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PILOT DESCRIPTION AND ASSESSMENT

Vrana lake, Croatia

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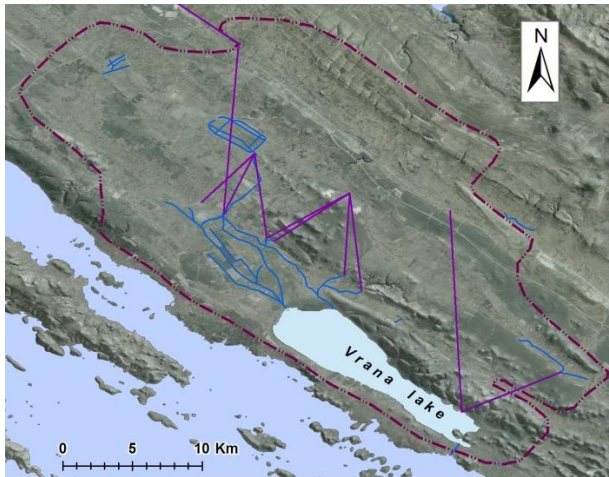
LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate Change
GC	Global Change
LULC	Land Use and Land Cover
SWI	Sea Water Intrusion
GSO	Geological Survey Organisations
PET	Potential evapotranspiration

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1 EXECUTIVE SUMMARY

Pilot name	Vrana lake	
Country	Croatia	
EU-region	Mediterranean region	
Area (km ²)	516 km ²	
Aquifer geology and type classification	Karstic limestones, Fissured aquifer	
Primary water usage	Drinking, irrigation	
Main climate change issues	Vrana lake is situated in the close vicinity of Adriatic Sea coast in highly karstified terrain (Dinaric Karst region). The lake is declared as a nature protection area. Permeable terrain between the lake and the sea enable underground inflow of sea water into the lake during dry periods when lake level is low. Therefore, the lake eco system is highly vulnerable to increasing duration of draughts as well as sea level rising. Pumping of groundwater for public water supply and irrigation in the catchment presents additional pressure on the lake system.	
Models and methods used	Time series analysis, conceptual and lumped model (GARDENIA-BRGM, METRAN-TNO)	
Key stakeholders	Vrana lake nature park (public institution), water supply company, private farmers	
Contact person	Andrej Stroj, Croatian Geological Survey, astroj@hgi-cgs.hr	

Vrana lake is situated in Croatian coastal region Dalmatia, separated from the Adriatic Sea by a narrow carbonate ridge less than 1 km wide in its narrowest parts. The lake and its immediate surrounding is declared as a nature protection area. Carbonate ridge, which separates the lake from the sea, is intensely karstified, i.e. permeable for groundwater flow. This enables sea water intrusion (SWI) to the lake through permeable subsurface during the low lake water levels. Lake water level above the sea level is the main factor that prevent SWI. Although occasionally slightly brackish lake water is natural characteristic of the lake, inflow of a sea water during prolonged draught periods, which are generally concurrent with summer seasons in the area, produce excessive salinization of the lake and a major threat to the ecosystem. The most important cause for lowering the lake water levels during relatively hot summer seasons is direct evaporation from the lake. High water and air temperatures, together with large lake surface area (approx. 30 km²) and shallow depth (up to a few meters) produce very high rates of evaporation. Lake level and salinization dynamics shows significant inertia, so major lake salinization events typically occur when the lake was not sufficiently replenished during preceding wet season, resulting in low water level and increased salinity at the beginning of summer/draught periods.



The lake is fed solely by groundwater from the extensive karstic catchment with approx. area of 500 km². Pumping of groundwater for public water supply and irrigation in the catchment presents additional pressure on the lake system, as sufficient fresh water inflow is essential to control SWI to the lake. Additional unfavourable factor presents presence of artificial channel for evacuation of the lake water during high water levels. The channel was firstly built in 18th century, reconstructed additionally several times afterwards, with the aim to drain the extensive wetlands in the area upstream from the lake. Before the channel construction the lake was drained naturally through the permeable subsurface, but channel considerably fastens that process resulting with lower water levels at the beginning of dry summer periods, when lake water losses continue by strong evaporation. Intensive agriculture is still present in the area upstream from the lake, and closing of the channel during the wet seasons would cause flooding of the agricultural lands. This prevents restoration/closing of the channel in order to re-establish natural conditions.

As already explained, SWI feed lake during low lake water levels, resulting in lake level stabilization at levels slightly below sea water level despite high evaporation and low fresh water inflow during prolonged draughts. Therefore, CC, which results in increasing temperature and prolonged draughts in the area, presents major threat to the lake ecosystem. Increasing trend of the sea water level, which is also a consequence of CC and GC, would additionally amplify lake salinization processes in the future. In depth understanding and significance estimation of all processes, influencing the lake SWI is necessary to predict future CC scenarios, as well as to consider potential adaptation and mitigation strategies.

All available data time series, related to the historical lake level and salinity dynamics, were collected: over 70 years of the lake level data; almost 60 years of rainfall, air temperature and relative humidity data which served also for calculation of potential evapotranspiration (PET) data based on Turc method (Etp Turc software developed by BRGM); data on direct evaporation from the lake surface; and 18 years of monthly lake salinity measurements. Preliminary time series analysis was carried out including descriptive statistics, autocorrelation and cross correlation functions to examine system inertia and interdependence of different parameters. After the preliminary time series analysis, lumped modelling tools were used to model lake level dynamics based on precipitations, PET and direct lake evaporation. GARDENIA (developed by BRGM), METRAN (developed by TNO) and AQUIMOD (developed by BGS) lumped modelling tools were tested for modelling purposes. Although all used tools were principally developed for modelling groundwater levels in aquifers, they were tested for modelling lake level, which is in strong connection with the surrounding karst groundwater. Water fluxes to the lake are happening mainly dispersedly through the karst subsurface, and consequently impossible to be directly measured and monitored. This prevents modelling the lake level based on direct inflow, outflow and lake geometry. Lumped groundwater modelling tools were used as an option to overcome this problem. GARDENIA and AQUIMOD models enable level modelling based on precipitations and additionally pumping dynamics, which was used as equivalent process to direct evaporation from the lake. METRAN model is pure transfer function model which can use several input time series in order to model output series. Simple transfer function was also used to model lake salinity response to the low lake levels.

Best results for lake level modelling were obtained by GARDENIA software due to effective way to take evaporation effect into account as a pumping. GARDENIA software calibrates pumping influence with pumping coefficient, determined automatically through calibration. AQUIMOD software also has option to include pumping to the model, but its influence is not calibrated through coefficient, resulting in largely overestimated effect when it was expressed in



recommended units. Therefore, pumping/direct evaporation was not included in the AQUIMOD model, resulting with low final model efficiency. Moreover, we experience additional problems with automatic calibration process: final parameters for the model were calibrated manually. METRAN software succeeded to produce relatively efficient model based by two input series: precipitations and air temperatures. Direct lake evaporation is strongly correlated to air temperature, and together with the precipitation is main controlling factor for the lake level dynamics. This enables good efficiency of the METRAN model. Main problem with the METRAN is that it is not user friendly in the present form, so all the modelling work had to be done by TNO expert who developed the tool.

The second considered model for the lake salinity study was dependence of the lake salinity on the lake levels. First, critical lake level was determined, below which salinity start to increase. Afterwards, only levels below critical level were taken as a input series, and lake salinity values as an output. Simple transfer function that summed influence of 10 months historical period of lake levels below threshold value produced good agreement with the observed vales. Finally, usage of lake level model and lake salinity model together enabled possibility for prediction of future lake salinity, based on predicted precipitations and air temperature from various CC scenarios.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and has the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, has established the project “Tools for Assessment of Climate change Impact on Groundwater and Adaptation Strategies – TACTIC”. By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infrastructure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (<http://www.europe-geology.eu>).

