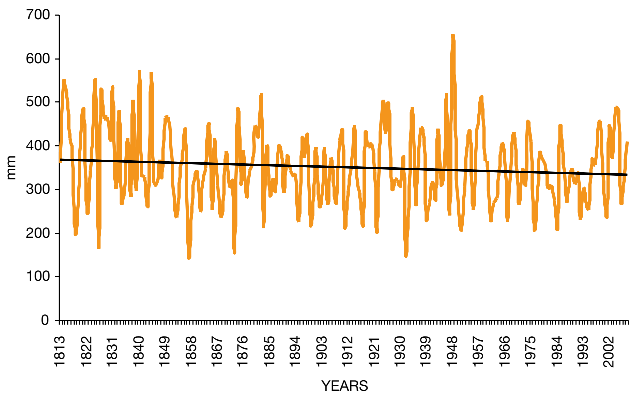
Month of December

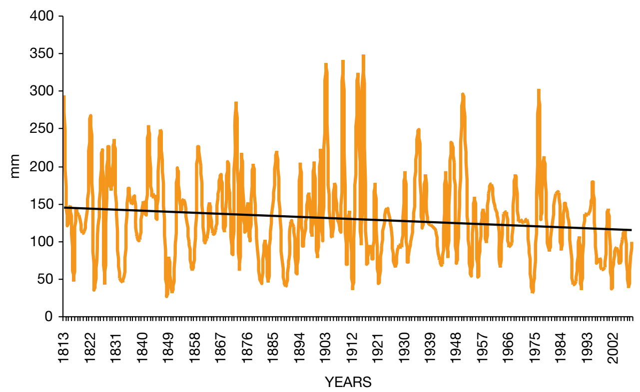


	Period: 2004 - 2009	
	Rate: °C per month	
	Month of March	Month of December
Surface	+ 0,01	+ 0,066
Bottom	+ 0,001	+ 0,003

Precipitation

Summer (JJA)	Winter (DJF)

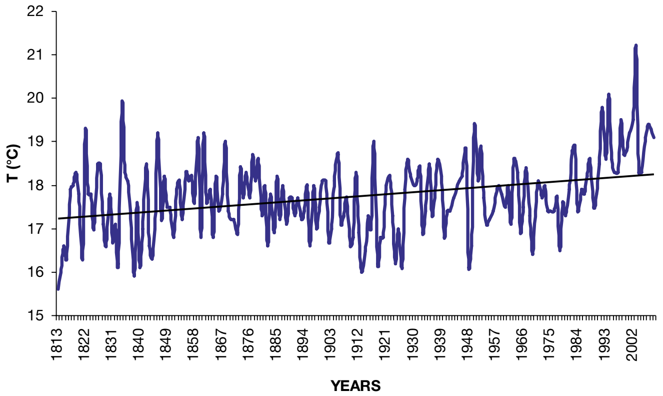


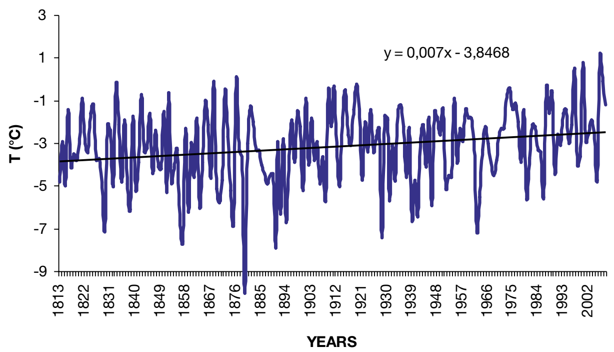


Period: 1813 - 2011	
Histalp Project - Klaghenfurt - Flugafen station	
Rate: mm per decade	
JJA	DJF
- 1,8	- 1,5

Air temperature

Summer (JJA)	Winter (DJF)



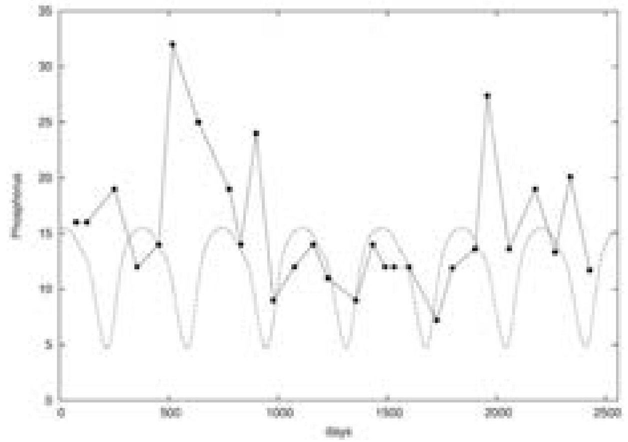


Period: 1813 – 2008	
Histalp Project - Klaghenfurt - Flugafen station	
Rate: °C per decade	
JJA	DJF
+ 0,05	+ 0,07

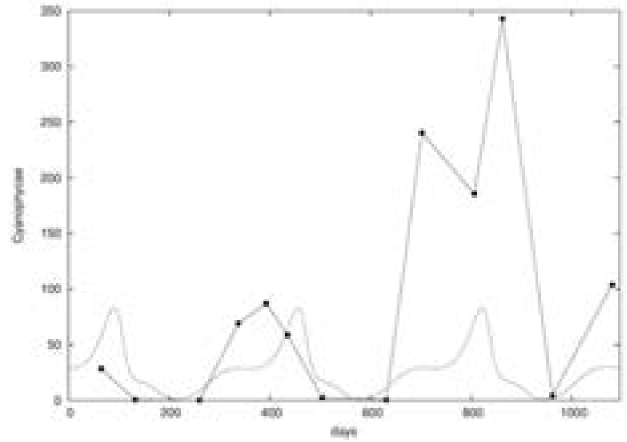
Ecological model

Two layer model

Owing to the importance of the vertical mixing in this lake, it is necessary to consider only the two layer model.

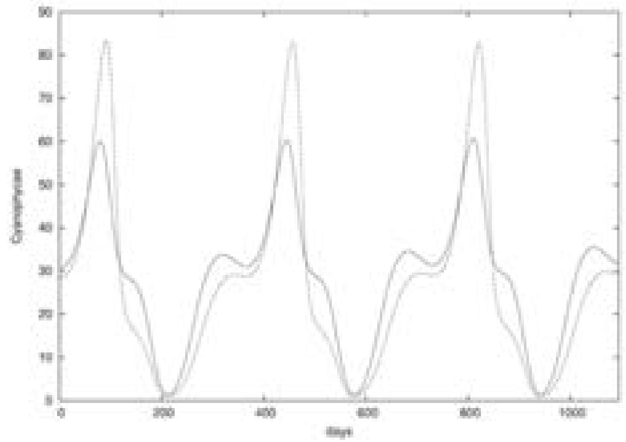


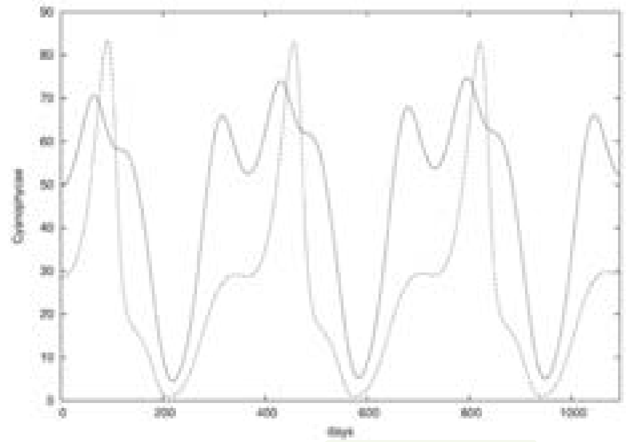
Total Phosphorus concentration in μg-P/L from measurements (solid points and connecting line) and from the two-layer model (dashed line).



