INCOME Water Care

Improved Management of Contaminated Aquifers by Integration of Source Tracking, Monitoring Tools and Decision Strategies

A.3.2. Numerical hydrological modelling

Final report

Geological Survey of Slovenia

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1 Introduction

The present report presents activities and results of the action A.3.2. Numerical hydrological modelling, performed by Geological Survey of Slovenia within the project INCOME (LIFE07 ENV/SLO/000725). The main objective of the project is long-term effective management of aquifers and preservation of the quality of these water resources for future generations. The project INCOME is co-financed by the European Commission, Municipality of Ljubljana and the Ministry of the Environment and Spatial Planning.

The objective of the action A.3.2 was to construct reliable physically-based hydrological model, based on groundwater/surface water integrated modelling system which will enable accurate simulation of the groundwater dynamics and transport of pollutants in the aquifer. Previous models, also the most advanced one, constructed in year 2000 (Kristensen et al., 2000) and updated in 2005 (Janža et al., 2005), showed big uncertainty in the simulation of occurred TCE pollution transport in the aquifer (Janža et al., 2005). Therefore special attention was paid to the transport modelling.

Hydrological conditions in the model area are characterised by interaction between surface and groundwater, therefore modelling system which can take into account exchange of groundwater and surface water is recommended. MIKE SHE enables integrated modelling of groundwater, surface water, recharge and evapotranspiration. Fully coupling with MIKE 11 that has advanced description of river processes represents one of the most advanced hydrological modelling tools. In the project INCOME integrated MIKE SHE/MIKE 11 (v. 2011) was implemented. The constructed model covers time period from 1984 to 2009.

2 Code description

MIKE SHE is a deterministic, generally physically based, and distributed modelling system that is able to describe the most important flow processes in the land phase of the hydrological cycle (DHI, 2005; Graham and Butts, 2005). It can be linked with the river hydraulic model MIKE 11 (DHI, 2004), which makes an integrated surface water and groundwater modelling system.

The code is divided into components or modules, each dealing with separate parts of the hydrological cycle. The modules can be used separately or integrated, which is assured by the exchange of water between the modules.

Simulation of actual evapotranspiration *Ea* in the model is based on the Kristensen and Jensen model (Kristensen and Jensen, 1975). It uses crop characteristics, land-use, potential evapotranspiration *Ep*, and empirical parameters as input data.

The snow melt process in the model is calculated on the basis of a simple degree-day method, which only requires air temperature *T*, a degree-day factor *DDF* and a threshold melting temperature *To* as input. If the air temperature is above the threshold melting temperature, the snow will melt at the rate specified by a degree-day factor (the amount of snow that melts per day for every degree the air temperature is above the threshold melting temperature).

The water flow in the unsaturated zone is described in MIKE SHE by the one-dimensional Richards' equation (Richards, 1931). This requires information about two hydraulic functions, hydraulic conductivity function (partially saturated hydraulic conductivity versus water content) and the soil moisture retention curve (capillary pressure versus water content). Bypass (macropore) flow is the part of infiltrated water that is routed directly to the groundwater table. It is described by a simple empirical function:

$$Q_{bypass} = P_N \cdot byp\sqrt{\alpha_{10}\beta_{50}} \ \text{(mm/h)}$$

where P_N (mm/h) is the net rainfall rate, *byp* (-) is the maximum fraction of the net rainfall which can bypass the matrix (under wet conditions), and α_{10} (-) and β_{50} (-) are variables between 0 and 1, reducing the total bypass fraction under more dry conditions. The variables α_{10} and β_{50} depend on the actual water contents of the unsaturated zone 10 cm and 50 cm below the ground surface. Calculation of α10 and β50 is made internally by MIKE SHE, using linear relationship. Variables vary between 0 and 1, when the water content is between user defined θ_1 and θ_2. If the water content is below θ_2, α_{10} and β_{50} equal 0. If the water content is above θ_1, α_{10} and β_{50} equal 1.

Groundwater flow in the saturated zone is simulated by solving the governing equation for three-dimensional flow:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q_e=S_s\frac{\partial h}{\partial t}$$

where K_{xx}, K_{yy} and K_{zz} (m/s) are hydraulic conductivity along *x*, *y*, *z* axes; *h* (m) is the hydraulic head; Q_e (s^{-1}) is the volumetric flux per unit volume representing source/sink term and S_S (m^{-1}) is the specific storage coefficient. The equation is solved numerically by an iterative implicit finite difference technique.

3 Model construction

The basis for the model were made within the project Water Resources Management Model for Ljubljansko Polje and Ljubljansko Barje, financed by VO-KA public utility and performed by DHI and partners (Kristensen et al., 2000).

Conceptual model used for construction of hydrological model is described by Janža et al. (2011). Larger changes were made for Barje model that is based on new conceptual model. In the model new approach of connecting karst area (Krimsko-Mokriško pogorje) with the alluvial aquifer was implemented and according to the new borehole data and well logging data (see Janža et al., 2011) adjusted layers boundaries.

3.1 Model area

Model area is defined by recharge area of Ljubljasko polje and Ljubljansko barje aquifers - main groundwater resources exploited for the public water supply of the capital city Ljubljana. Due to the different hydrogeological conditions and limited exchange of water between them, they were treated separately by two models (Figure 1).

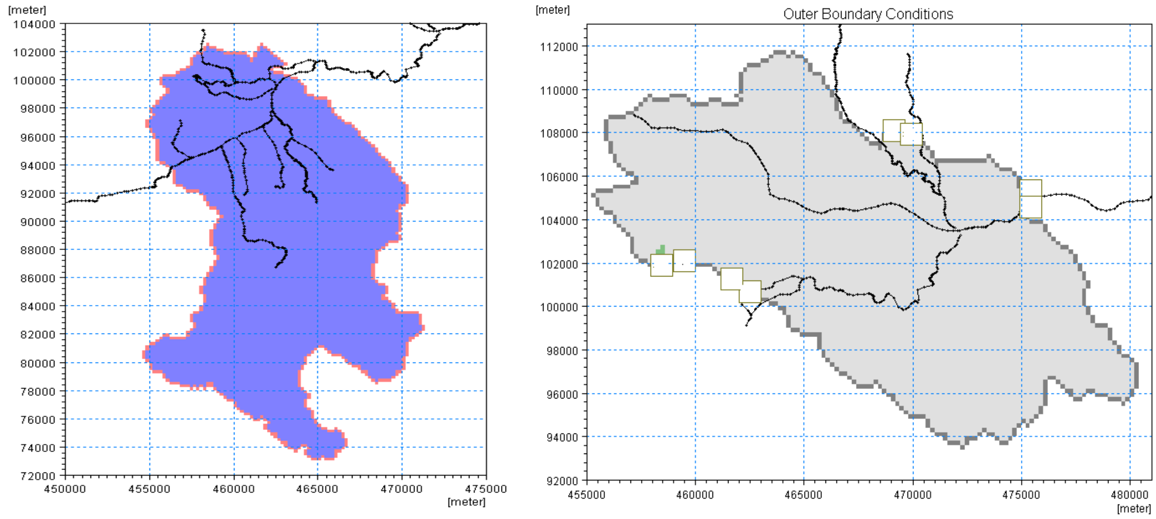

Figure 1: Extent of integrated MIKE SHE/MIKE 11 model areas (left: Barje, right Ljubljansko polje).

3.2 MIKE SHE boundaries

The boundaries of the model were adopted from conceptual model (Kristensen, 2000). Improvements were implemented in the SW part of Ljubljansko polje, in area between Ljubljanski grad and Rožnik and between Šišenski hrib and Šentviški hrib, boundary of the aquifer is not closed and inflow into the aquifer is assumed. In order to achieve more realistic boundary conditions, time dependent head boundary was introduced. Defined oscillations of the heads in the boundaries are based groundwater level measurements in the closest observation wells. For the boundary between Šišenski hrib and Šentviški hrib measured data in observation well OP-12 and for the boundary between Ljubljanski grad and Rožnik measured data in KT-3/08 were used (Figure 2). Due to the short observation period in those wells, head oscillations in the boundaries were generated with the use of Šujica-Razori stream discharge that covers the whole modelling period. Relation between stream discharge and groundwater levels (GWL) in the observation wells was determined and later used to calculate GWL in the boundaries for the whole modelling period.

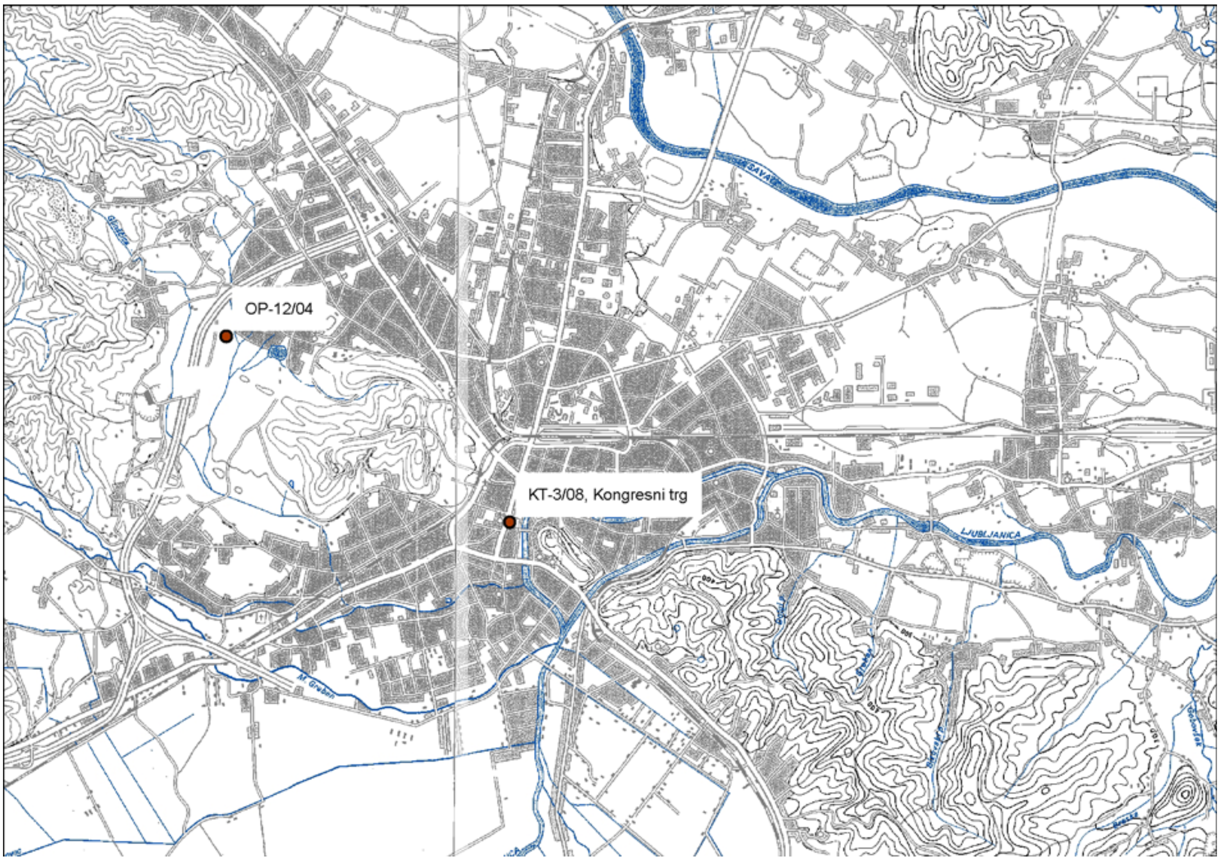

Figure 2: Locations of the observation wells OP-12 and KT-3/08.