The present document reports the TACTIC activities in the pilot Vrana lake located in the Adriatic Sea coast of Croatia, in Dalmatia province. The lake is declared as a nature protection area (Nature Park) because of its rare natural habitats and biodiversity. It has been included in the list of Important Bird Areas in Europe and became Ramsar site. Lake is fed mainly by a groundwater from a large karstic catchment. The lake is separated from the sea by relatively narrow (in places less than 1 km wide) carbonate tidge. Carbonate ridge is intensely karstified, what enables SWI to the lake during low lake water levels through the permeable subsurface. Although occasionally brackish lake water is natural characteristic of the lake, more and more pronounced draught periods, increasing temperatures and sea level rising due to a CC and GC are the main thread for the vulnerable lake ecosystem. Detailed knowledge of all processes, influencing the lake SWI, is necessary to assess and summarise impacts of potential future CC and GC scenarios, and to identify potential measures for mitigation of adverse consequences and to estimate their impact. Therefore, the Vrana pilot was included in TACTIC WP5: *Assessment of salt-/sea water intrusion status and vulnerability* and WP6: *Groundwater adaptation strategies* in order to examine potential future CC scenarios for the lake SWI, as well as to consider potential adaptation and mitigation strategies. Within the TACTIC project different modelling tools were used and tested for modelling the lake level based on historic climatic measurements, as well as future CC predictions, which were developed and provided by partner GSOs (GARDENIA by BRGM, AQUIMOD by BGS and METRAN by TNO).

3 PILOT AREA

3.1 Site description and data

3.1.1 Location and extension of the pilot area

The pilot area is located in the western part of Croatia (Dalmatia) beside the Adriatic Sea coast (Fig 1). It is located within the broader Dinaric Karst region which spreads across the several countries (Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, northern Albania) parallel to the eastern Adriatic sea coast. Vrana lake catchment area belongs to Mediterranean region and covers approx.. 515 km² (Fig. 1).

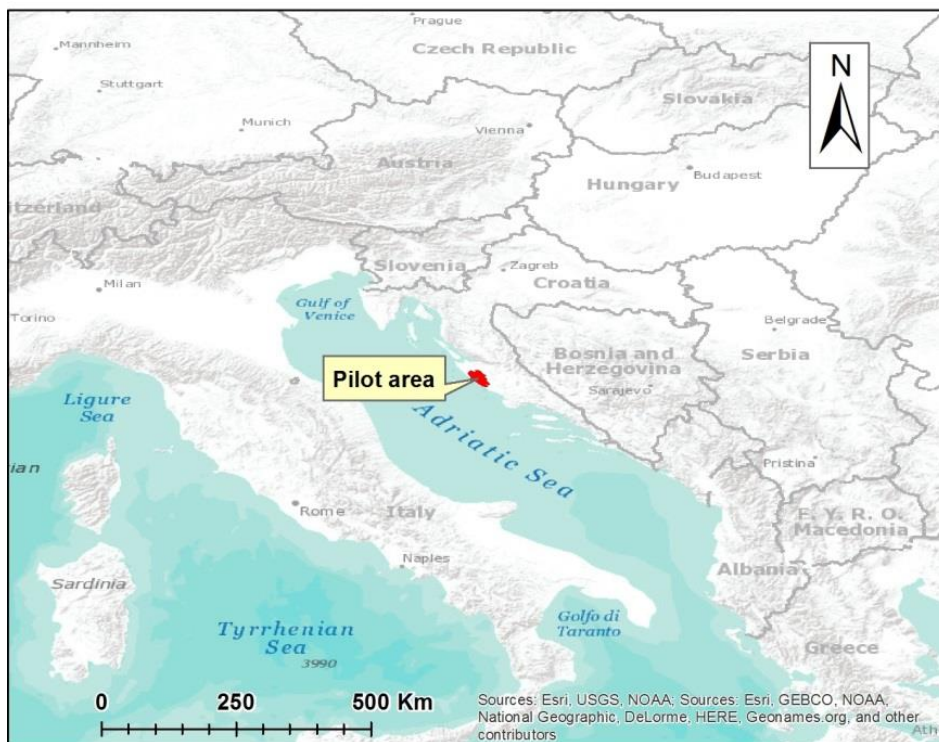


Figure 1. Location of the pilot area

Vrana lake is situated in the close vicinity of Adriatic Sea coast in highly karstified terrain (Dinaric Karst region). It is located in a shallow kryptodepression with the bottom at –3.5 m a.s.l. Lake water levels vary annually approx. in the range 0–2.5 m a.s.l. Permeable terrain between the lake and the sea enable underground SWI into the lake during dry periods, in conditions when the lake level drop close or even slightly below sea level. Therefore, the lake eco system is highly vulnerable to increasing duration of draughts as well as sea level rising.

Upstream of the lake, within the same karstic catchment, there is agricultural lowland area called Vrana polje (45 km²). Agricultural activities include groundwater abstractions for irrigation purposes (mostly uncontrolled). Public Water Supply Company also use groundwater from the catchment with pumping stations located on the major freshwater springs upstream from the lake, mostly at the NE edge of the Vrana polje.

In the SE part of the lake, across the narrowest part of the carbonate ridge that separates the lake from the sea, there is an 850 m long artificial channel for evacuation of the lake water during high water levels. The channel was firstly excavated in 18th century, additionally reconstructed and deepened afterwards, with the aim to drain the extensive wetlands in the area upstream from the lake (Vrana polje, agricultural area that was marshy area prior the channel). Before the channel construction the lake was drained only through the permeable (karstified) subsurface, and channel considerably fastens that process. Although the channel bottom is slightly above average sea water level, fast drainage through the channel in high lake level conditions results with lower water levels at the beginning of dry summer periods. During low lake levels, when drainage through the channel ceases, lake water losses continue by strong evaporation. As intensive agriculture is present in the area upstream from the lake, closing of the channel during the wet seasons would cause flooding of the agricultural lands. This prevents restoration/closing of the channel as a measure to re-establish natural conditions.

3.1.2 Climate

Climate in the area of Vransko Lake is typically Mediterranean, with mild, considerably short and rainy winter periods, and dry, hot summers. By Köppen, this type of climate is called “Olive tree climate”. Holm oak forests, maquis (Mediterranean scrubland) and dry grasslands on rocky karst terrain characterize its vegetation.

Mean annual temperature varies within the watershed in the range 12-15°C, and average annual precipitation amounts 950 mm/y (Zaninović et al. 2008). Warmest months of the year are July and August (21-24°C monthly averages), and January and February are the coolest (5-8 °C). October and November have the highest precipitation (approx. 120 mm monthly average), and June and July are the driest months (approx. 50 mm monthly average). Infiltration coefficient is estimated to be approx. 0.2-0.3. Based on the estimated infiltration coefficient, mean annual recharge is approx. 250 mm, which equals $129 \times 10^6 \text{ m}^3/\text{y}$.

3.1.3 Topography and soil cover

Water catchment of Vrana Lake consists of levelled surfaces of karst poljes, separated by moderately elevated hills and ridges. All the morphological features are elongated in NW-SE direction, known as a Dinaric strike direction. Elevation of the area ranges from 0-300 m a.s.l. (Fig. 2), generally rising in NE direction. Soil cover of variable thickness covers levelled surfaces, while on elevated hilly areas soil cover is almost absent with bare limestone rock outcrops on the surface.