Comparison between measured *Cyanophycae* concentration (solid points and connecting lines) and the phytoplankton concentration produced by the two-layer model (dashed line). Concentrations are in μg-C/L assuming a carbon-to-biomass ratio R=0.2.

Effects of temperature and environmental changes



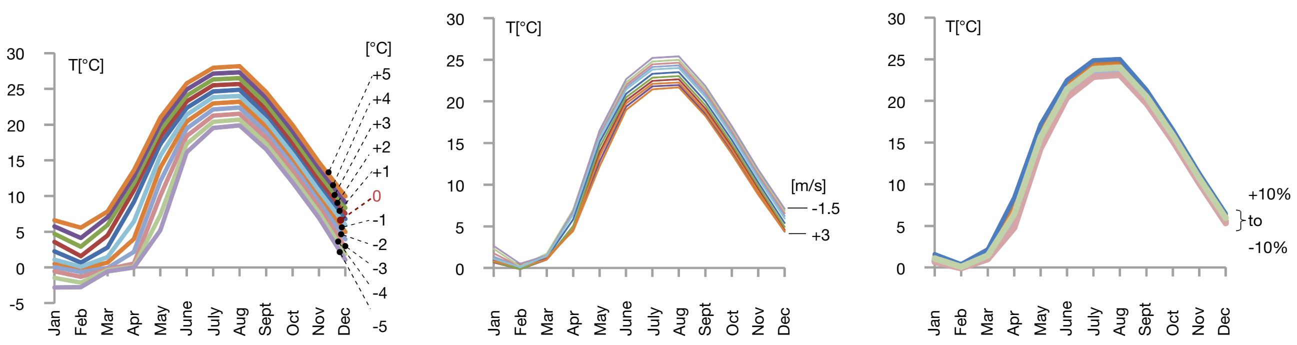


Left panel: comparison between the two-layer model phytoplankton concentration in the upper layer for faster winter turbulent exchange between the two layers, μ_0=0.2 day^{-1}, and warmer summer and winter conditions (+3 °C) (solid line) and current conditions (dashed line). Right panel: comparison between the two-layer model phytoplankton concentration in the upper layer for slower nutrient export from the upper layer, ß=0.05 day^{-1} (solid line), and current conditions (dashed line). Concentrations are in μg-C/L.
Since in this version of the model the phytoplankton growth rate is rather insensitive to temperature, an increase in the maximum summer temperature leads to almost no change in the model behavior. An increase of +3 °C in winter temperatures does slightly modify the model behavior.

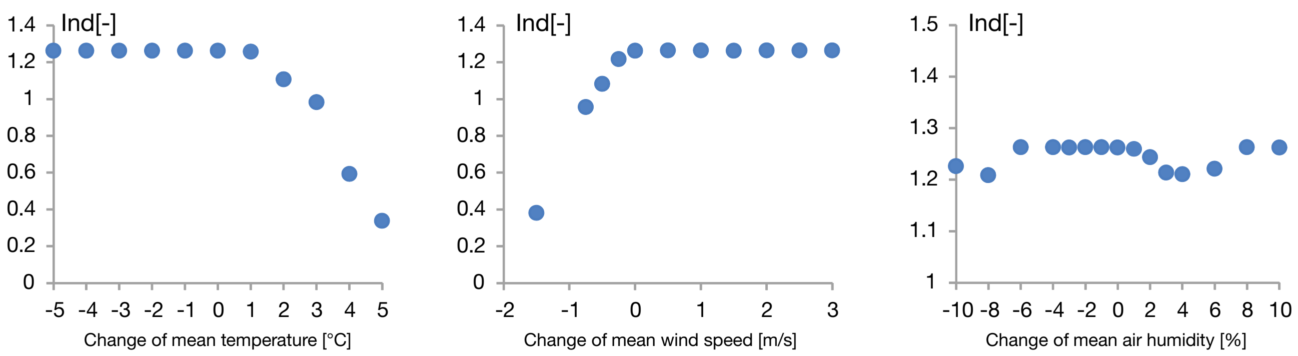
Thermodynamic model

Temperature scenarios			Wind speed scenarios			Air humidity scenarios			
Changes of the mean air temperature in [°C]:			Changes of the mean wind speed in [m/s]:			Changes of the mean air humidity in % of rF:			
0	4	- 3	- 1.5	0	2	- 10	- 3	1	6
1	5	- 4	- 0.75	0.5	2.5	- 8	- 2	2	8
2	- 1	- 5	- 0.5	1	3	- 6	- 1	3	10
3	- 2		- 0.25	1.5		- 4	0	4	

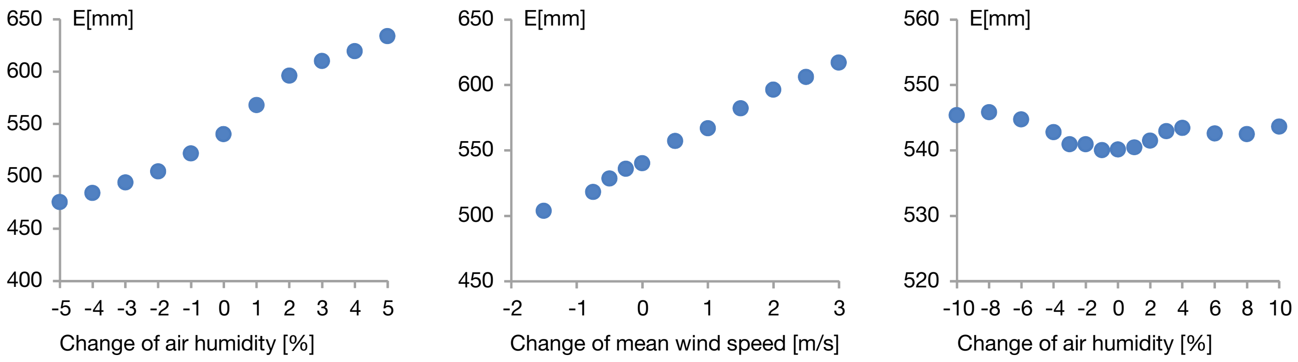
Surface water temperature



Mean mixing index(1)