Correlation coefficient between observed and generated groundwater levels in OP-12 observation well for time period 1. 1. 2005 – 31. 12. 2009 is R=0.82 (Figure 3) and for the case of observation well KT-3 for time period 9. 10. 2009 – 31. 12. 2009 R=0.88 (Figure 4).

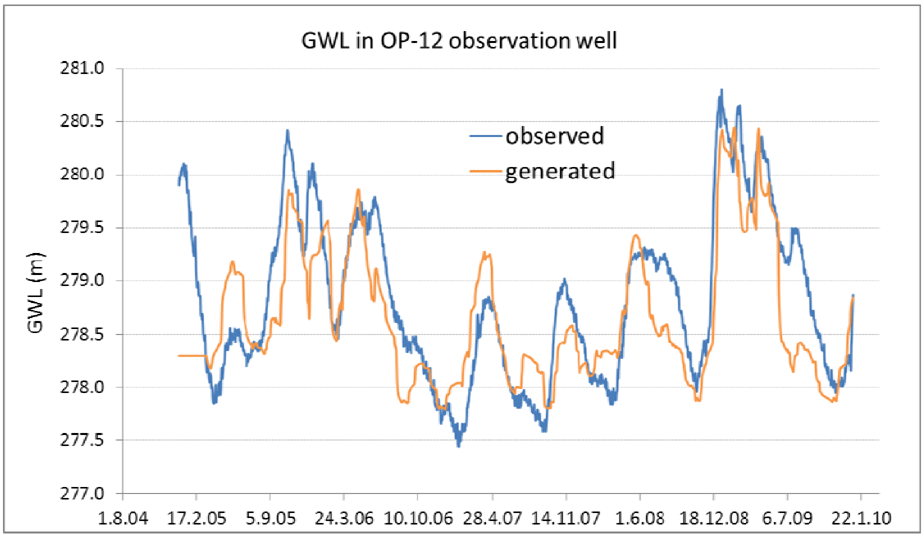

Figure 3: Comparison of observed and generated GWL in OP-12 observation well.

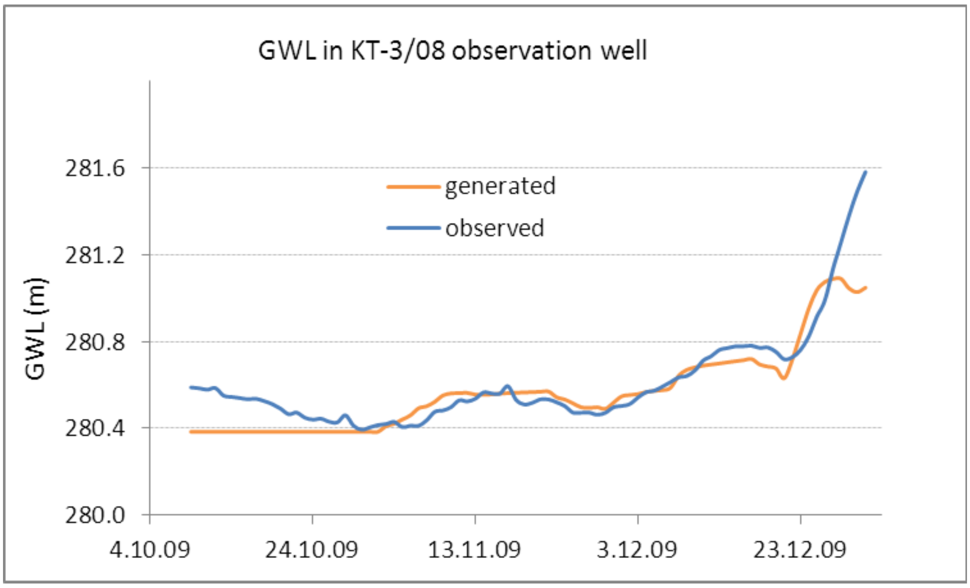

Figure 4: Comparison of observed and generated GWL in KT-3/08 observation well.

3.3 River model

3.3.1 MIKE 11 boundaries

For Barje surface water model (MIKE 11) new boundary conditions were created - NAM models for Gradaščica and Ljubljanica which cover period from 1984-2009.

NAM model for Gradaščica was constructed for catchment upstream from Dvor measurement station (80 km^2), where discharge measurements are available. They were used for model calibration (1997-2006) with autocalibration method (Figure 5). Later the NAM model was extended to Bokalci measurement station which is a boundary condition (inflow) to MIKE 11 model and covers 110 km^2 catchment. For the point source inflow to Gradaščica from Horjulščica (Šujica) at Razori discharge measurements at this station were implemented.

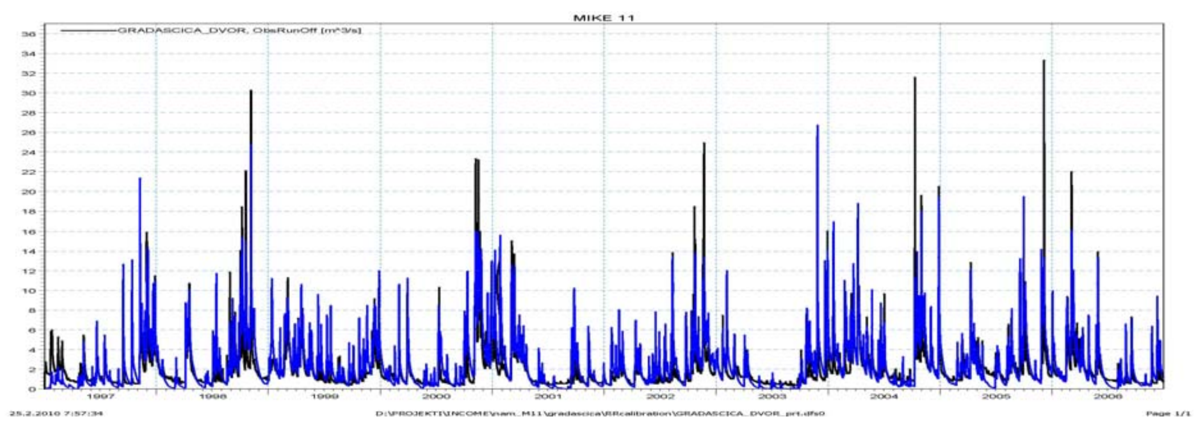

Figure 5: Comparison of simulated (blue line) and observed (black line) discharges at Dvori (Gradaščica) measurement station.

For the inflow of Ljubljanica river at the boundary of MSHE Barje model new NAM model was constructed that uses the same approach as existing model. NAM model was calibrated against Ljubljanica discharge at Moste measurement station (Figure 6) taking into acount all catchmement in the size of 1762 km^2. After the autocalibration the size of the catchment was reduced to 1510 km^2 and modeled discharge was used as point source inflow to Ljubljanica at the entrance to the MSHE Barje model. Equaly weighted (0.33) rainfall data from Vrhnika, Črna vas and Sveti Vid and temperature and potential evapotranspiration data from Bežigrad meteorological station were used.

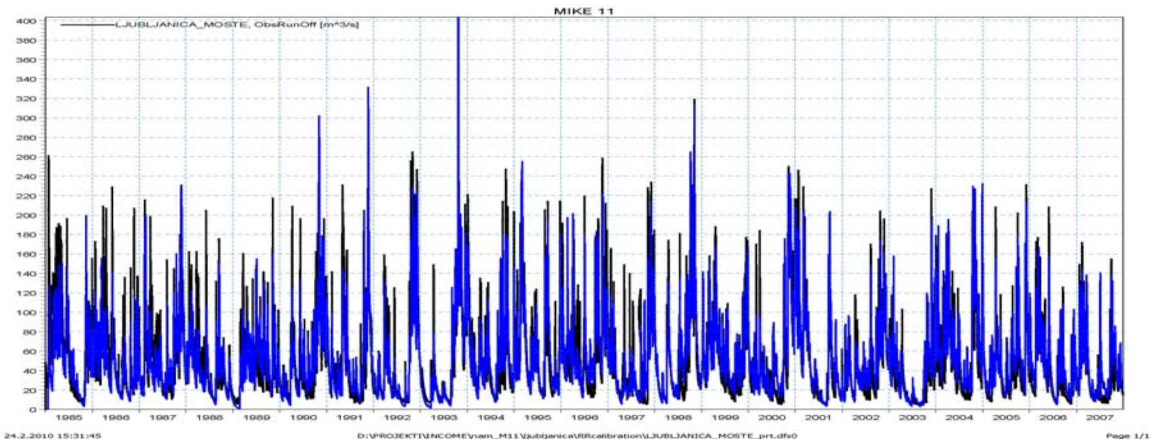

Figure 6: Comparison of simulated (blue line) and observed (black line) discharges at Moste (Ljubljanica) measurement station.

For the Ljubljansko polje model for the catchments Rača, Pšata, Kamniška Bistrica and Gameljščica NAM models, constructed in the updates of the existing models (Janža, 2005) were used.

3.3.2 River cross sections

The bed topography of surface streams in the model is defined with cross sections. The existing cross sections were updated with new set of data.

For river Sava 21 cross sections which were made in year 1997 were used. Data was received from Environmental Agency of Slovenia in Auto Cad "dwg" format (Figure 7). Because some of received data were already implemented in the model (Kristensen, 2000), comparison of locations and visual inspection of new and existing cross sections was done. Out of 21 cross sections, 6 cross sections were new and 15 were already in the model.

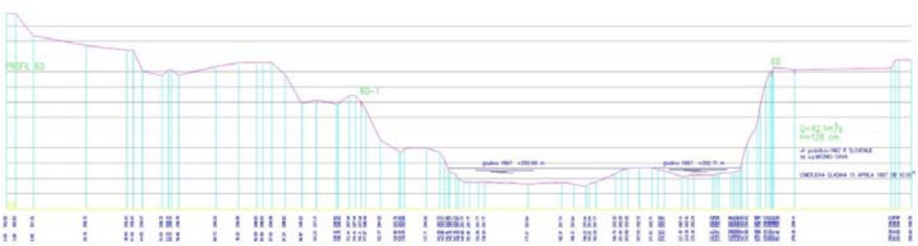

Figure 7: Received cross section in Auto Cad.

New cross sections were exported from Auto Cad file to Excel spread sheet and converted in form which was implemented in MIKE 11 model. Coordinates of initial and final points of cross sections were obtained from the map of cross sections in Arc Map software.