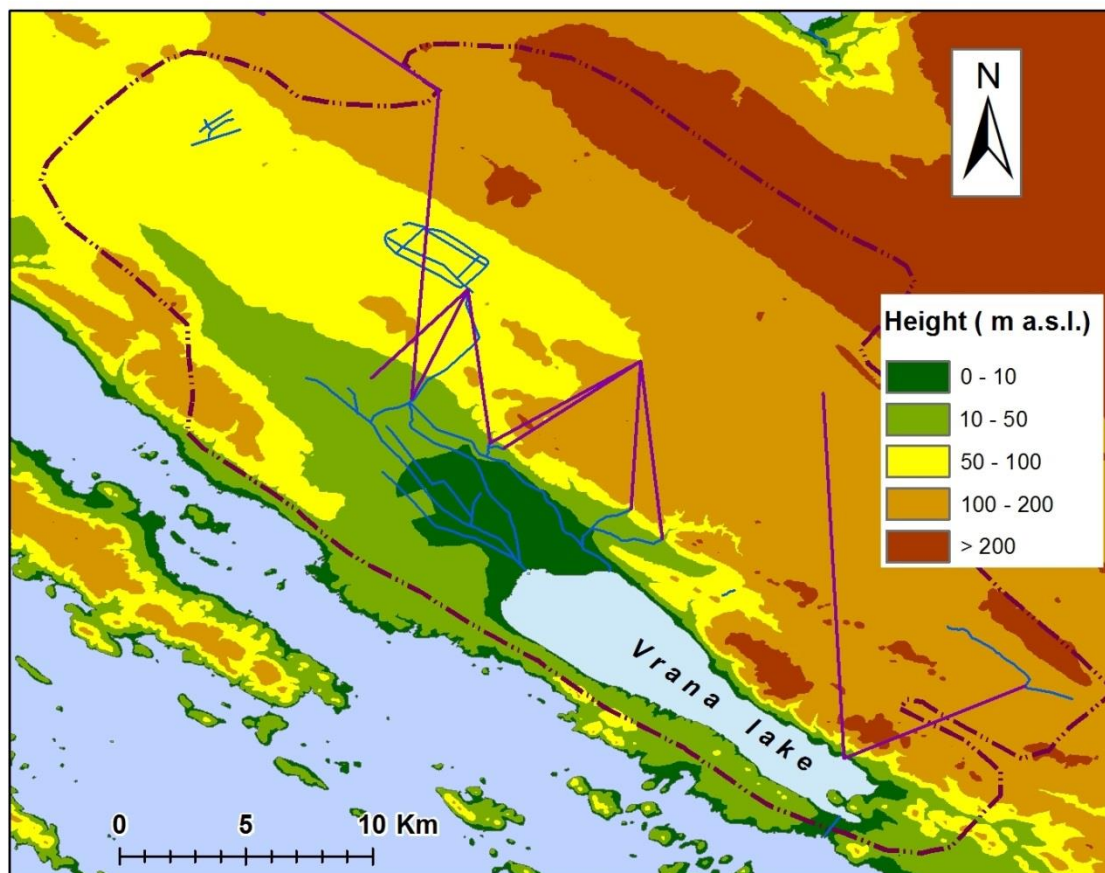


Figure 2. Topography of the pilot area.

3.1.3 Land use

Vrana lake and its immediate surrounding is declared as a nature protection area (Nature park) because of its rare natural habitats and biodiversity. It has been included in the list of Important Bird Areas in Europe and became Ramsar site. Lake is fed mainly by a groundwater from a large karstic catchment ($>500 \text{ km}^2$). Nature protected area, which is in natural condition, presents only a small part of the catchment (approx. 57 km^2 , of which 30 km^2 is extent of the Lake).

Vrana polje area was historically occasionally flooded swampy area upstream from the lake. Artificial drainage of the Vrana polje begun in 18th century with construction of the channel connecting the lake with the sea. The Channel serve for evacuation of the lake water during high water levels up to present day. Additional network of drainage channels across the polje area converted wetland to arable land. Today Vrana polje is agricultural area which is both drained and partly irrigated during dry seasons.

There are additional agricultural areas in the catchment area, typically situated within the elongated shallow valleys and levelled surfaces (karst poljes), separated with rocky hills and ridges. Rocky carbonate hills are covered with shrubs and Mediterranean woods. Larger settlements are located at the sea coast (downstream from the lake), while inner parts of the catchment are relatively sparsely inhabited, without larger individual settlements.

3.1.3 Geology/Aquifer type

Study area is dominantly built of limestones (karst rocks) of Cretaceous and Paleogene age, and in lesser extent of flysch rock complex of Paleogene age (Fig. 3). Flysch rocks are generally covered by soil cover, while soil cover is almost absent on limestones (Fig. 3). Area is tectonically folded and thrust, with dominant NW-SE strike of the structures (faults and fold axes). The Flysch rocks, representing the stratigraphically youngest rocks, are situated in the core areas of the synclines. Thrust faults often intersect and deform continuation of synclines and anticlines in the area.

Limestones are well karstified, proven by a number of tracing tests performed in the area (Fig. 3). Surficial water flows are mostly absent on the limestone areas, and precipitations quickly infiltrate into the epikarst (surficial most intensively karstified zone, usually few to ten meters thick). Infiltrated water is partly transported from epikarst further to the deeper karst conduit networks, but it is also partly lost through evapotranspiration processes as epikarst zone is typically within the reach of plant roots.

Ground water flow in karst terrains is concentrated within karst conduits, while surrounding rock mass usually have very low porosity and consequently low permeability. Low permeability of the rock mass is reflected by general unproductiveness of wells that failed to intercept significant conduits. Storage of water is mainly related to shallow epikarst zone, as well as fractured rock mass within the deeper vadose and phreatic zone. Exact significance of epikarst zone and deeper zones for water storage is still relatively unclear. However, storage and regulation capacity of the karst system is limited, resulting in typical extreme oscillation of spring discharges during dry and wet seasons. This causes occasional floods of low lying karst terrains during wet seasons, as well as water scarcity in dry seasons.

Flysch rock complex consist of intercalation of marl, sandstone and limestone beds. In contrary to limestone terrains, flysch terrains are generally non-karstified and impermeable, forming hydrogeological barriers in the subsurface. Therefore, in flysch areas water flow mostly on the terrain surface. Position of flysch rocks above limestones within synclines often form “hanging” groundwater flow barriers which enable deep karstic flows beneath them (Fig. 4).

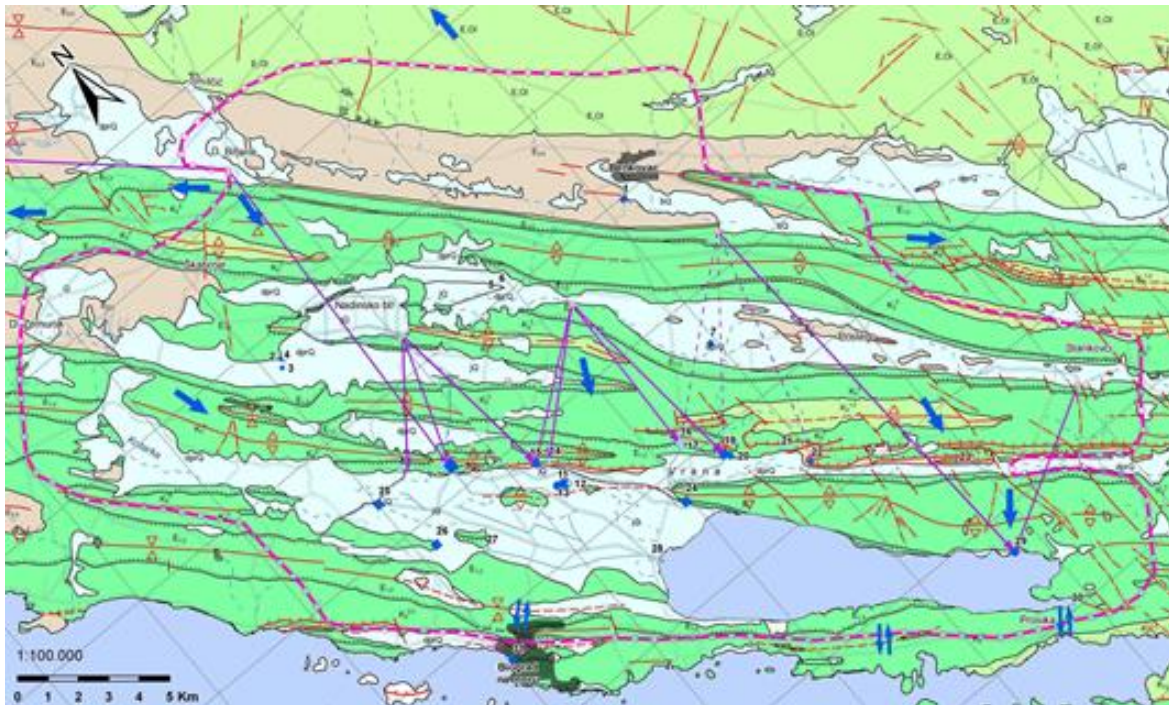


Figure 3. Hydrogeologic map of the Vrana lake catchment (karst rocks in green colors, low permeable flysch rocks in brown, unconsolidated sediment cover in light blue, ground water tracing connections are marked with purple lines, groundwater flow directions with blue arrows, adapted from Stroj 2012).