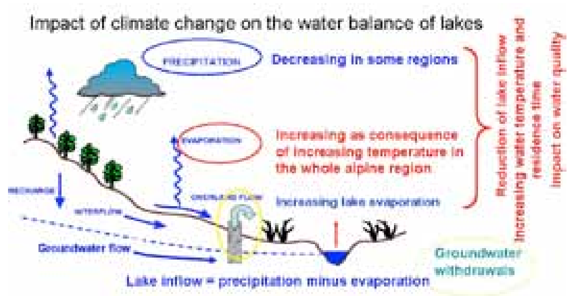
Evaporation

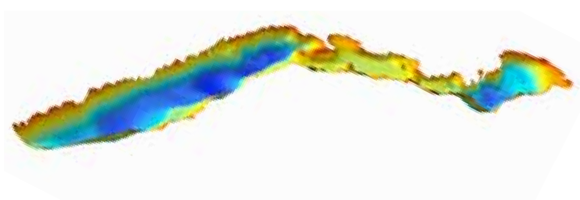


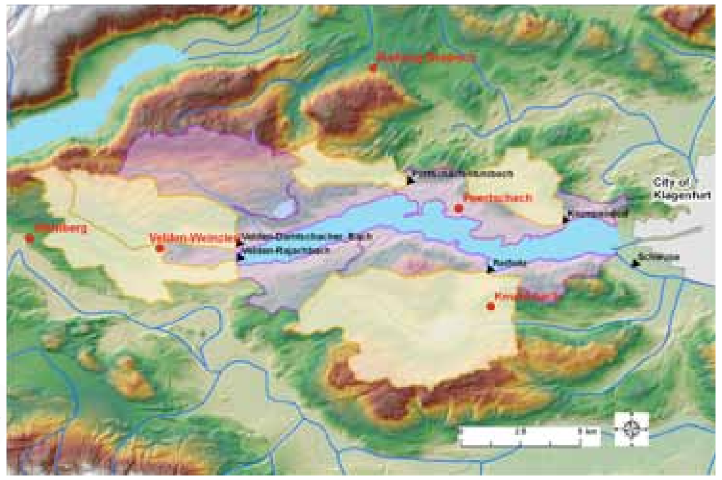
If the mean air temperature increases the surface water increases approximately with the same amount. Increasing temperature leads to a decline of circulation intensity. Lower air temperatures have no effect onto the mixing. But a decline in mean wind speed results in a less mixing intensity.The higher the wind speed the higher is the amount of evaporation. A Change in the mean air humidity has fewer effects to evaporation from the lake's surface.

(1) This mixing index describes the vertical circulation and mixing intensity in winter/spring. The higher the index, the more intensive is the mixing. 0 means no exchange between surface and bottom water layers. Maximum at Woerthersee: 1.26.

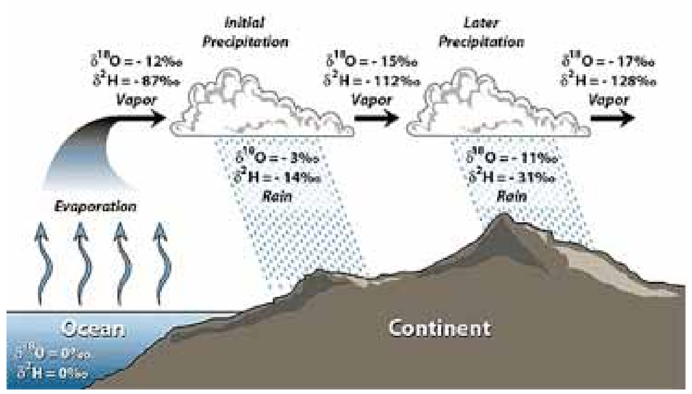
Hydrological modelling and isotope investigations



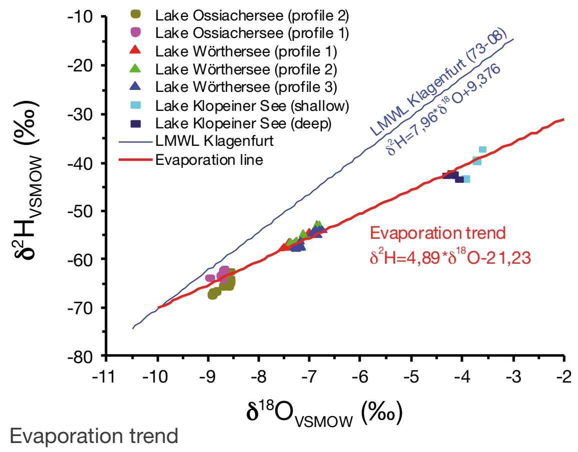




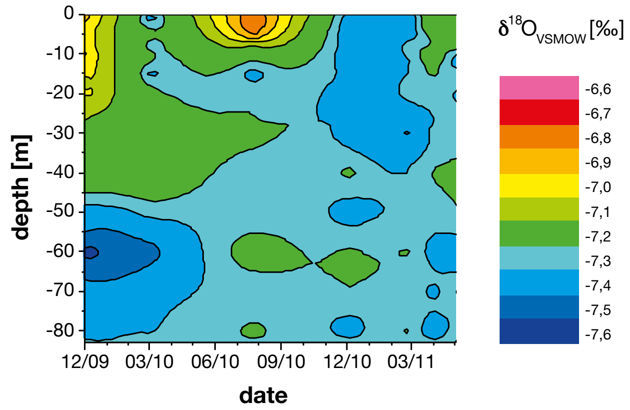
Investigation of the actual circulation and evaporation processes using environmental isotopes



Mean residence time in the deepest part: 9.5 years



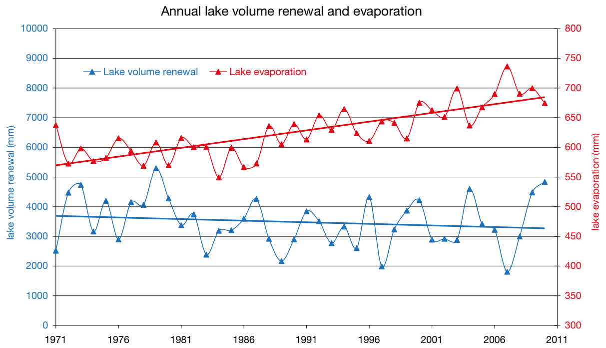
Evaporation trend



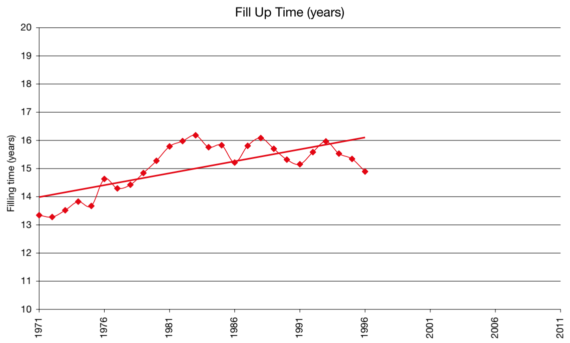
Actual circulation behaviour (Oxygen- 18 contents)

Past water balance changes and trends

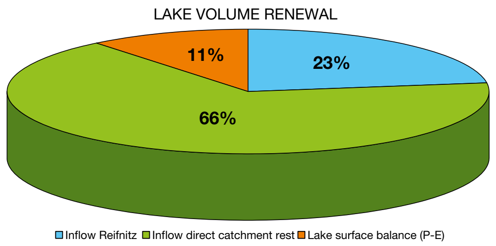
Trends of lake water renewal and evaporation