For the update of bed topography of surface streams in Barje LIDAR digital elevation model (DEM) and cross sections, received From Municipality IG were used (Figure 8).

For Iška river 138 cross sections were processed, for Iščica river 52 cross sections, for stream Mliščica 5 cross sections, for stream Draščica 29 cross sections, for stream Smoligojnik 13 cross sections, for stream Želimeljščica 19 cross sections, for stream Dremavščica 24 cross sections and for stream Strajanov breg 21 cross sections were processed. Procedure of exporting cross section from Auto Cad into input form for MIKE 11 was same as described for Sava river.

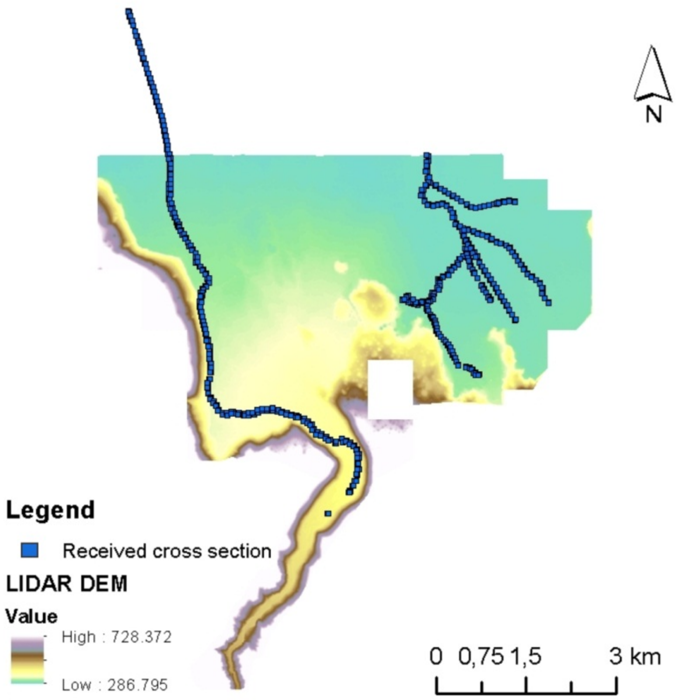

Figure 8: LIDAR and Cross sections.

In the areas where no cross sections were available, LIDAR DEM was used to define shape of the channels. For river Iška 66 cross sections were defined this way.

In the area not covered with LIDAR data Digital Elevation Model, cell size 5 m, was used. For river Iška created 73 cross sections, for river Iščica 58 cross sections and for artificial channels at Barje 51 cross sections were defined this way (Figure 9).

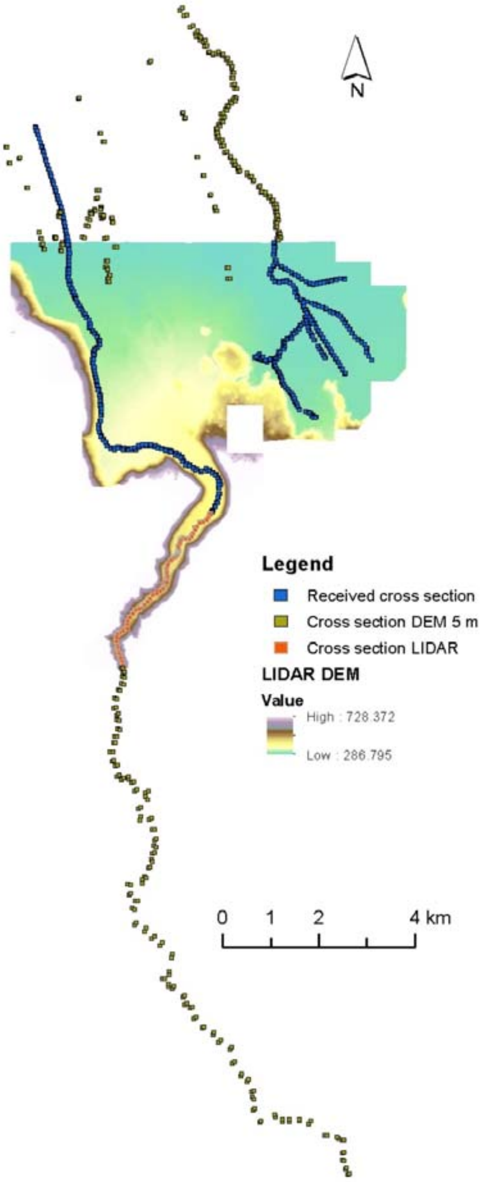

Figure 9: Map where cross section from LIDAR or DEM 5m was made.

Procedure for extracting cross sections of channels from LIDAR DEM or DEM 5 m was made in Arc Map software. Cross sections were defined with polyline (Figure 10) which were converted into 3D polylines to which elevation data from DEM were assigned (Figure 11).

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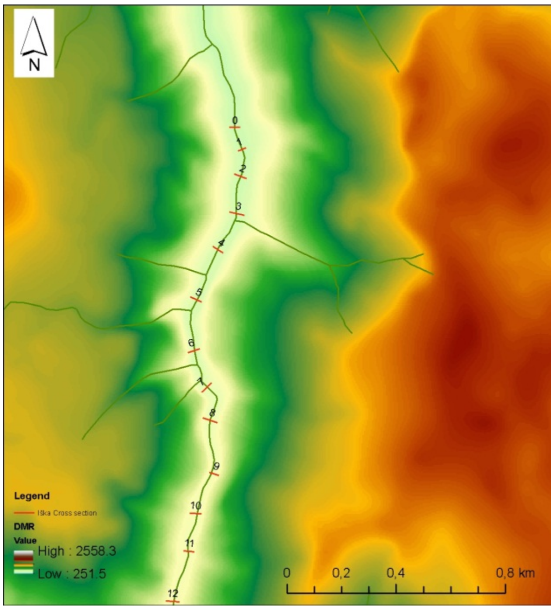


Figure 10: Polylines over the stream.

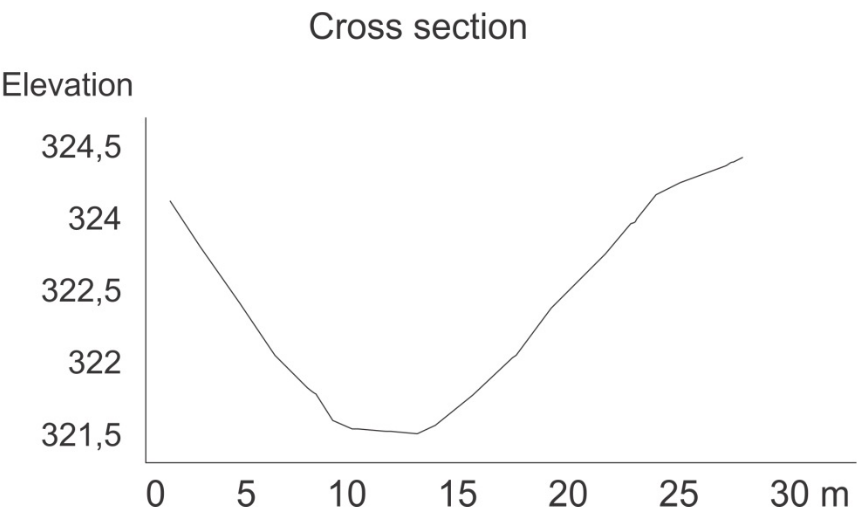


Figure 11: Cross section in Arc Map from 3D polyline.

3.4 Ljubljansko polje bedrock

Since the last interpretation of pre-quaternary bedrock of the Ljubljansko polje aquifer, new boreholes have been drilled which enabled update of the bedrock (lower boundary condition) in the hydrological model. Data set consist of archive data and new data from the boreholes which were drilled within the INCOME project. It contains basic borehole information (location, surface and bedrock altitude. All the data has been compiled in Excel spreadsheet and imported into Arc Map software (Figure 12).

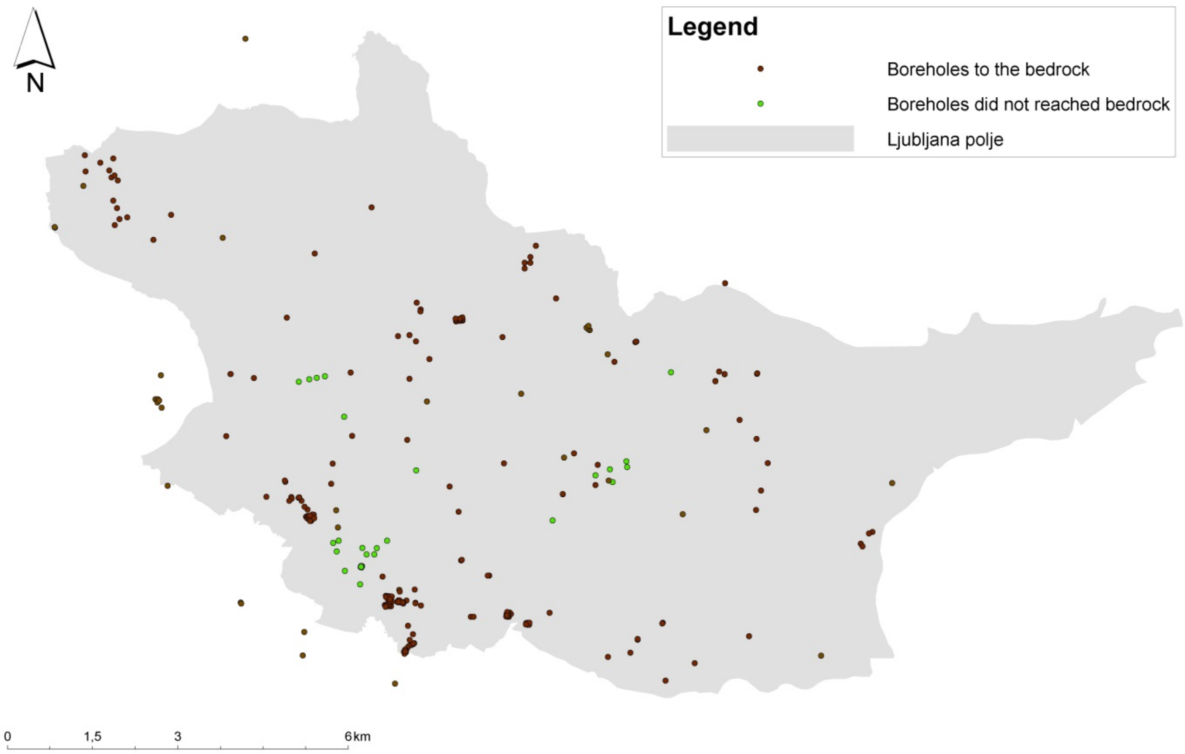


Figure 12: Locations of the used boreholes.

Entire correction procedure of pre-quaternary bedrock was done with the use of Arc Map software. As an input we used existing raster with cell size 200 m, which contains pre-quaternary bedrock elevation data and boreholes depth data. Pre-quaternary bedrock was compared with borehole data and at the areas of inconsistency manuall correction was done. By the interpretation also boreholes deeper than 50 m, which did not reach the bedrock were taken into account. After the manual correction digitalization of contours was done (Figure 13).