While majority of the karstic springs in the Vrana polje area discharges fresh water, there are also a few springs discharging brackish water. SWI on the springs is not controlled directly by their distance from the sea coast, but rather by depth of water circulation (Fig. 4). More precisely, springs that are fed by the water from deep lying karst conduits, which are situated below fresh water-brackish water interface, discharges brackish water. Seawater share in the spring water is variable depending on hydrological conditions, i.e. inflow of fresh water to the conduit system.

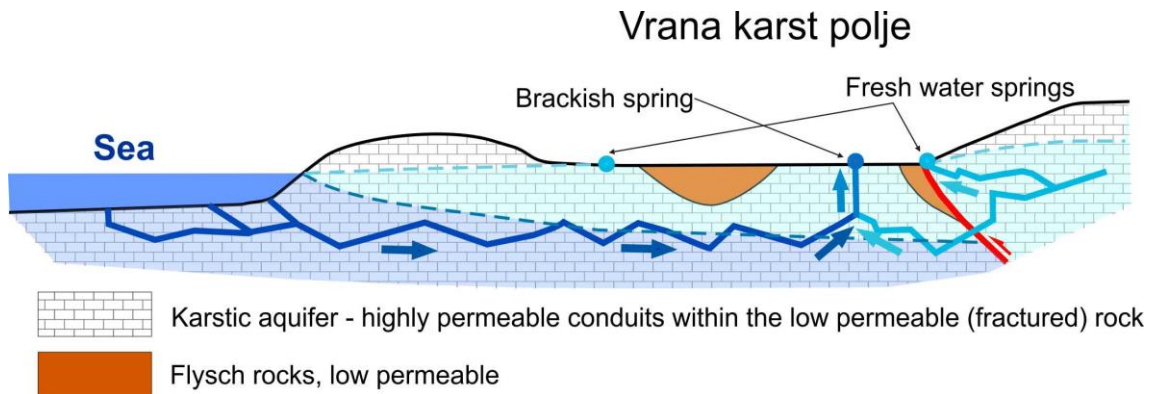


Figure 4. Conceptual model of sea water intrusion affecting some of the inland springs on the Vransko polje area (upstream/NE from the lake, Fig. 2).

Vrana Lake is separated from the sea by karstified limestone ridge, on the narrowest part slightly less than 1 km wide. This allows fast drainage of fresh water from the lake to the sea during wet periods, both through the artificial surface channel for high water evacuation and karstified subsurface. On the other hand, lowering of the lake level near or even slightly below the sea level due to the high evaporation during summer draught periods enable direct SWI through the karstified subsurface into the lake (Fig. 5). This direct SWI to the lake is the main cause for the major lake salinization events, as salinity of the brackish springs are below the lake salinity in such periods. In addition, highest salinity is typically measured in the lake area closest to the Sea coast (SE part of the lake). Therefore, the main factor for prevention of excessive salinization of the lake is sufficiently high lake level above the sea level, what directly prevents SWI.

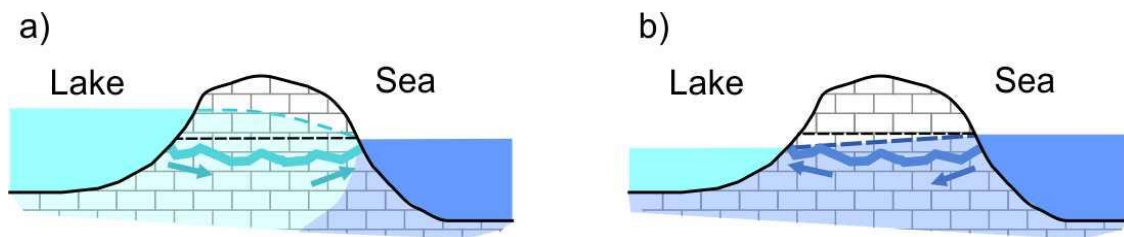


Figure 5. Conceptual model of sea water/fresh water dynamics between the lake and the sea: a) high lake water level during wet season; b) low lake water level during draught periods.

3.1.3 Surface water bodies

Vrana lake with its surface of approx. 30 km² and average depth of 1-2 m is major surface water body in the area. It is separated from the Adriatic Sea by a narrow land stretch. The lake is fed by karstic springs, majority located across Vransko polje area and its edges, and some located immediately at the lake coast (Fig. 3). Springs located upstream in the Vrana polje area form relatively short and intermittently dry watercourses which inflow to the lake. Watercourses are

mostly modified and incorporated in a network of artificial drainage channels, which spreads across the Vrana polje area.

3.1.3 Abstractions/irrigations

Major fresh water karst springs in the Vrana polje area are captured and pumped for the public water supply. During dry season water level in the spring pools (and shallow wells, dug or drilled at spring locations) are pumped below the terrain surface, drying the watercourses downstream. Estimated mean annual pumping rates are approx. 100 l/s, with maximum pumping capacity of 180 l/s.

Groundwater is additionally pumped for irrigation purposes on a number of shallow dug wells in the polje area, typically excavated at intermittent spring locations. Irrigation pumping quantities are mostly uncontrolled. Estimated yearly mean abstraction for irrigation is approx. 200-300 l/s.

Both abstractions for agriculture and drinking water supply are most intensive during relatively dry and hot summer seasons. Pumping of groundwater in the catchment presents additional pressure on the lake system, as it lowers fresh water supply to the lake during draughts.

3.2 Climate change challenge

In accordance with the EEA map, the main expected issues due to CC in the broader area are those described in Fig. 9 for the Mediterranean regions. Main expected changes are increasing temperatures, especially during summer season (Croatian Meteorological and Hydrological service, www.meteo.hr). In addition, draught periods during summer seasons are expected to be more frequent and severe. Increasing temperatures will intensify direct evaporation from the lake, resulting in decreased lake levels in summer periods. This, together with rising trend of the sea level, will enhance SWI to the lake, what presents major threat for the lake ecosystem. Fresh water inflow to the lake during summer season is also expected to lower due to a combination of expected decrease of groundwater recharge within the karstic catchment and increase in demands for water abstractions for irrigation during summer seasons.

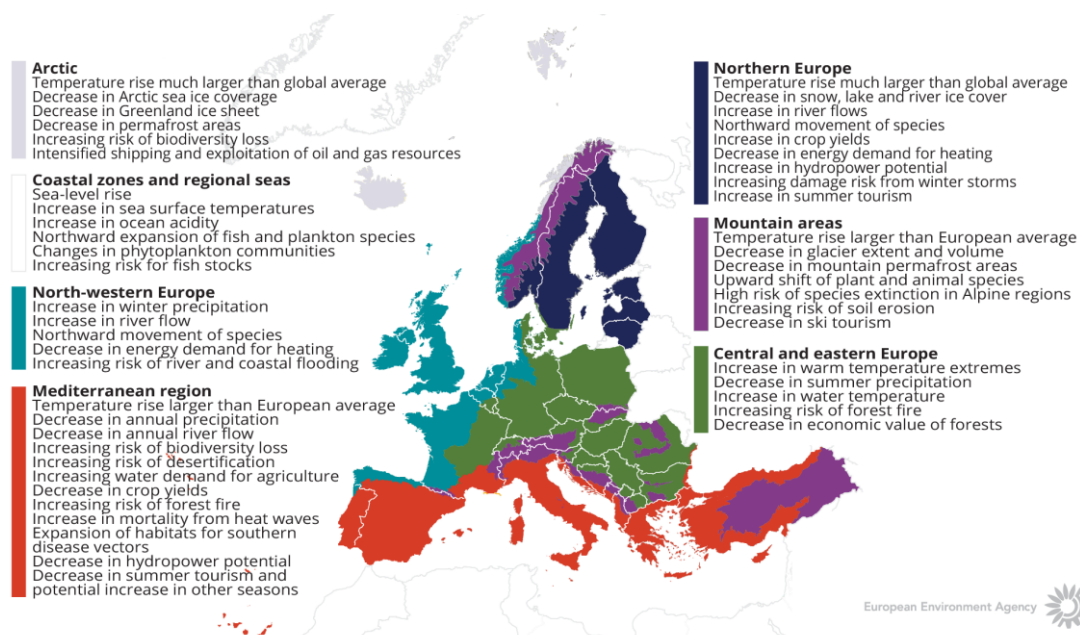


Figure 6. How is climate expected to change in Europe. The European Environment Agency map