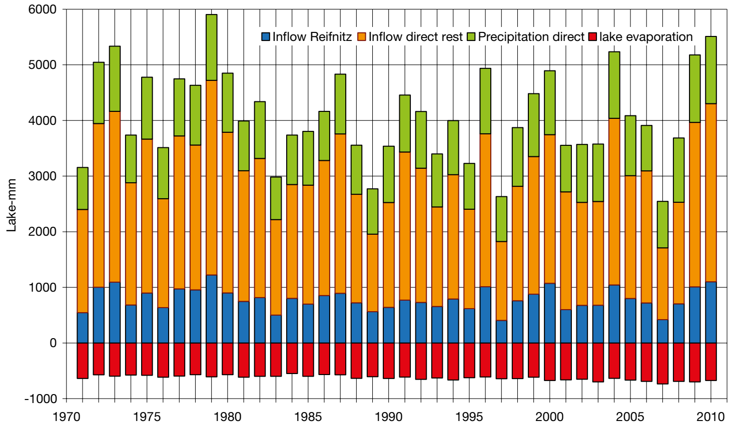


Trend of the filling time



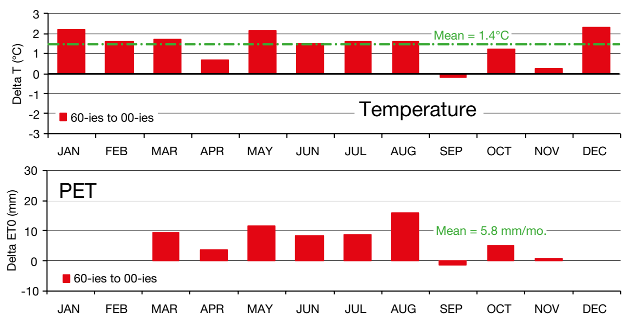
Annual lake water components

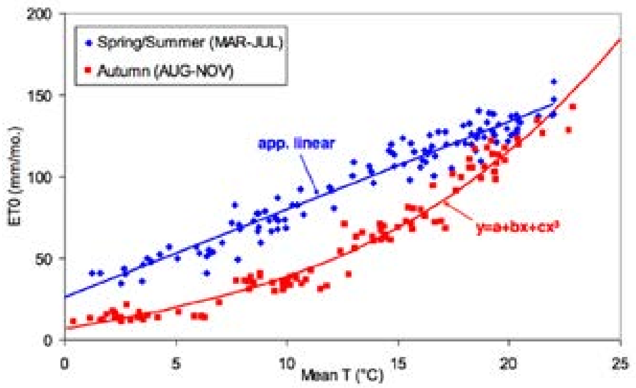




What could happen in the future?

Meteorological scenarios

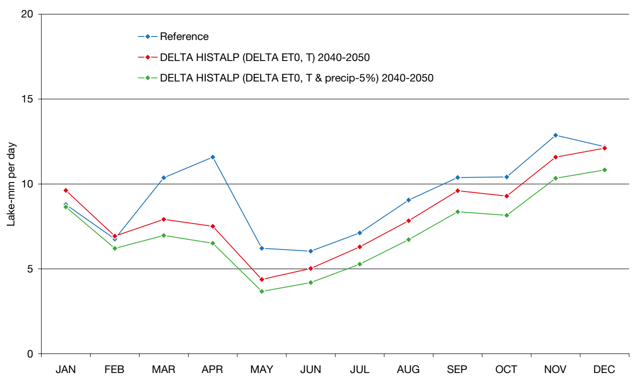


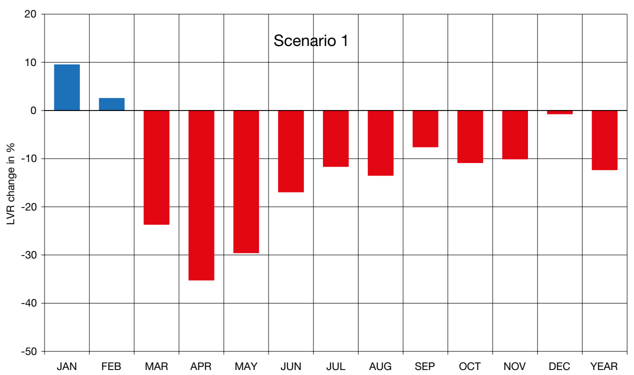


Scenario 1: Temp. and pot. evapotranspiration from HISTALP trend (50 years) extrapolated

Scenarios 2040-2050: monthly distribution of the lake water renewal

Scenario 2: Scenario 1 with a decrease in precipitation of 5% equally distributed over the year





The lake is characterized by a relatively slow circulation, the catchment is more dominant for the water balance as the lake itself.

A semi-distributed conceptual rainfall-runoff model has been used with the aim to simulate past changes and develop scenarios of the lake volume renewal depending on land use and climatic conditions and of the lake evaporation. The graphs show significant changes in the water balance (decrease of the lake volume renewal, increase of the lake evaporation) and consequently an increasing fill up time.

The past development and the simulated scenarios show, that the lake water balance is very sensitive to changes in the air temperature. A temperature increase of 1.5 °C until the decade 2040-2050 with stable precipitation produces a mean reduction of the lake water renewal of 12%. In April-May the reduction even reaches more than 30%.

The superposition with a 5% reduction of precipitation gives a mean reduction of 23%, in April-May even more than 40%. Furthermore land use changes in the catchment of the lake can have important additional impacts.

Consequently a continuation of the increasing trend of the filling time and residence time can be expected, parameters which have an impact on the ecology of the lake.

Percentual change of the lake water renewal

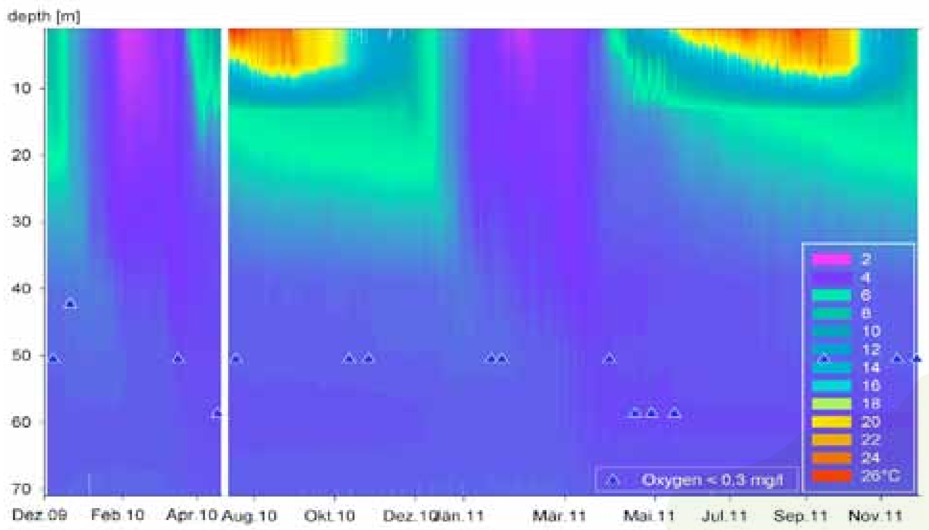
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Scenario 1	9	3	- 24	- 35	- 30	- 17	- 12	- 13	- 8	- 11	- 10	- 1	**- 12**
Scenario 2	- 2	- 8	- 33	- 44	- 41	- 31	- 26	- 26	- 19	- 22	- 20	- 11	**- 23**

Change in water temperature and water circulation

Medium water temperature at surface

	January	April	August	November
Wörthersee: 1930 - 2010	**+ 1,2 °C**	**+ 1,5 °C**	**+ 1,2 °C**	**+ 1,0 °C**

Development of temperature stratification



There is a clear increase in surface water temperature in January, April and August due to global warming – later cooling in winter and earlier warming in spring. In August the impact is lower than in April because of increasing evaporation (cooling effect on water surface).

Lake Wörthersee is a meromictic (partly mixing) lake. In the 1930th the water body was circulating down to 50 meter. In the last decades there was sometimes a circulation that went down to 80 meters indicated by the presence of oxygen concentration in the depth. The temperature situation and oxygen concentration is shown in the figure above for the time period December 2009 to November 2011. The spring and winter circulation is going down to 60 meters. A clear indication of a deeper circulation is a decrease in water temperature and an increase of oxygen concentration in the deep zone of the lake.