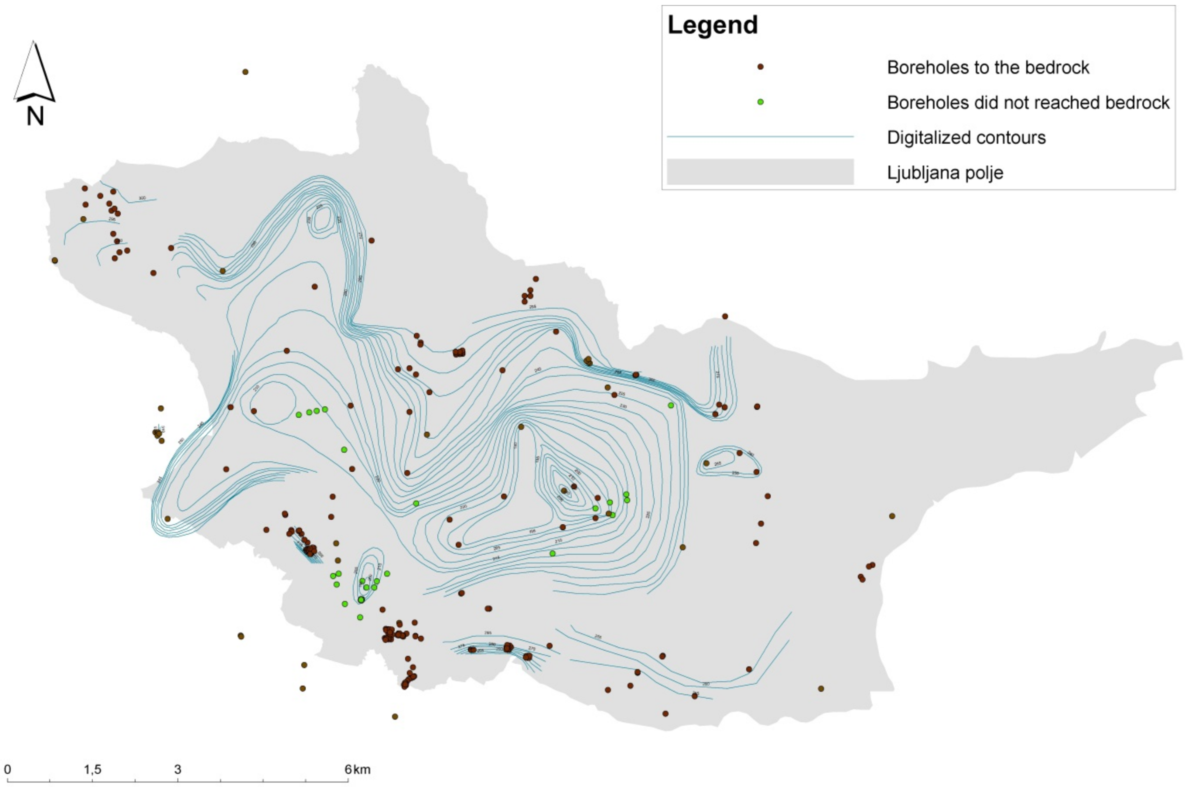


Figure 13: Digitalized contours.

To compile corrected contours with existing bedrock raster data, both files were transformed into point information layer. Points from existing raster have been selected at the area with 200 m buffer, where they intersected with points from corrected contours. Selected points have been deleted. Filtered points were joined and new raster information layer with cell size 25 m was created which contains information of pre-quaternary bedrock elevation (Figure 14). Interpolation method ordinary kriging was used. The difference between old and new pre-quaternary bedrock raster data could be seen in Figure 15.

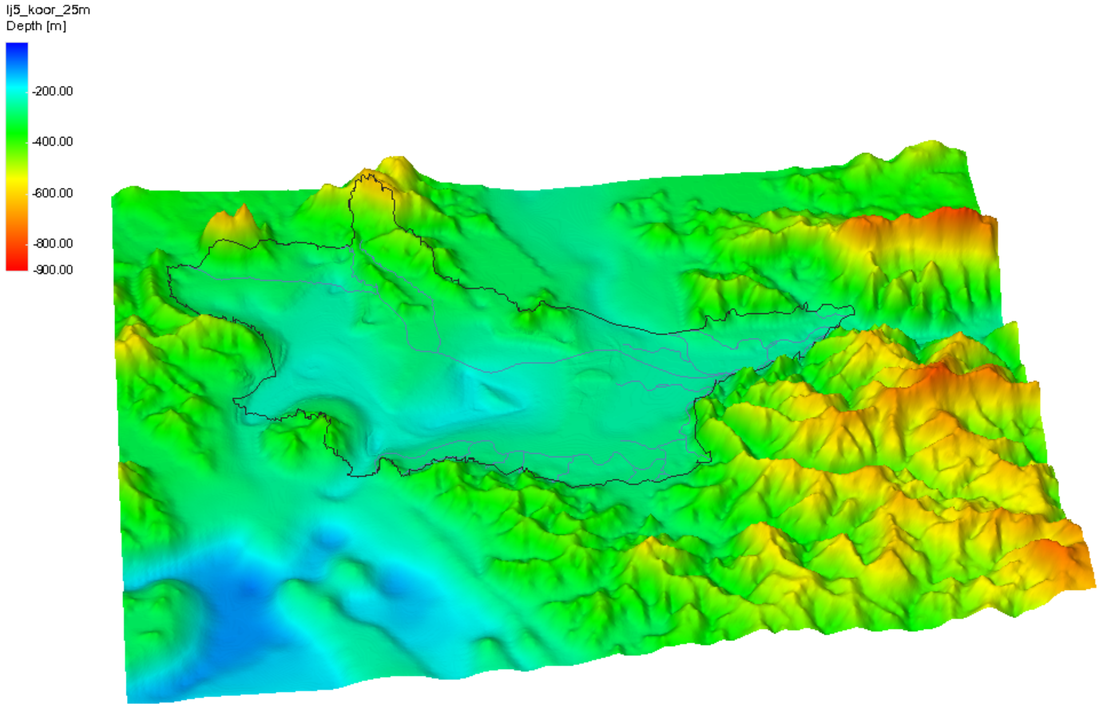


Figure 14: New interpolated pre-aquaternary bedrock of Ljubljansko polje aquifer, 3D view.

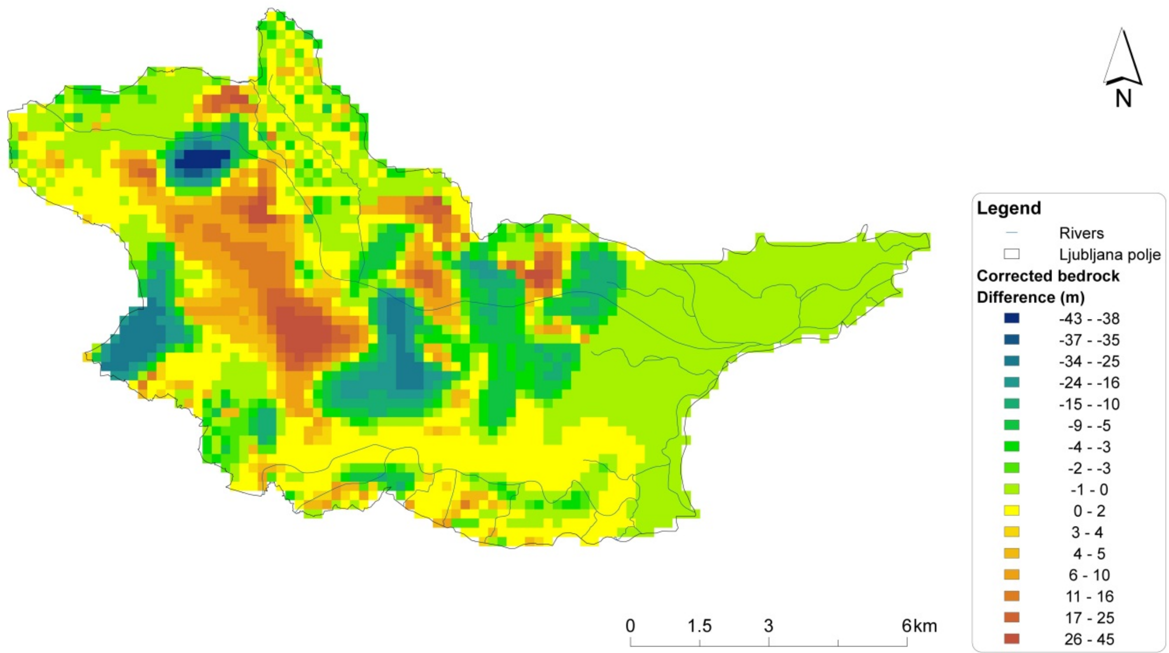


Figure 15: Difference between old and new pre-quaternary bedrock raster data.

3.5 Data

3.5.1 Abstraction

Abstraction data for the update (2005 – 2010 for Polje and 1998 – 2010 for Barje) were received from VO-KA. For abstractions in industrial wells for the period after the year 2004 no reliable were available, therefore last available pumping amounts from 2003 were used. For some industrial wells (Union-3,4,6,8; Kličevo karton v-1, v-2, Helios Domžale v-1, v-2; TE Tol v-1, v-2, P-1, P-2; Belinka B1, B2L, B2D, B3-V1, B3-V2, B3-V3) yearly abstraction amounts were available. They were converted into daily amounts and used in the modelling.

3.5.2 Groundwater level measurements data

Groundwater level measurement data were received from VO-KA and were combined with existing data into one database for time period 1984 – 2010. In the INCOME area there are 130 groundwater monitoring stations which were included into modelling (Figure 16).

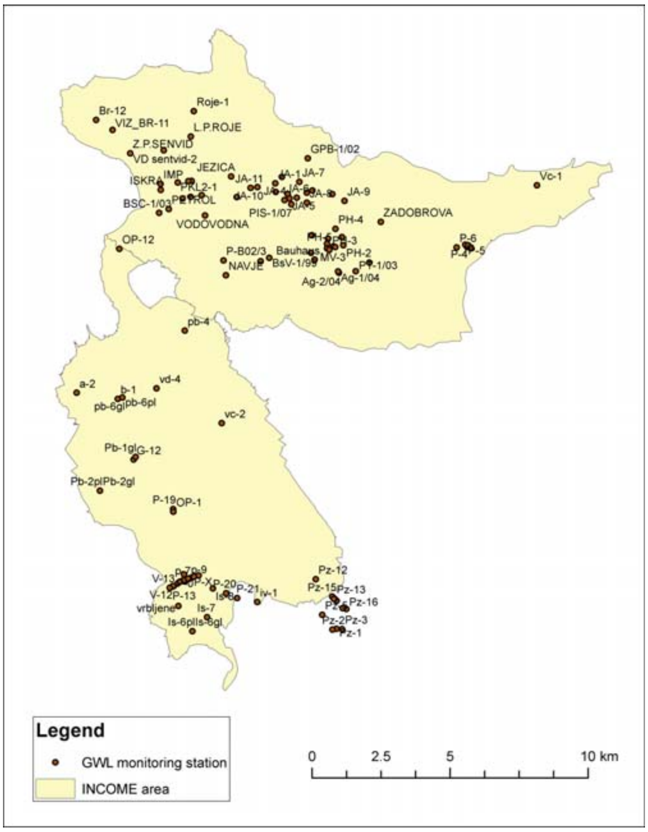


Figure 16: Groundwater level measurement locations.