4 METHODOLOGY

4.1 Methodology and climate data

4.1.1 Tools/ model description

Assessment of Vrana lake pilot area was done using several lumped modelling softwares/tools: GARDENIA (including EtpTurc module), METRAN and AQUIMOD modelling tools, all included in the TACTIC Toolbox (WP2). Prior to modelling, preliminary analysis of available data time series was done by usage of common statistical softwares (Excel, XLSTAT). Lumped modelling was used to model lake level response to precipitation and temperatures in the catchment, as well as lake water salinity in response to critically low lake levels. Modelling lake levels based on precipitations and temperatures within the catchment as a first step, and lake salinity based on lake levels as a second step enabled analysis how CC future scenarios will affect SWI to the lake. Very heterogeneous nature of karstic subsurface, together with generally scarce data on subsurface parameters, especially regarding karst conduits geometry, prevents usage of spatially distributed groundwater flow models.

GARDENIA is a lumped hydrological model for the simulation of relationships between series of stream or spring flow data at the outlet of a watershed, and/or groundwater level data at an observation well situated in the underlying aquifer and the rainfall received over the corresponding watershed. Withdrawals by pumping groundwater can be considered if necessary. The calibration phase of the model is done automatically by the software under control of the user.

GARDENIA enables to set a hydrological balance for the basin: actual evapotranspiration, runoff, infiltration, recharge. The hydrological balance can be used for the evaluation of natural groundwater recharge of aquifers. GARDENIA gives the extension of river flow, groundwater level or recharge data over a long period for which precipitation and potential evaporation data are known.

EtpTurc module, installed with the GARDENIA, allows the calculation of the potential evapotranspiration at daily, ten-weekly or monthly time steps by using the monthly Turk formula (1961). Calculated PET is further used in GARDENIA together with precipitation as an input file.

AQUIMOD is a simple, lumped-catchment groundwater model. It simulates groundwater level time-series at a point by linking simple algorithms of soil drainage, unsaturated zone flow and groundwater flow. It takes time-series of rainfall and potential evapotranspiration as input, and produces a time-series of groundwater level. Hydrographs of flows through the outlets of the groundwater store are also generated, which can potentially be related to river flow measurements.

METRAN is transfer-noise modelling tool for time series modelling, mostly used with piezometric heads as explained variable and precipitation and reference evaporation as explanatory variables.

Tool can also perform factor analysis of residuals of multiple time series models. Simple parametrization of transfer functions, which allows spatial correlation and interpretation of the physical system.



All described tools were used for modelling Vrana lake level based on historic, and predicted future precipitation and temperature data. METRAN was also used to model lake salinity based on precipitations data. It should be emphasized that described modelling tools are primarily developed for modelling groundwater level instead of surface water level in the lake. However, Vrana lake is situated within the karstic environment, and the lake level is strongly influenced by groundwater recharge from the extensive karstic catchment, as well as by discharge through the permeable subsurface to the sea. Groundwater recharge and discharge are largely happening dispersedly along the lake shores and below lake level, so direct measurements of total inflow and outflow are not available nor possible to measure. Usage of lumped groundwater modelling tools enabled to solve the problem of non-measurable total inflow and outflow by modelling level based on lumped values of precipitation and air temperatures over the catchment, as well as lumped values of subsurface permeability and local base level. However, due to specifics related to modelling lake, i.e. surface water instead of groundwater level, several approximations and unrealistic parameter settings in the modelling process were necessary (GARDENIA and AQUIMOD modelling tools).

4.1.2 Climate data

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5°C global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (a.o. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set were selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).
2. A reference period was selected as 1981 – 2010 and an annual mean temperature was calculated for the reference period.
3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature were calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occurs varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these end members often reflect outliers.



5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

For the analysis in the present pilot the following RCP-GCm combinations were employed:

Table 1. Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	rcp4p5	hadgem2-es
	"Wet"	rcp6p0	noresm1-m
3-degree	"Dry"	rcp4p5	hadgem2-es
	"Wet"	rcp6p0	hadgem2-es

4.2 Tool(s) / Model set-up

After the preliminary time series analysis, lumped modelling tools were used to model lake level dynamics based on precipitations, potential evapotranspiration (PET) and direct evaporation from the lake surface. GARDENIA (developed by BRGM), METRAN (developed by TNO) and AQUIMOD (developed by BGS) lumped modelling tools were tested for modelling purposes. Although all used tools were principally developed for modelling groundwater levels in aquifers, they were tested for modelling lake level, which is in strong connection with the surrounding karst groundwater. Water fluxes to the lake are happening mainly dispersedly through the karst subsurface, and consequently impossible to be directly measured and monitored. This prevents modelling the lake level based on direct inflow, outflow and lake geometry. Lumped groundwater modelling tools were used as an option to overcome this problem. GARDENIA and AQUIMOD models enable level modelling based on precipitations and additionally pumping dynamics, which was used as equivalent process to direct evaporation from the lake. METRAN model is pure transfer function-noise model which can use several input time series in order to model output series. Additionally, manually adjusted simple transfer function was also used to model lake salinity response to the low lake levels.

4.3 Tool(s)/ Model calibration/ test

4.3.1 Observation data

58 years (1961-2018.) of monthly average lake level, sea level, air temperature and relative humidity measurements were available for the historical modelling of the Vrana lake level dynamics. Potential evaporation (PET) was calculated based on Turc method (EtpTurc modelling tool, developed by BRGM). Data of direct evaporation from the lake was available only for two



shorter periods (few years in total). High correlation of monthly evaporation with air temperature enabled calculation of direct evaporation from the lake for the whole period based on air temperature measurements solely.