Lake Klopeiner See

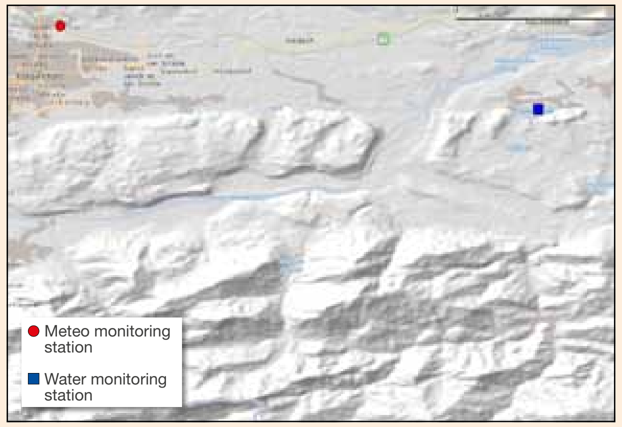
The lake

It is a relic of a former much lager post glacial lake. The lake gets filled up by detrital of the post glacial River Vellach until the Lake Klopeiner See and nearby Kleinsee remained for now. The shore lost most of its nativeness due to settlements and tourism infrastructure. The partly mixing lake is characterized by lime marl in the eastern and western bay. It has now noteworthy tributary, so it gets mainly feeded through small inflows and ground water. The outflow with a low mean flow condition of 35 l/sec. is situated in the western bay. Finally the outflow goes in the River Drau. It is the less pervaded and therefore the warmest lake of Carinthia.

The lake is nearly egg shaped, about 1.8 km long and 0,8 km wide. Due to the long water residence time the municipality St. Kanzian as owner of the lake, try hard to preserve the water quality. Since the lake showed eutrophication in the early 1980s the whole catchment got a sewerage system. Since 1975 the lake gets treated by a unique drainage of deep water in order to reduce the nutrient load. The lake is used for touristic purposes; the first visitors arrived in 1885. At that time the region had 40 beds and most visitors came to recover from lung disease. Now a day the region has nearly one million overnight stays.

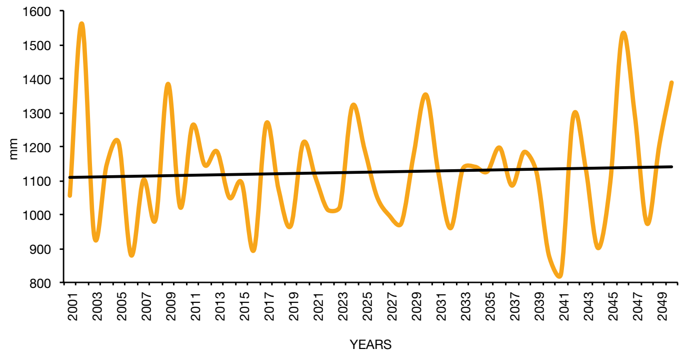
Identity Card

Catchment area	2.40	km²
Lake area	1.14	km²
Maximal depth	48	m
Average depth	23	m
Volume	22.9	m³ x 10^6
Average altitude	446	m a.s.l.
Mean fill up time	20.6	years
Mean residence time of deep lake water	6.8	years
Mean annual inflow 1971-2010 (mainly from groundwater)	23.8	l/s
Mean annual out flow 1971-2010 (including losses to spring)	34.0	l/s
Trophic state of the lake	oligotrophic	

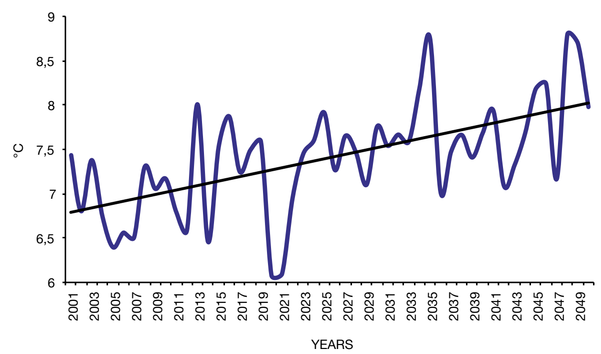


Climate driven scenarios 2001 - 2050

Precipitation



Temperature

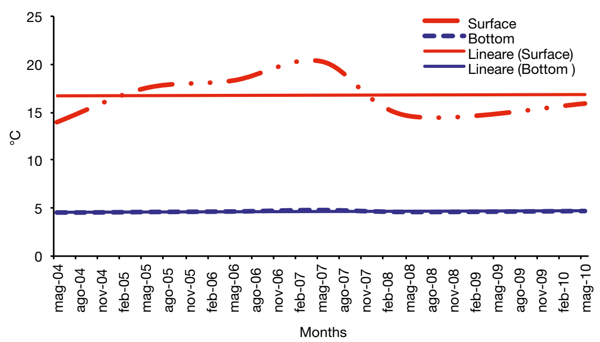


	2020	2030	2040	2050
Precipitation scenarios (mm)	- 72,8	- 19,2	- 43,2	+ 31,5
Air temperature scenarios (°C)	+ 0,32	+ 0,6	+ 0,96	+ 1,25

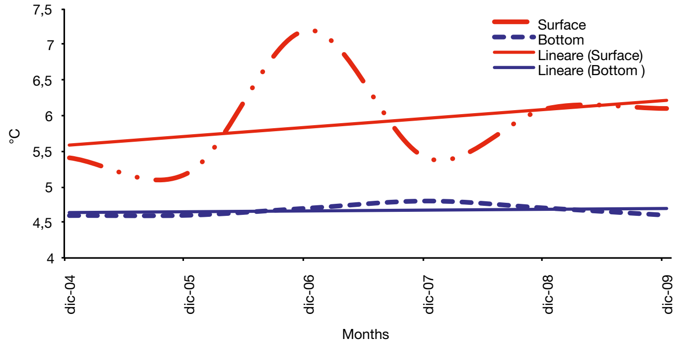
Past trend

Water temperature

Month of May



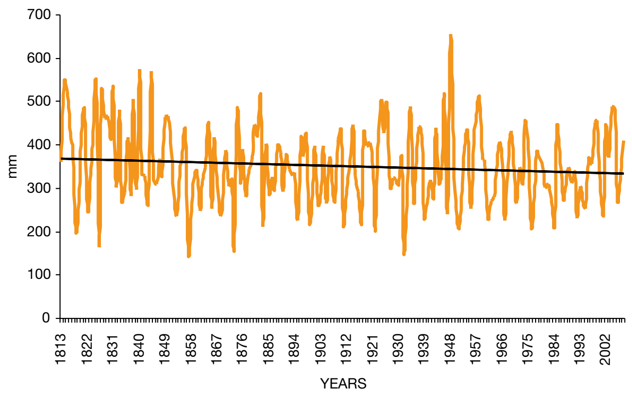
Month of December

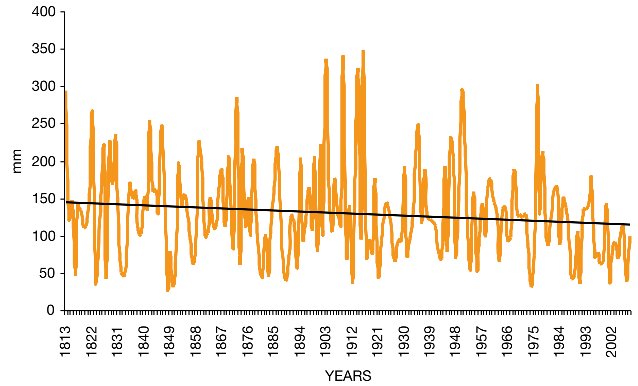


	Period: 2001 - 2010	
	Rate: °C per month	
	Month of May	Month of December
Surface	+ 0,02	+ 0,16
Bottom	+ 0,03	+ 0,12