3.5.3 Hydrological data

Hydrological data are used for boundary conditions of the river model (MIKE 11) and for the validation of the model. Data for the previous modelling period were combined with new one which makes all available hydrological time series for the period 1984 – 2009. Data were provided by the Environmental Agency of the Republic of Slovenia.

3.5.4 Meteorological data

The driving force in a hydrological model is the precipitation in terms of rain and snow. Precipitation data on daily basis from 9 stations distributed in the model area was collected and corrected for wind and wetting effects. Gaps in the time series were filled with data from nearby stations taken the differences in annual precipitation into account. The precipitation was distributed over the Ljubljansko polje using simple Thiessen polygon method (Kristensen et al., 2000). Due to complex spatial pattern of distribution of meteorological variables in Barje model area, grid-based interpolation method, described in the following chapters, was implemented. Meteorological data cover the period 1984 – 2009.

3.5.5 Spatial Interpolation of meteorological data in model area of Ljubljansko Barje area

Spatial interpolation of precipitation daily time series in the Ljubljansko Barje model area was made, while the amount of precipitation varies in the area. Spatial interpolation of temperature daily time series is not so demanding while primary dependence of temperature is on altitude. For the spatial interpolation of meteorological time series a module of the grid-based **Wa**ter Flow and Balance **Si**mulation **M**odel WaSiM-ETH (Schulla et al., 2007) was chosen. Model WaSim-ETH provides 11 various methods for interpolation of climate data. For interpolation of precipitation in high mountain areas Schulla et al. (2007) suggested ID 11 method, which is a linear combination of IDW (Inverse Distance Interpolation) and EDRINT (Elevation Dependent Regression with Internal Processing). Method is suitable for data that depend only partly on elevation, e.g. precipitation in high mountain areas. Linear combination of IDW and EDRINT method described Schulla (2009).

Spatial interpolation of meteorological data in Ljubljansko Barje was performed for the period from 1983 to 2011.

3.5.5.1 Method

Method ID 11 was used, module in model WaSim-ETH, for spatial interpolation of meteorological time series. It is most suitable model for high mountain areas (Schulla et al., 2007). Method enables a linear combination of IDW and EDRINT methods.

3.5.5.1.1 Inverse distance weighting (IDW)

IDW interpolation method takes into account all stations within a specified search. If all stations have identical values, the interpolation is skipped and the constant value is taken instead. The interpolation result is the sum of all contributing weighted station data. WaSiM-ETH offers the possibility to change some parameters: a maximum distance d_{max} as well as two parameters specifying the anisotropy (slope of the anisotropy-ellipsis, ratio short to long axis of anisotropy-ellipsis) (Schulla et al., 2007).

The interpolation result is the sum of all contributing station data (Schulla et al., 2007):

$$\acute{z}(u) = \sum_j (w_j \cdot z(u_j))$$

with $w_j = \frac{1}{d(u,u_j)^p} \frac{1}{C}$ and $C = \sum_j \frac{1}{d(u,u_j)^p}$ follows $\sum_j w_j = 1.0$.

ź(u) …. interpolated value at location u;

w_j …… weight of the observed value at station j;

$z(u_j)$ … observed value at station j;

$d(u,u_j)$ distance to the station j;

p ……. Weighting power of the inverse distance (between 1 and 3, 2 is recommended).

3.5.5.1.2 Elevation dependent regression (EDR)

Method interpolation result is estimated using the altitude dependence of a variable. Elevation dependent regression method is estimated using the elevation dependence of a variable. If there are data of more than three stations available, an additional trend surface is estimated in order to correct shifts in the horizontal directions. The trend surface uses only the residuals of the elevation dependent regression. The altitudinal gradients can be given for at maximum three variable ranges separated by (lower and upper) inversion from each other (Schulla et al., 2007). For the Ljubljansko Barje model area only one inversion is determined, where cross section of both regressions is between lower and upper (theoretical) inversion.

The interpolation of specified spot in the model is done by (Schulla et al., 2007):

$$T(h_m) = a_{r,j} + b_{r,j} \cdot h_m$$

h_m …… altitude (m above sea level),

T …… variable (temperature, precipitation),

i …….. index for lower, medium resp. upper regression (i=1..3),

$a_{r,j}$,$b_{r,j}$ parameter of the respective regression,

with $a_{r,j}$ (for data of more than 3 stations):

$$a_{r,j} = u_r + \nu_1 x_r + \nu_2 y_r$$

$a_{r,j}$ …………….. trend surface through the residuals of the regression,

u_r, v_1, v_2 ……. regression parameter,

x_r, y_r ………….. coordiantes.

3.5.5.1.3 Linear combination of IDW and EDR

Method (method 11) is a linear combination of method IDW and EDR, using internal regression preprocessing. WaSim-ETH uses prepared data time series in defined textual format and control file (defined textual format) with all parameters needed for interpolation.

In control file some important parameters have to be set. Regression coefficients (Schulla et al., 2007):

- 1st parameter: lower inversion in m
- 2nd parameter: upper inversion in m
- 3rd parameter: tolerance
- 4th parameter: bolean value, 0 for strictly separating both elevation ranges, 1 for following an overlap
- 5th parameter: minimum elevation spread for the stations in one elevation range to be really used for a linear regression.

All five parameters are set to values, which enables only one linear regression.

For the combination of IDW and EDR interpolation also relative weight for IDW, maximal distance of station, slope of the anisotropy ellipsis and ration short to long axis of anisotropy ellipsis is necessary. In the interpolation, IDW weight 0.5 was chosen (0.5 for IDW and 0.5 for EDR). Slope of the anisotropy ellipsis is 0 and ration short to long axis of anisotropy ellipsis is 1.

3.5.5.2 Meteorological data

Meteorological data of daily precipitation and air temperature were provided by Environmental Agency of the Republic of Slovenia (ARSO). Measured time series of meteorological data, used in the interpolation model, are for the period from the year 1983 to 2011.

3.5.5.2.1 Measured meteorological data

For the spatial interpolation in Ljubljansko Barje model area, we chose 11 precipitation station (Table 1) and 3 temperature stations (Table 2). Measured temperature data are average daily temperatures of air on 2 meters height in °C. Measured precipitation data are 24 hour sum of precipitation at 7 am in mm.

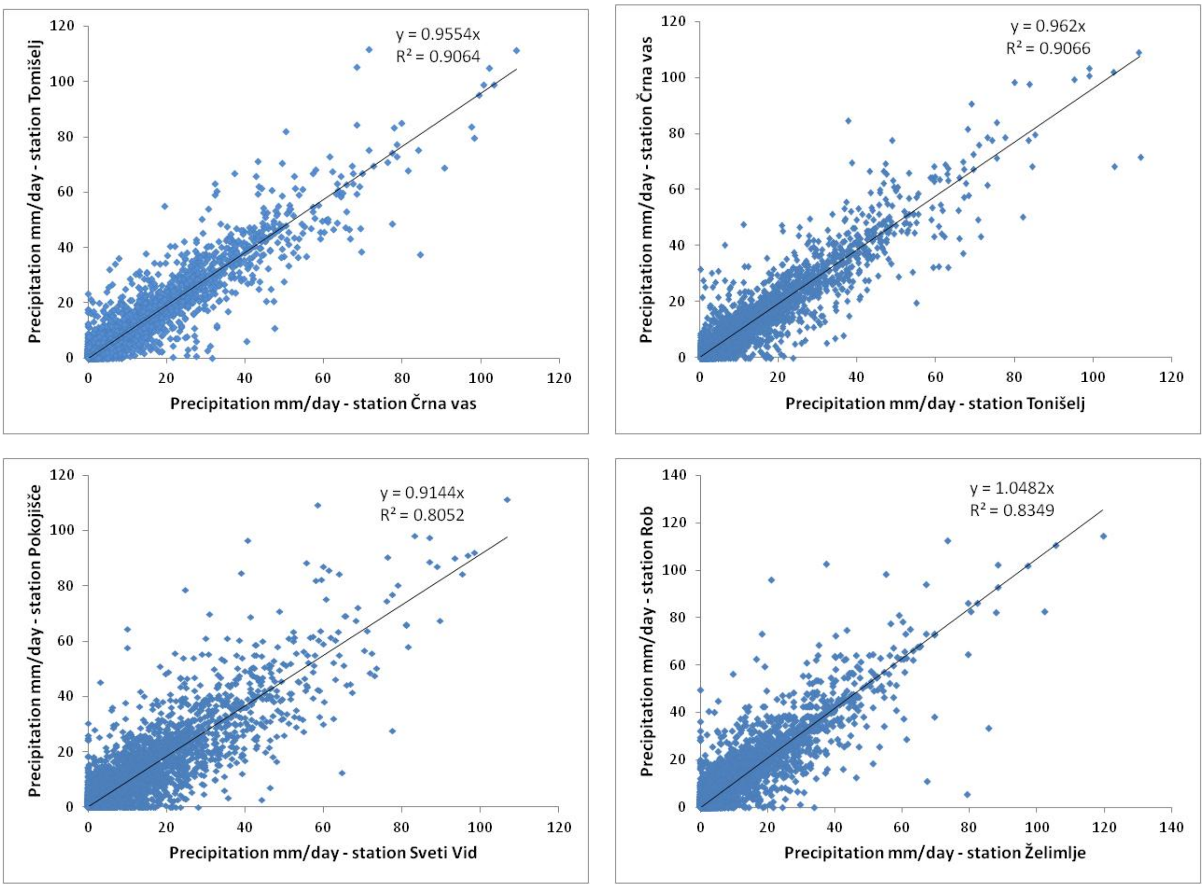
Table 1: Precipitation stations and periods of measurement.

PERCIPITATION STATION	PERIOD OF MESAURMENT
Tomišelj	1.1.1983-31.1.2008
Cerknica	1.1.1983-31.12.2011
Rob	1.6.1983-31.12.2007
Sveti Vid	1.1.1983-31.3.2007
Borovnica	1.1.1983-30.9.1994; 1.2.1995-28.21999; 1.1.2000-31.10.2003; 1.12.2003-31.12.2003
Sodražica	1.1.1983-8.4.1987; 1.1.1988-26.2.1992; 1.1.1993-31.12.2011
Ljubljana-Dobrunje	1.1.1983-31.12.1989; 1.11.1990-31.12.2011
Zdenska vas	1.2.1983-31.12.2011
Želimlje	1.1.1983-3.12.2010; 5.12.2010-31.12.2011
Pokojišče	1.1.1983-31.12.2005; 1.4.2006-31.12.2011
Črna vas	1.1.1983-30.9.1992; 1.11.1992-13.12.2011

Table 2: Temperature stations and periods of measurement.