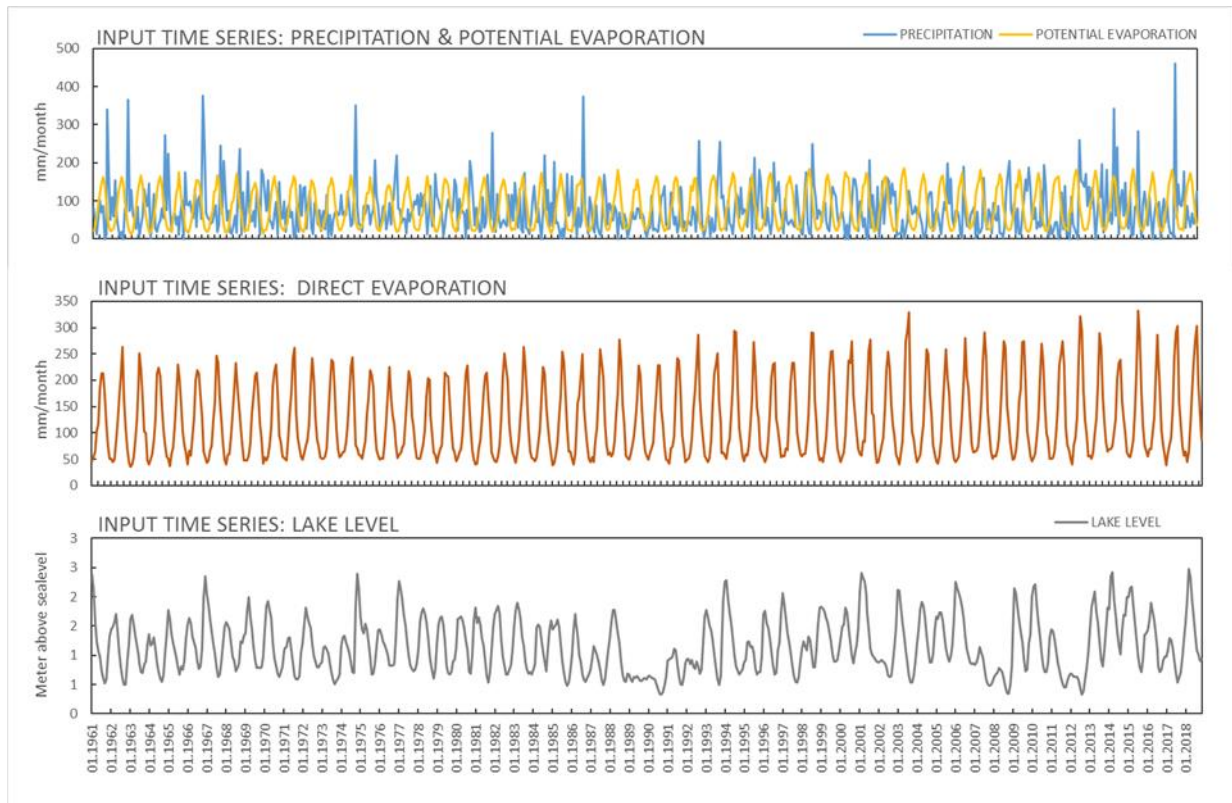


Figure 7. Input time series used for modelling the Vrana lake level dynamics.

4.3.2 Model calibration/adjustment

GARDENIA

GARDENIA modelling tool has a large number of parameters that can be calibrated automatically, or fixed at certain values. Initial calibration attempts, with all parameters non fixed/calibrated ended at unrealistically low effective recharge, accompanied by unrealistically low efficient porosity. Therefore, efficient porosity was fixed at 5%, which is realistic value for the karstified limestone in the area. Base level was also fixed at 0.5 m, as this was average sea level measured close to the Lake, and sea level presents base level for the lake subsurface outflow. Direct lake evaporation was included in the model as pumping. Evaporation was expressed in m^3/s units, converted from monthly evaporation height multiplied by the lake area. GARDENIA model optimize pumping influence on modelled water level by calibration, which enabled efficient inclusion of direct evaporation from the lake surface to the model.

AQUIMOD

Aquimod modelling tool was adjusted in similar way as GARDENIA. The main difference between GARDENIA and AQUIMOD is that AQUIMOD is not able to optimize pumping influence, and therefore inclusion of direct evaporation from the lake in the model resulted with largely exaggerated lowering of the modelled water level. Therefore, direct evaporation could not be included in the model, which resulted in much lower model efficiency comparing to GARDENIA. Therefore, only GARDENIA was used for future climate assessment.

METRAN

Metran transfer-noise modelling tool was used both for modelling lake level based on measured precipitations and air temperatures, and for modelling lake salinity increases based on lake levels. As transfer-noise modelling is purely stochastic model, unlike GARDENIA and AQUIMOD which are physically based lumped models, modelling lake level in METRAN didn't require any approximations and manipulation of input parameters in order to model lake level with groundwater modelling tool. Also, as transfer-noise modelling can be used for modelling any output time serie based on one or more input time series, this model was also used to model lake salinity based on lake level. Prior to modelling lake salinity, critical lake level bellow which lake salinity start to increase was determined. Final model use only lake levels below this threshold value as an input serie.

4.4 Uncertainty

Main source of uncertainty for future CC predictions and scenarios is non-linearity of the processes involved both in lake level response to rainfall and temperature and lake salinity response to low lake levels. All modelling approaches assume linearity of the processes involved in transfer of input to output signal. However, modelled processes are probably not linear, especially lake salinity response in the case of extremely low lake level. Therefore, it can be concluded that presented models are relatively reliable within historically observed conditions, while uncertainty significantly rises in conditions outside them.

5 RESULTS AND CONCLUSIONS

5.1 Performance to historical data

Gardenia model of lake the level (Fig. 8) shows correlation coefficient of 0.83, and NSE of 0.684. However, the greatest importance was attributed to simulation in extremely low lake level conditions, as that are the critical conditions for the lake salinization process. Therefore, model performance is better simulation in drought periods in comparison to the whole modelling period.

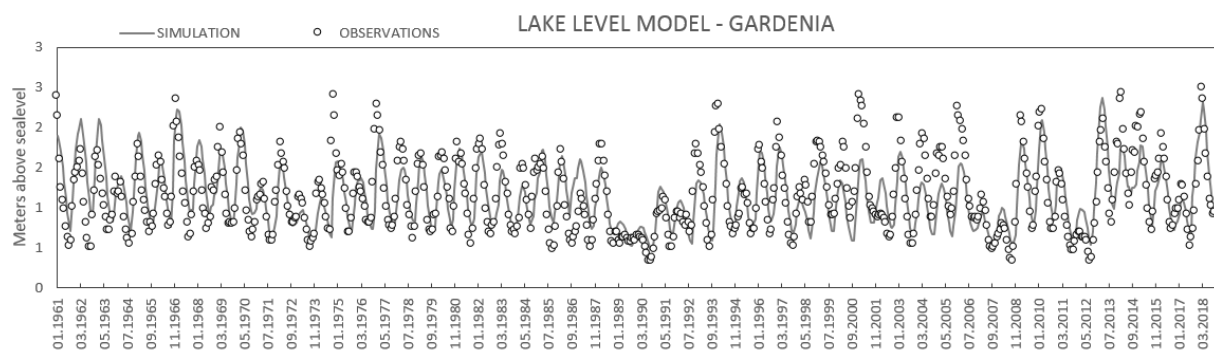


Figure 8. Historical modelling of the Vrana lake level with GARDENIA modelling tool.

As already explained, impossibility to efficiently integrate direct evaporation from the lake surface in the model, AQUIMOD model shows much lower efficiency in comparison to GARDENIA (Fig. 9). NSE of AQUIMOD lake level model is 0.42 wich is not acceptable for reliable lake level predictions. Furthermore, the model was not able to model extremely low lake levels, which are the most important for the lake salinity increases.

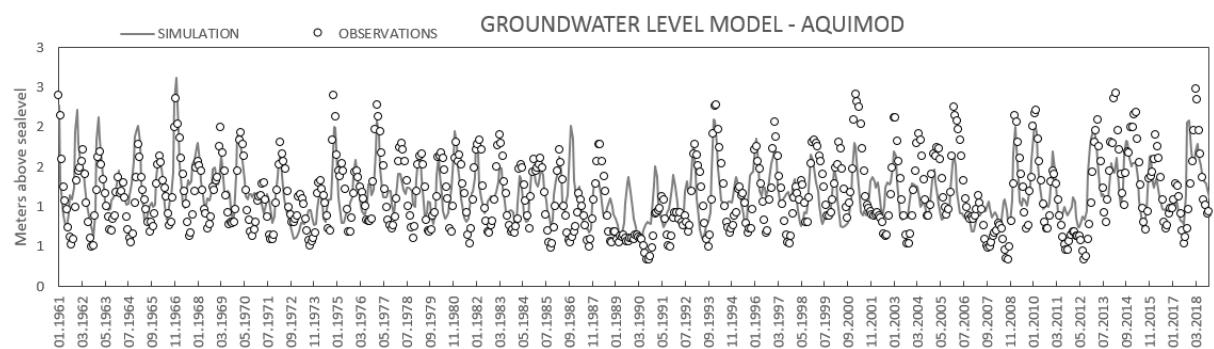


Figure 9. Historical modelling of the Vrana lake level with AQUIMOD modelling tool.

METRAN model shows relatively good efficiency ($R^2 = 0.62$), and it simulate extremely low levels very well (years 2008 & 2012 in Fig. 10). However, model is designed to work in daily timesteps, and montly timesteps (not exactly same timesteps in days) presented some problems. Addittional problem is related to non-applicability of the modelling with METRAN by non-modelling experts (modelling was done by TNO expert), which slightly reduced posibility to more extensive model



modification and development. However, pure stochastic modelling with METRAN is probably the most correct approach to model Vrana lake level, despite slightly better modelling result obtained with GARDENIA tool.