Precipitation

Summer (JJA) | **Winter (DJF)**



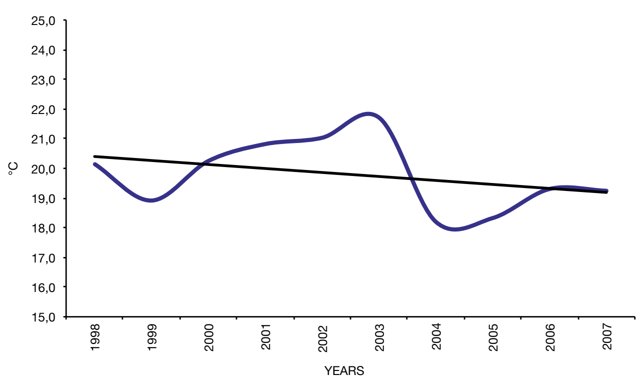


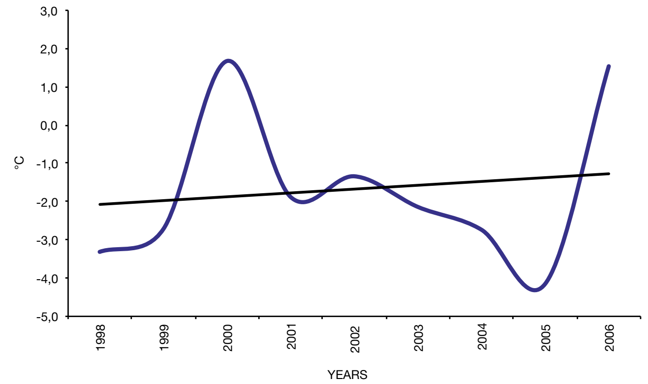
Period: 1813 - 2011

Histalp Project - Klaghenfurt - Flugafen station	
Rate: mm per decade	
JJA	DJF
- 1,8	- 1,5

Air temperature

Summer (JJA) | **Winter (DJF)**

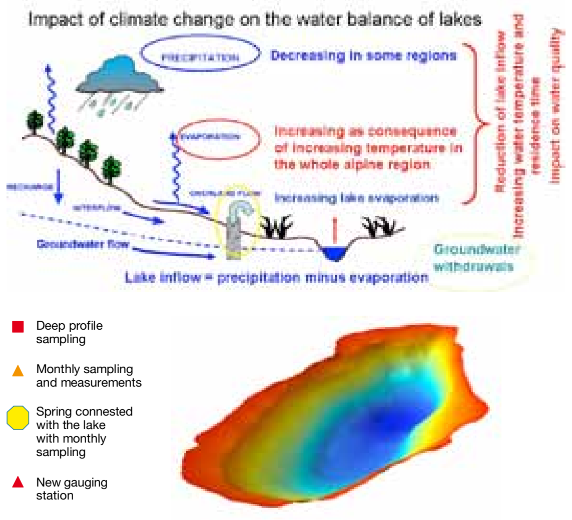


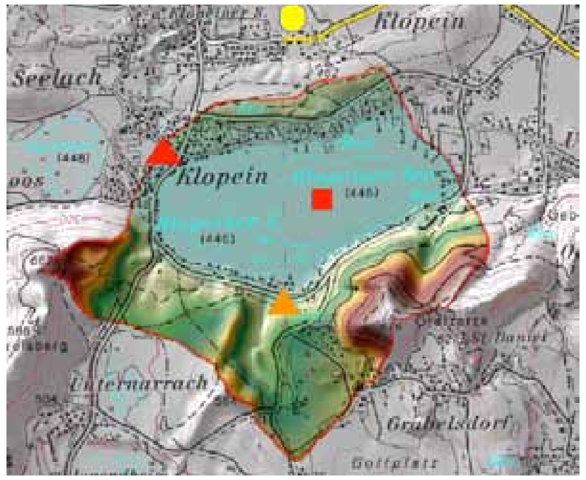


Period: 1813 – 2008

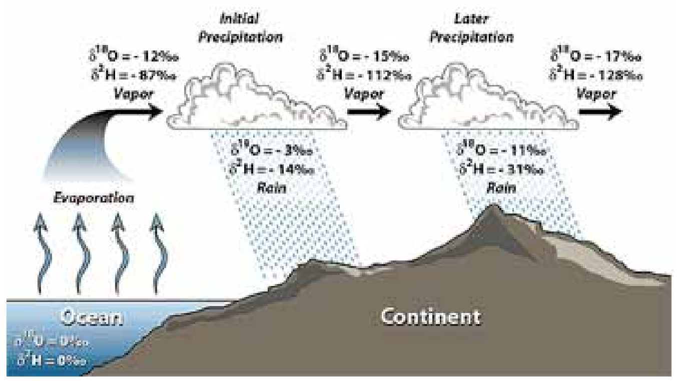
Klopein station	
Rate: °C per decade	
JJA	DJF
- 0,13	+ 0,10

Hydrological modelling and isotope investigations

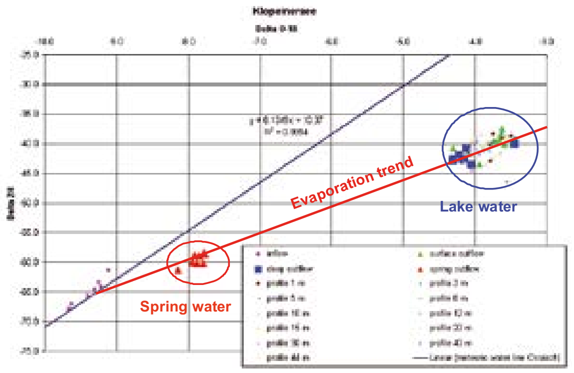




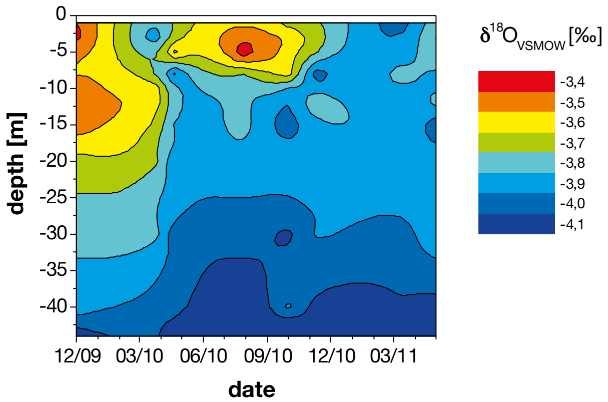
Investigation of the actual circulation and evaporation processes using environmental isotopes



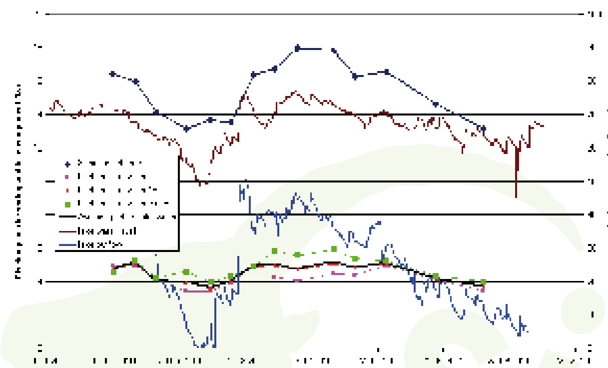
Mean residence time in the deepest part: 6,8 years