TEMEPERATURE STATION	PERIOD OF MESAURMENT
Nova vas na Blokah	1.1.1983-31.12.2011
Ljubljana-Bežigrad	1.1.1983-31.12.2011
Lipoglav	1.1.1983-31.12.2011

Missing values on precipitation stations with missing data in different sections were replaced on a base of data from the other station in the area (Figure 17). For calculation of missing values linear regression method was used. It determines the relation of daily precipitation values between pair of stations with the highest determination coefficient (Figure 17).



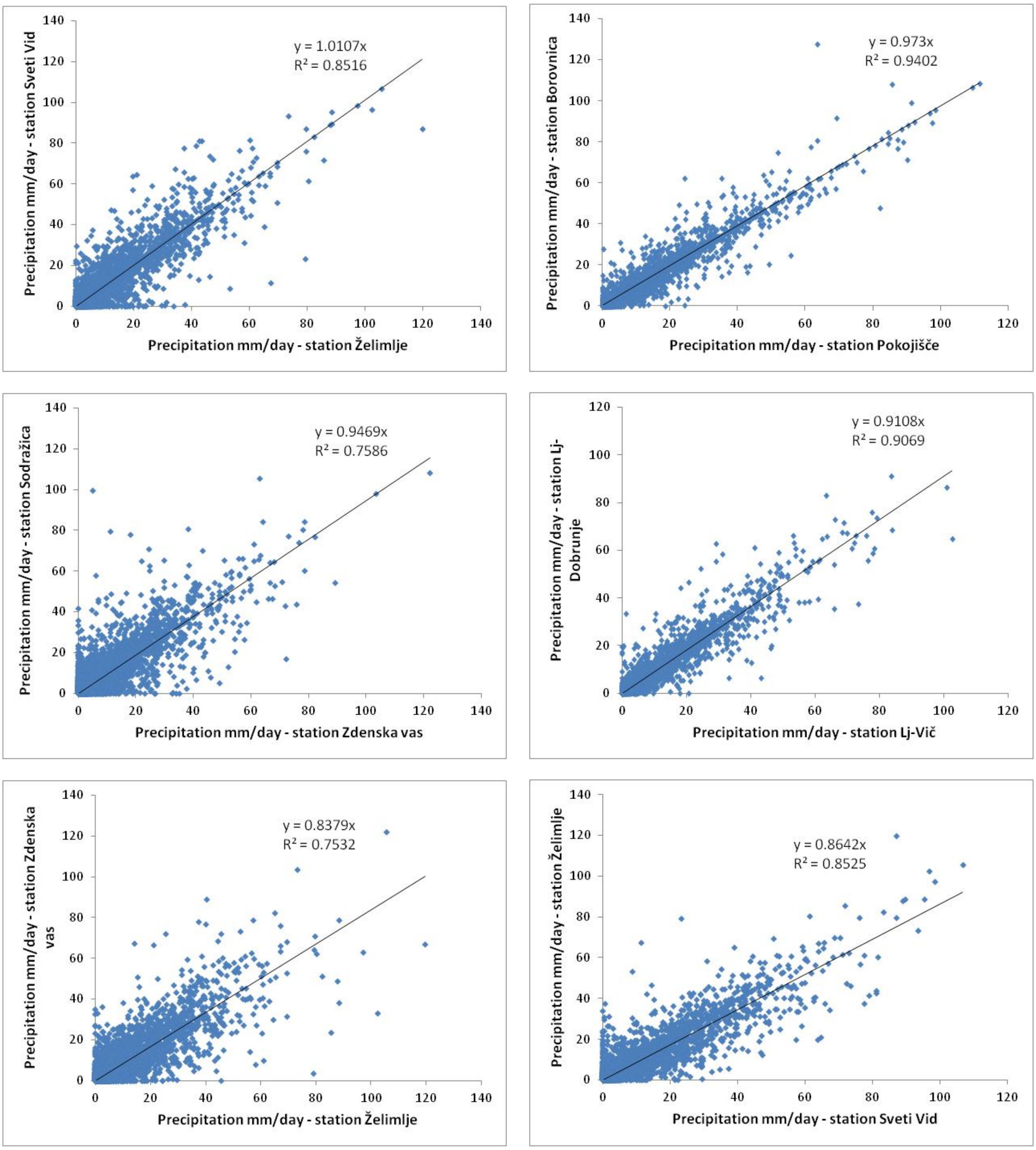


Figure 17: Relation of daily precipitation data among station pairs used for calculation of missing data.

Measuring of precipitation are underestimated because of various effects. Therefore the correction of precipitation data was made. Correction factors were calculated, considering the effect of the wind, the precipitation intensity and the wetting of the rain gauge (Bat et al., 2008).

In the precipitation correction the average correction factors for individual station from (Bat et al., 2008) were used (Table 3).

Table 3: Correction factors for precipitation stations (Bat et al., 2008).

PRECIPITATION STATION	MEASURED MEAN YEAR PRECIPITATION 1971-2008 (mm)	CORRECTED MEAN YEAR PRECIPITATION 1971-2008 (mm)	CORRECTION FACTOR
Tomišelj	1474	1556	1,06
Cerknica	1659	1732	1,04
Rob	1643	1700	1,03
Sveti Vid	1552	1652	1,06
Borovnica	1498	1575	1,05
Sodražica	1406	1466	1,04
Ljubljana-Dobrunje	1291	1354	1,05
Želimlje	1372	1430	1,04
Pokojišče	1525	1616	1,06
Črna vas	1385	1473	1,06

3.5.5.3 Potential evapotranspiration

Potential evapotranspiration (PE) is calculated with a simple formula proposed by Oudin et al. (2005). Formula uses mean daily air temperature as only input and global extraterrestrial radiation (a function of the Julian day and latitude) calculated as proposed by Morton (1983). Proposed is simple formula according to the following equation (Oudin et al., 2005):

$$PE = \frac{R_e}{\lambda_\rho} \frac{T_a + 5}{100} \quad \text{if} \quad T_a + 5 > 0,$$

$$PE = 0 \quad \text{otherwise},$$

PE …. potential evapotranspiration (mm/day),

Re …. extraterrestrial radiation (MJ/m^2 day),

λ …… latent heat flux (MJ/kg),

ρ …… density of water (kg/m^3),

T_a …. Mean daily air temperature (°C).

3.5.5.4 Validation

Spatial interpolation of point data always brings approximations. For validation of interpolated daily precipitation data, method leave one out was used. Validation was made with simple linear correlation between measured and interpolated data for 4 stations that are in the area of interpolation (Figure 19).

For validation purpose, 4 separate interpolations were made and compared the results of measured and interpolated data. Every interpolation one station was excluded. Figure 18 represents four example graphs of stations that were not included in the interpolation model and Table 4 coefficients of determination (R^2). Correlation shows good agreement between measured and interpolated daily precipitation data.

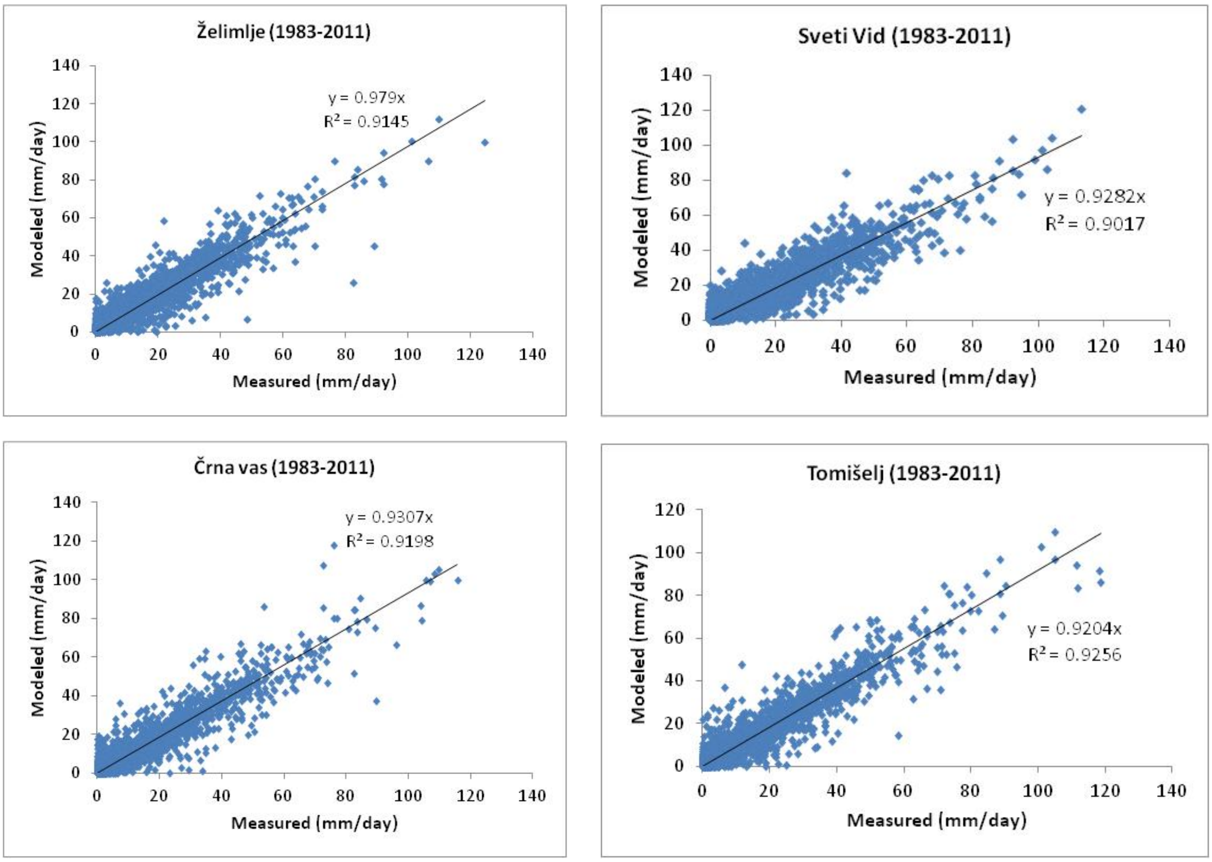


Figure 18: Correlation between measured and interpolated daily precipitation on stations Želimlje, Sveti Vid, Črna vas and Tomišelj.

Table 4 represent also coefficients of determination for station included in the interpolation and show very good agreement between measured and interpolated daily precipitation data.

Table 4: Comparison of determination coefficients on precipitation stations.

Precipitation station	Stations included in interpolation - R^2	Stations not included in interpolation - R^2
Črna vas	0.99	0.92
Tomišelj	0.99	0.93
Sveti Vid	0.99	0.90
Želimlje	0.99	0.91

Validation for interpolate temperature data was not performed, because no temperature station is in the interpolation area. Available data on daily temperature time series are on three stations, which are spread outside the interpolation area (Figure 20).

3.5.5.5 Results

Interpolation results of daily meteorological data are daily time series averaged on defined areas, spatially distributed annual averages and spatially distributed averages for the period of interpolation (Figure 19, Figure 20).