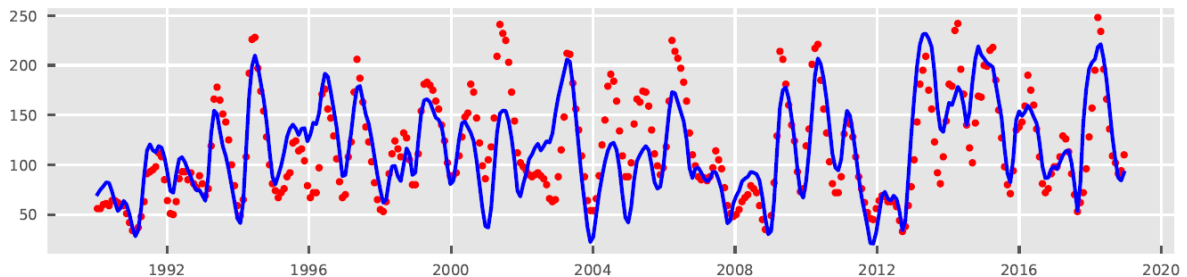


Figure 10. Historical modelling of the Vrana lake level with METRAN modelling tool.

METRAN stochastic transfer-noise model was also possible to use to model the lake salinity with the lake levels as an input. Model performed reasonably well ($R^2 = 0.76$), but it was not able to simulate extremely high salinity values (Fig. 11). If low values below natural lake water salinity background in normal conditions had been substituted by background values, model would show even higher efficiency.

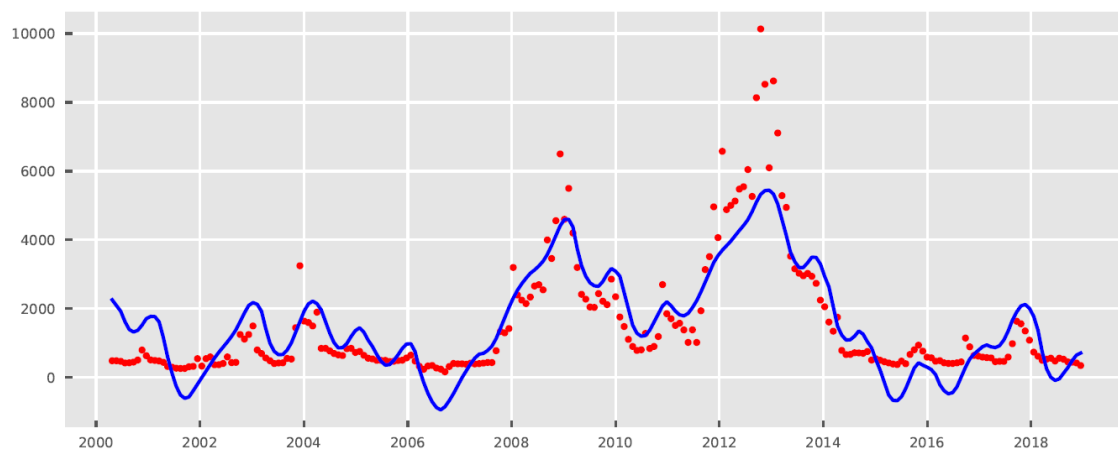


Figure 11. Historical modelling of the Vrana lake salinity with METRAN modelling tool.

Additional approach to model the lake salinity based on lake level was done by using simple transfer function, manually adjusted in excel software. Simple model uses lake levels below threshold value, determined as a critical value below which salinity starts to increase, as an input. The model simulates salinity dynamics very well ($R^2 = 0.78$).

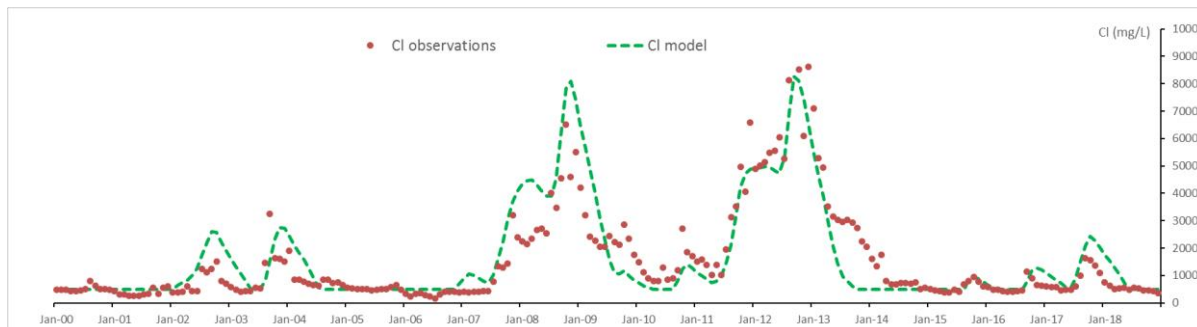


Figure 12. Historical modelling of the Vrana lake salinity with manually calibrated transfer function.

5.2 Results of assessments

Assesment of future CC scenarios, based on four selected scenarios (Table 1) was done with GARDENIA tool, as this tool provided best performance on modelling based on historical observations. Modelled future lake levels based on all four scenarios are considerably lower than historic levels (Figs. 13, 14). The most significant influence on lowering lake levels in GARDENIA model has largely increased direct evaporation from the lake (Fig. 15) due to significantly increased air temperatures in summer months according to all four considered CC scenarios. Moreover, the lake level below determined threshold value of 0.5 m a.s.l., in which case salinity of the lake start to significantly increase, historically appeared only in the cases of severely dry years, while according to the considered future CC scenarios it will appear regularly (Fig. 14). Also, all four CC scenarios ended with relatively close future lake level predictions.

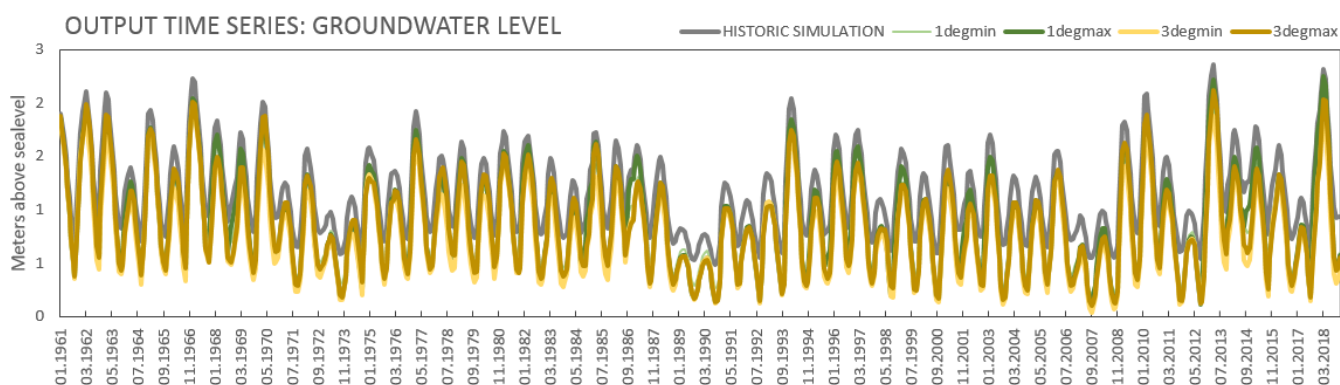


Figure 13. Future projection of the Vrana lake levels for four selected CC scenarios (Table 1), modelled with GARDENIA tool calibrated on historical observations.

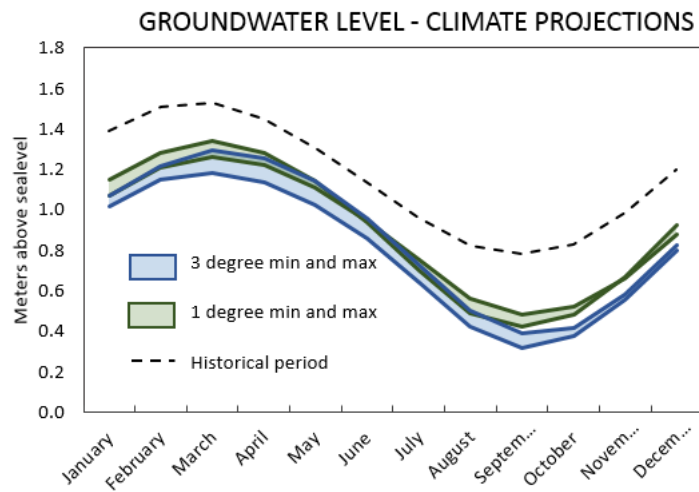


Figure 14. CC projection of the average monthly levels of the Vrana lake, modelled with GARDENIA tool calibrated on historical observations.