Evaporation trend



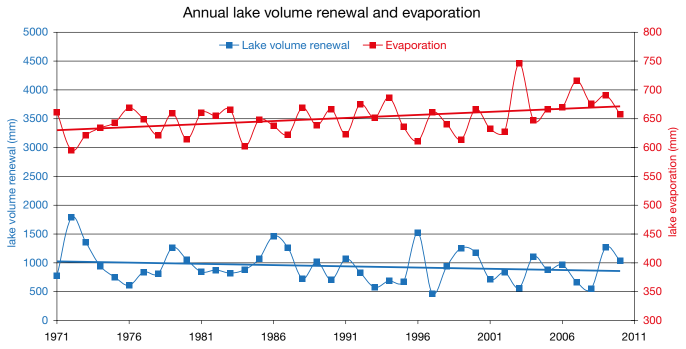
Actual circulation behaviour (Oxygen-18 contents)



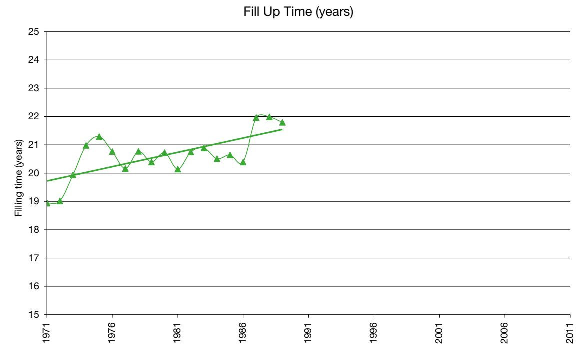
Quantification of lake losses to a spring

Past water balance changes and trends

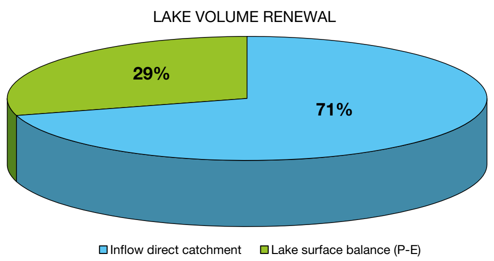
Trends of lake water renewal and evaporation

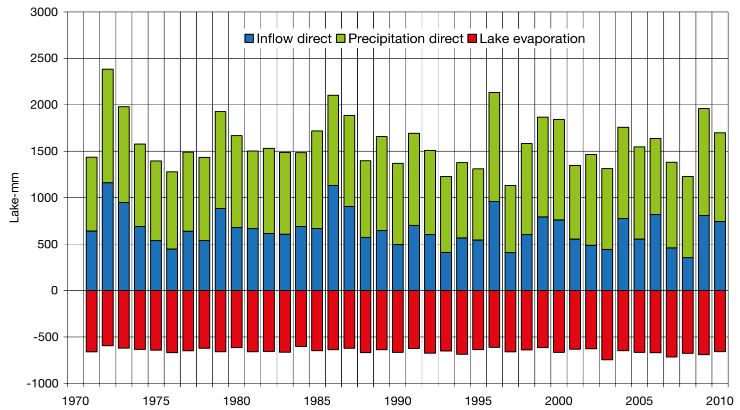


Trend of the filling time



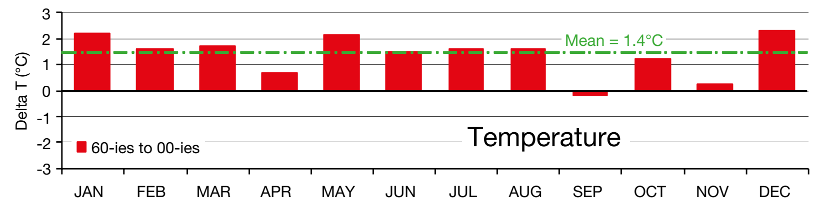
Annual lake water components

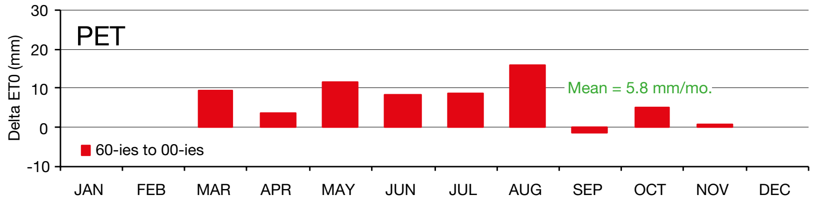




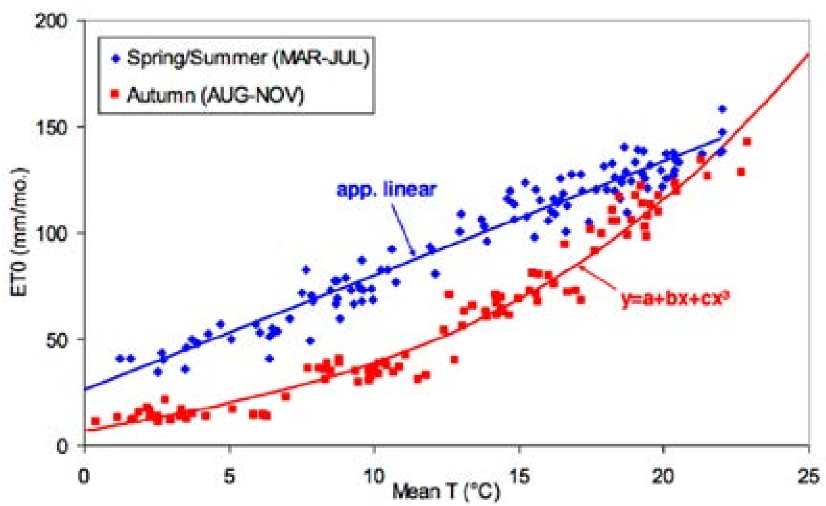
What could happen in the future?

Meteorological scenarios

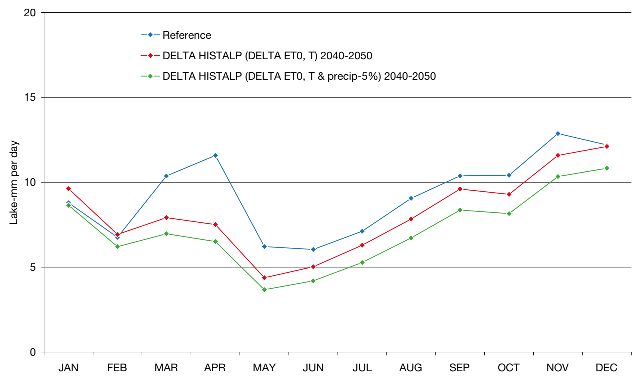


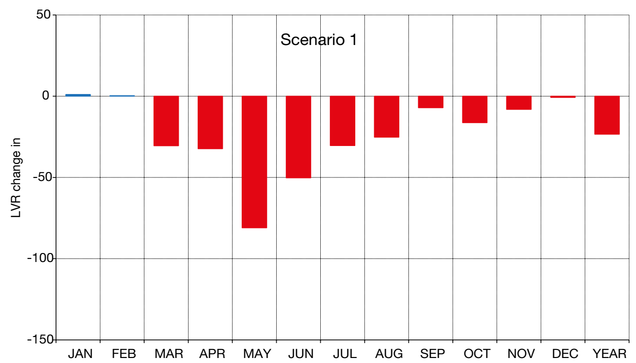


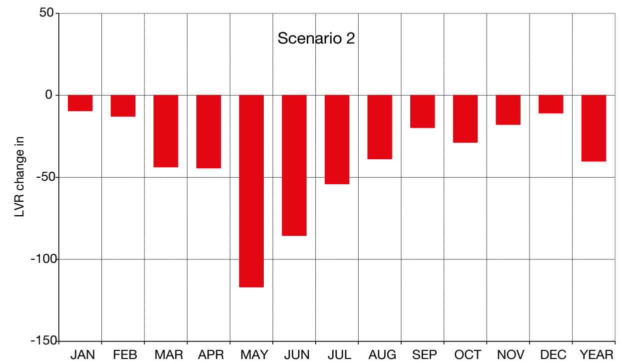
Scenario 1: Temp. and pot. evapotranspiration from HISTALP trend (50 years) extrapolated.