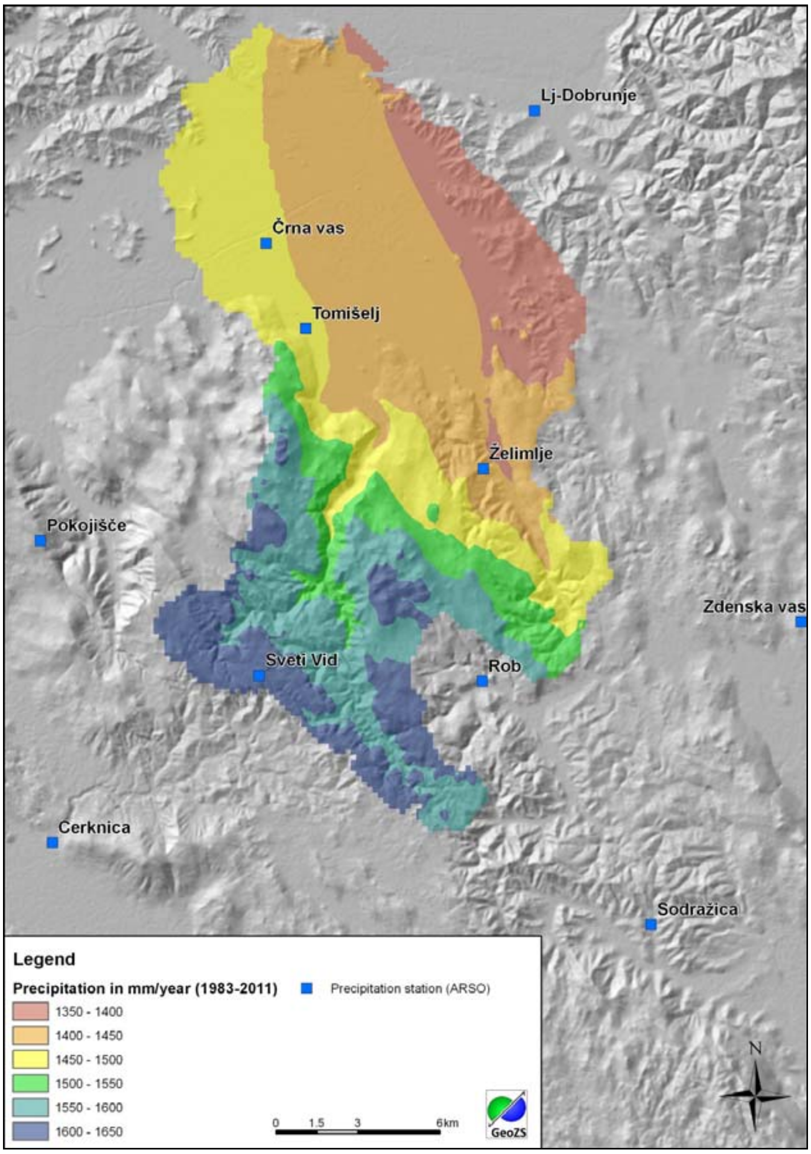


Figure 19: Mean precipitation (mm/year) for the period 1983 to 2011 in the Ljubljansko Barje model area with precipitation stations.

Average yearly precipitation estimated by described method for the period 1983 to 2011 on Ljubljansko Barje model area is 1484,5 mm/year. For the rough comparison, the average precipitation for the period 1961 to 1990 (Kolbezen et al., 1998) is 1461 mm/year.

Deviation of interpolated from measured precipitation (mm/year) for the period 1983 to 2011 on stations in the model area is represented in Table 5. The highest deviation was detected on station Sveti Vid (8,5.%), with negative deviation (interpolated value was lower than measured). Significant was also deviation on station Želimlje (3,4%), with positive deviation (interpolated value was higher than measured).

Table 5: Deviation of interpolated from measured precipitation.

Precipitation stations on the model area	Deviation (%) of interpolated from measured precipitation for the period 1983-2011
Črna vas	-1,3
Tomišelj	-1,7
Sveti Vid	-8,5
Želimlje	3,4

Average yearly temperature estimated by described method for the period 1983 to 2011 on Ljubljansko Barje model area is 9,7°C (Figure 20). For the rough comparison, the average temperature for the period 1961 to 1990 (Kolbezen et al., 1998) is 8,3 °C.

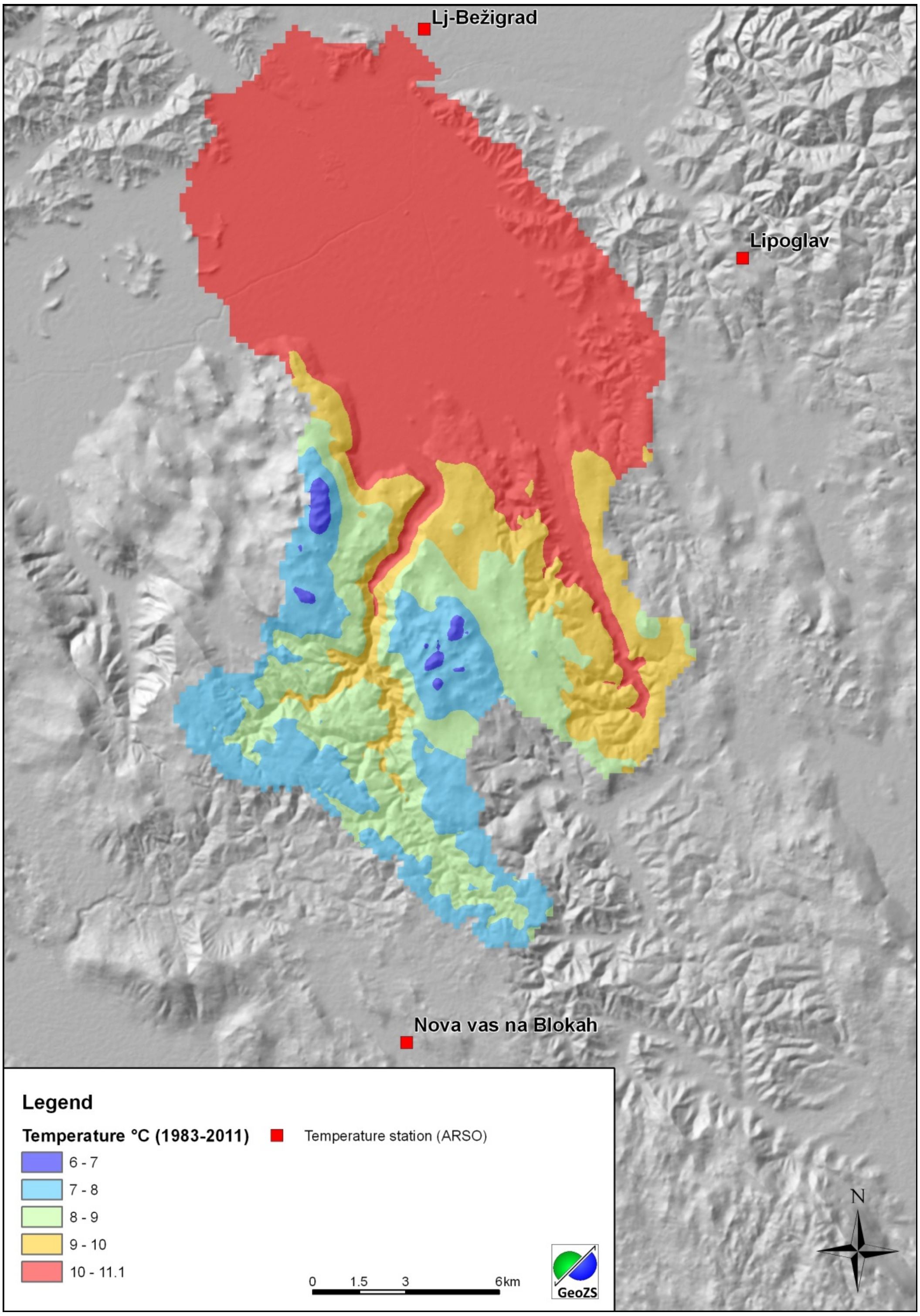


Figure 20: Mean temperature (°C) for the period 1983 to 2011 in the Ljubljansko Barje model area with temperature stations.

3.6 Heterogeneity of the aquifer

In the Ljubljansko polje model heterogeneity of the aquifer, defined with geostatistical model (Janža, 2009), was implemented. Realizations of geostatistical model, presenting aquifer's heterogeneity by spatial distribution of four sedimentological/hydrogeological units (30 layers, consisting of grid cells 200X200 m) was made (Figure 21). Procedure for transformation of these results into numerical model Mike SHE was established.

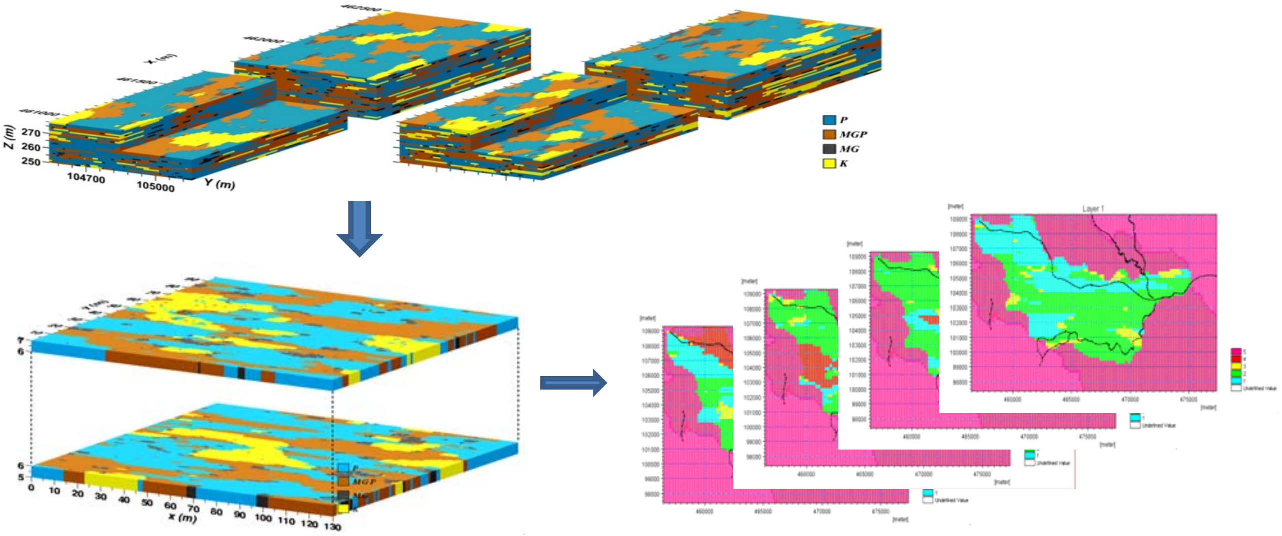


Figure 21: Schematic presentation of procedure of transformation of results of geostatistical modelling into numerical model Mike SHE.