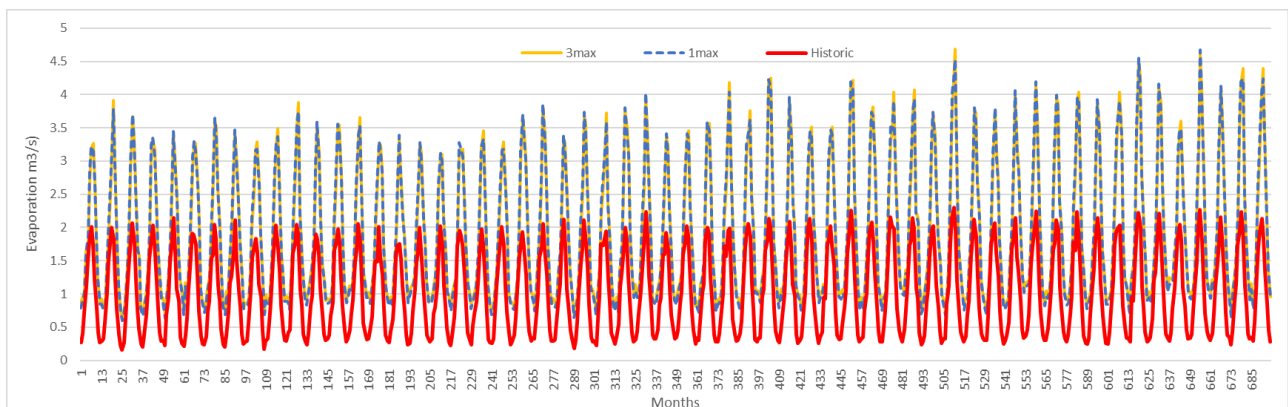


Figure 15. CC projection of direct evaporation from the Vrana lake (m^3/s), based on established relation to air temperatures on historic measurements.

On Figure 16. Future CC projection of the Vrana lake chloride content, based on 3deg max scenario is shown. Future CC projection is modelled by using a simple transfer function. Other future CC scenarios shows similar output, as future levels (input fore chloride model) modelled with GARDENIA (Figs. 13, 14) are relatively close. However, it should be noted that transfer function is linear model, while response of salinity to the low lake levels is probably non-linear. Therefore, modelled future CC salinity results should be regarded as very approximate. Regardless of exact values of expected future salinity increase due to CC, it is certain that generally large increase in the lake salinity is expected, which will result in transition of the system state from mostly fresh water lake with occasional brackish episodes to all the time brackish lagoon with variable salinity (maximum approaching seawater salinity).

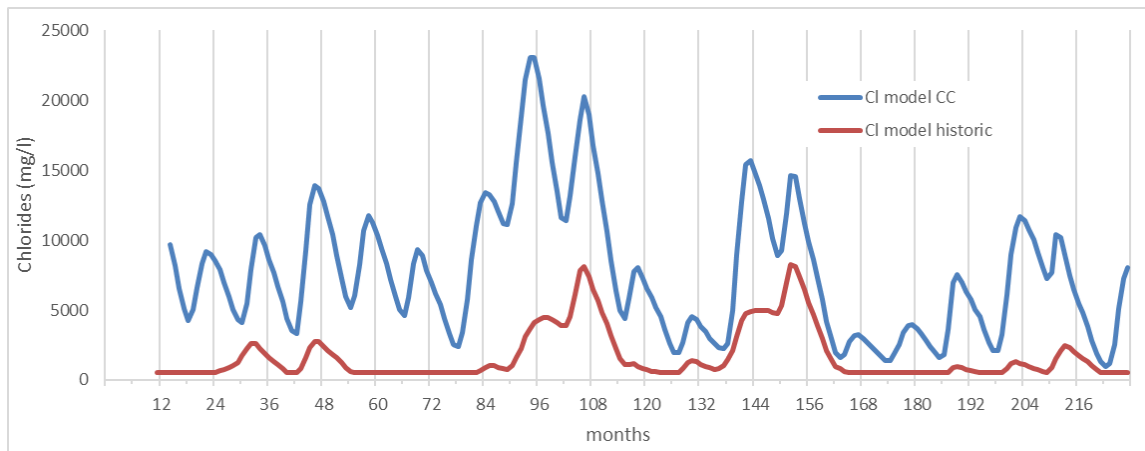


Figure 16. Future projection of the Vrana lake chloride content, modelled by using simple transfer function (Fig. 12).

5.3 Adaptation strategies

Permeable karst terrain separating the lake and the sea enable underground inflow of sea water into the lake during dry periods when lake level drops near (or even below) sea level. Excessive salinization of the lake presents a major threat to the lake ecosystem. The main preventing factor for lake salinization is sufficient lake water level, i.e. sufficient freshwater quantity within the lake. Major sink of the freshwater from the lake during hot and dry summer months is very high evaporation from the lake surface. Due to the large lake volume system has considerable inertia. Therefore, sufficiently high lake level at the beginning of dry period usually prevents subsequent excessive level drop. Also, sufficient inflow of freshwater into the lake during critically low lake levels prevents excessive lake salinization. Consequently, two main factors that can prevent excessive lake salinization are high lake level at the start of dry period, as well as sufficient inflow of fresh water to the lake during dry periods. Adaptation strategies applicable to Vrana lake ecosystem are therefore aimed at achieving these two goals.

Both pumping of groundwater for public water supply and irrigation within the lake catchment lower fresh water inflow to the lake. Therefore, adaptation measures that can be applied and tested include *Water transfer* from neighboring water supply systems and *Integrate water demands in conjunctive systems*. The local water supply system is already connected to the neighboring systems, but due to additional costs, water from other system is used only in the cases of water shortage from local sources. Nevertheless, effects of possible water transfer on reducing lake salinization should be analyzed in more detail. In addition, *improved planning, control and resources allocation* between public water supply, agriculture and freshwater depending ecosystem should be applied. *Improved monitoring and early warning system* should be established in order to anticipate conditions leading to excessive lake salinization, and start applying the *Water transfer* measures.

Additional measures aimed at insuring high water level before start of the dry season include *Create/restore wetlands*, which were historically converted to agricultural lands by digging



artificial evacuation channel for high lake waters. The channel can be partially blocked and actively managed in future, but some of agriculture lands in vicinity of the lake would probably be occasionally drowned (restoration of the wetlands) in order to have sufficiently high lake level in dry season.

Table 2. Adaptation strategies that applicable to Vrana lake system.

DEMAND
REDUCING ENVIROMENTAL IMPACTS
Increase water allocation for ecosystems
Create/restore wetlands
OFFER
COMPLEMENTARY RESOURCES
Water transfer
MIXED (improving resilience & adaptation capacity)
Improve planning, control and resources allocation
Improved monitoring and early warning
Integrate water demands in conjunctive systems

6 REFERENCES

Josip Rubinić & Ana Katalinić (2014) Water regime of Vrana Lake in Dalmatia (Croatia): changes, risks and problems, Hydrological Sciences Journal, 59:10, 1908-1924, DOI: 10.1080/02626667.2014.946417

Croatian water management (1994): Vrana lake – reservoir construction. Preliminary environmental impact study (In Croatian). Unpublished expert report.

Stroj, A. (2012): Vrana lake – hydrogeological study (In Croatian). Croatian Geological survey, unpublished expert report.

Zaninović. K., et al. (2008): Climate atlas of Croatia 1961-1990., 1971-2000 (In Croatian). Croatian Meteorological and Hydrological Service, Zagreb.