Scenarios 2040-2050: monthly distribution of the lake water renewal.







The small lake is characterized by a relatively slow circulation, the evaporation processes on the lake surface are more dominant for the water balance. The lake is recharged by small groundwater inflows and losses water to a spring. The variations of the isotope contents even in the highest depth prove together with the isotope signature of the spring nearby that there exists a slow circulation in the lake and a loss of about 5 l/s of lake water to the spring which has to be taken into account in the water balance calculations.

A lumped conceptual rainfall-runoff model has been used with the aim to simulate past changes and develop scenarios of the lake volume renewal depending on land use and climatic conditions and of the lake evaporation. The graphs show significant changes in the water balance (decrease of the lake volume renewal, increase of the lake evaporation) and consequently an increasing fill up time.

The past development and the simulated scenarios show, that the water balance of small lakes with small catchment areas is extremely sensitive to changes in the air temperature. A temperature increase of 1.5 °C until the decade 2040-2050 with stable precipitation produces a mean reduction of the lake water renewal of 23%. In the months from March to July the reduction even exceeds 30% with a maximum of 81% in May.

The superposition with a 5% reduction of precipitation gives a mean reduction of 40%, in May – July even more than 50% with a maximum of 117% in May. Furthermore land use changes in the catchment of the lake can have important additional impacts.

Consequently a continuation of the increasing trend of the filling time and residence time can be expected, parameters which have an impact on the ecology of the lake.

Percentual change of the lake water renewal

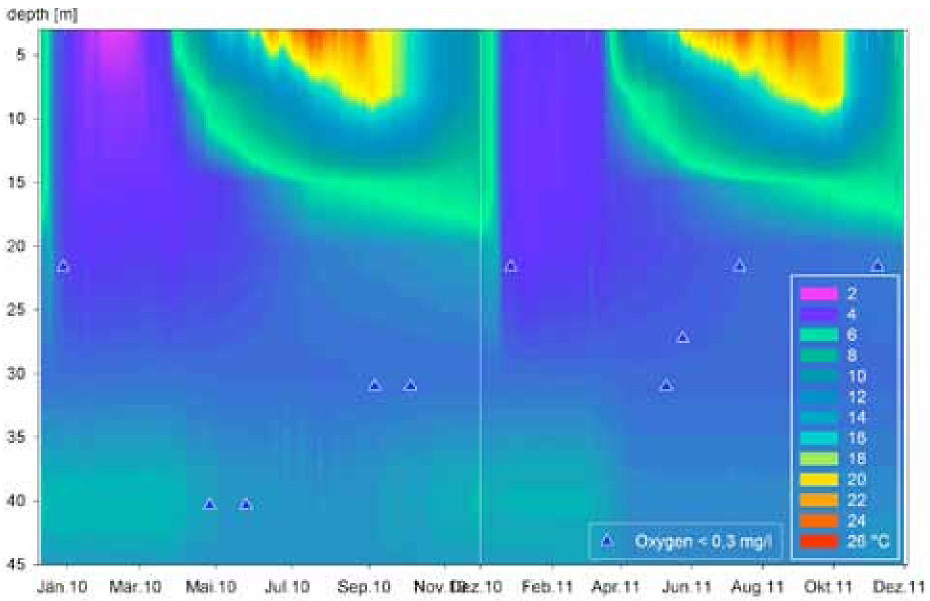
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Scenario 1	1	0	- 31	- 32	- 81	- 50	- 30	- 25	- 7	- 16	- 8	- 1	**- 23**
Scenario 2	- 9	- 13	- 44	- 44	- 117	- 85	- 54	- 39	- 20	- 29	- 18	- 11	**- 40**

Change in water temperature and water circulation

Medium water temperature at surface

	January	April	August	November
Wörthersee: 1930 - 2010	+ 0,2 °C	+ 1,1 °C	+ 0,2 °C	- 0,2 °C

Development of temperature stratification



There is a very slight increase in surface water temperature in winter, spring and summer in the period from 1990 to 2010. It seems that there is no influence of global warming on the water temperature of Lake Klopeiner See.
Lake Klopeiner See is a meromictic (partly mixing) lake. The water temperature in the stagnant water body in winter is slightly higher than in the layers above. The circulating water body goes down to 30 meters as the figure above shows.

The temperature situation and oxygen concentration in the depth informs about the mixing period and extension of water circulation. A clear indication for the depth of circulation is the appearance of oxygen. In general in this lake the oxygen limit is in the depth of 30 meters. In May 2010 the circulation went deeper and oxygen was measured down to 40 meters.

Conclusions

Before the 1990s, most environmental scientists considered climate to exert a relatively constant influence on freshwater ecosystems. In recent years, however, it has become clear that climate change exerts additional stress to surface waters and that it interacts with other drivers (such as eutrophication, hydromorphological change, acidification). The main impacts of climate change on lake ecosystems result from change in air temperature, precipitation and wind regimes.
The response of the lakes to climate change depends on their mixing characteristics, which, in turn, are influenced by their location, landscape setting, size and topography.

Global warming is already having an impact on the physical, chemical, biological and hydromorphological conditions of lake ecosystems. The magnitude of change induced by climate change is still relatively small in comparison with the impact of anthropogenic land use, and, at the same time, impose land use changes in catchments.
Change in the characteristics of lake ecosystem in the Alpine area, as illustrated here, are likely to continue and will become much more pronounced as greenhouse gas emission rise.

These changes will have consequences in Alpine Space area such as more likely frequent and more extreme weather events, with an increased sediment loads; a decline in rainfall, in particular in the western region could reduce the water level, and consequently, for example, to reduce the regularity of the port, to lead to a change in location of ecosystem and of spawning and nursery areas, to increase the eutrophication in shallow lakes; higher temperatures lead for example to a decrease in water supplies, to a change in growing season for plants, to an increase of evaporation, evapotranspiration and a probable drought state in late summer, with alterations of the oxygen concentrations in the water column and in the food web. The authorities involved in the lakes management in the Alpine Space must take action now to prepare for these impacts. This includes changing the way buildings and infrastructure are designed, improving our water use, rethinking the way we develop vulnerable shore zones, or planting more drought-tolerant crops.

Engineering solution, upgrade of infrastructures, water monitoring increase, proposals for new structures and facilities have to be applied to alpine lakes. On one hand some adaptation actions, such as behavioural adaptations, can be implemented at low cost while others, on the other hand infrastructural measures will require significant investment. But the decisions make today about management of the main uses of the lakes (irrigation, navigation, tourism/bathing, energy power…) will have lasting consequences for our children and future generations, and to reduce the future costs of management. By considering the future climate when making these decisions Alpine Space will be in a better position to deal with the unavoidable impacts of climate changes.

Long data series of climatic, chemical, physical and biological parameters are essential to better define water management and to set up decision making tools. Actually, through monitoring, modelling and system analysis, SILMAS project provided an early-warning system for climate change, helping decision makers at a political level to take adjustment strategies, in terms of water resource management and ecosystem preservation or restoration.

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