3.7 Perched aquifers

Based on the results of drillings it has been known that perched aquifer could found in the Western part of Ljubljansko polje, but their lateral extension was not known. In the model spatial distribution of low permeable lenses of clay made by Šram (2011) is implemented.

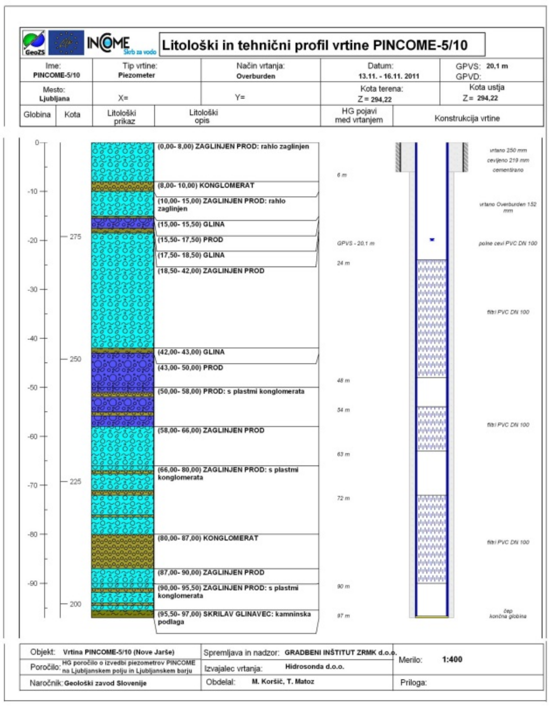
It was made in flowing steps:

- collecting lithological data from different available archives,
- processing collected data into joined data base and
- geostatistical interpolation of data in Jewel Suite 2011 software.

All available reports in archive of Geological Survey of Slovenia about perched aquifers at Ljubljansko polje were collected and reviewed. It was found that perched aquifers occur in the Western part of Ljubljansko polje (Figure 22).

Figure 22: Determined area where perched aquifers occur.

At the selected area all available lithological data from drilled boreholes were gathered (Figure 23).



Name	Depth to top	Depth to base	Lithology
V-4	0	1	ostalo
V-4	1	10	prod/pesek
V-4	10	11	prod/pesek
V-4	11	16,5	ostalo
V-4	16,5	17,5	glina
V-4	17,5	18,9	ostalo
V-4	18,9	21	ostalo
V-4	21	26	prod/pesek
V-4	26	27,5	glina
V-4	27,5	32,2	ostalo
V-4	32,2	34	ostalo
V-4	34	40	ostalo
V-4	40	44	ostalo
V-4	44	45	ostalo
V-4	45	46	glina
V-4	46	47,3	ostalo
V-4	47,3	50,2	ostalo
V-4	50,2	52	ostalo
V-4	52	53,4	ostalo

Figure 23: Lithological data from boreholes.

Data contains information about lithology and the depth where it appears. All together data for 1138 boreholes were classified into 37 classes, based on Arthur Casagrande classification and organised into one uniform data base.

For development of perched aquifers two main conditions must be fulfilled. First, sediment layer must have low hydraulic conductivity and second, area of the layer/lens must be large enough. To determine layers with low hydraulic conductivity, reclassification of lithological data into four hydrofacies which contain lithological classes with common sedimentological and hydrological characteristic were made (Janža, 2009):

1. Gravel (gravel, sandy gravel, sorted sand),
2. Clay and silt with gravel (silty gravel, silt or clay with gravel),
3. Silt and clay (silt, clay, poor sorted sand),
4. Conglomerate (conglomerate, conglomerate with sand or gravel lenses),
5. Everything else which does not correspond to first four groups.

These classes where imported to Jewel Suite 2011 software for further processing.

3.6.1.1 JEWEL SUITE 2011

Jewel suite 2011 is highly capable software for structural and geological modelling. Primarily it is developed for oil and gas industry, but with appropriate data can be used for other purpose, such as lithological modelling as well.

To create spatial distribution of 5 hydrofacies at Ljubljansko polje, 3D structural model of the area had to be created. Digital elevation model (DEM, cell size 12.5 m) and raster data set, which contains elevation data of pre-quaternary bedrock of Ljubljansko polje aquifer (cell size 200 m) (Figure 24) were used for this purpose. DEM represents upper boundary and pre-quaternary raster represents lower boundary of 3D model. Based on two layers and defined area of investigation, 3D structural model was made (Figure 25).

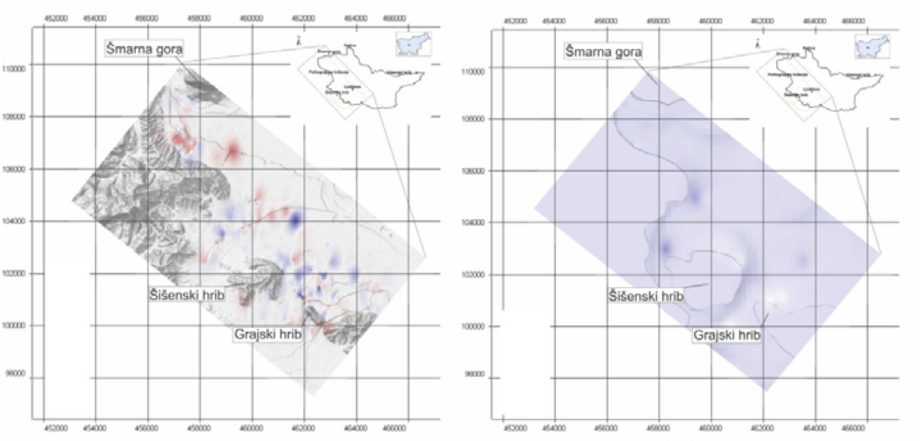


Figure 24: Digital elevation model (left) and pre-quaternary bedrock (right) at Ljubljansko polje (Z exaggeration is 5x).

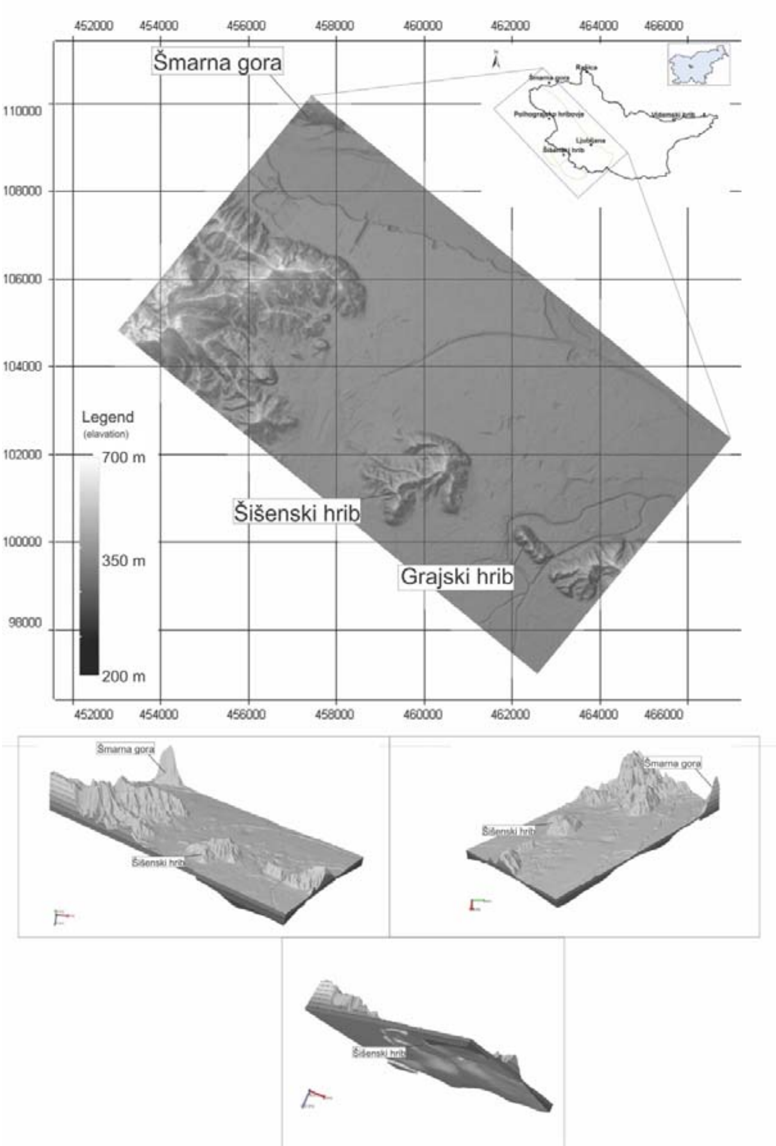


Figure 25: 3D structural model at Ljubljansko polje (Z exaggeration is 5x).

3.6.1.2 Geostatistics

Geostatistics is one of the branches of statistics and it is used to estimate unknown values of regional dependent variables. There are many methods for calculating unknown values between regional dependent variables, one among them is also kriging (Davis, 2002, Internet 1).

Kriging is an interpolation method which provides unknown value on the larger area with relative little known values. Values are calculated based on the know values around the unknown value and on the appropriate semivariogram as well (Webster, 2007).

Semivariance describes relation between two regional dependent variables. It is calculated for each pair specially and plotted on the graph. Given scatter plot is called experimental semivariogram. The relationship between the semivariance and distance from the central point will depend on the amount of regional dependence (Figure 26) (Mckillup, 2010).

Once the experimental semivariogram has been plotted, a smoothed line of best fit called the theoretical semivariogram is fitted through the points (Figure 26) (Mckillup, 2010).

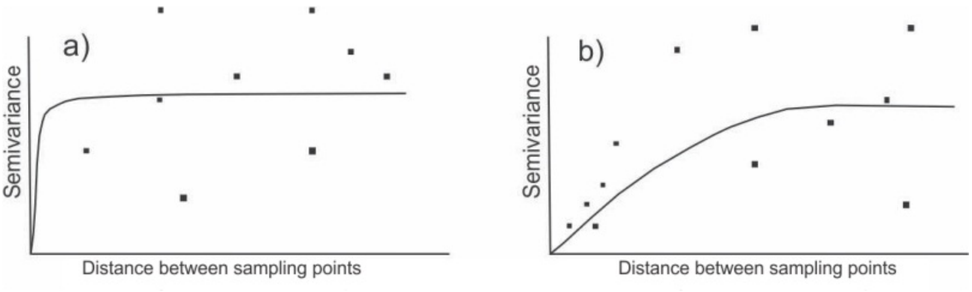


Figure 26: Semivariogram (a) No regional dependence, b) Strong regional dependence) (Mckillup, 2010).

Kriging is based on the assumption that the mean is not known. If we consider punctual estimation first, then we estimate Z at a point x_0 by ($\hat{Z}(x_0)$), with the same support as the data, by (Webster, 2007):

#

$$\hat{Z}(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i)$$

#

where λ_i are the weights.

3.5.1.2.1 Indicator kriging

Indicator kriging makes one step further than ordinary kriging. Beside the interpolated values we can also estimate if the value exceed or no the set threshold. For that we use indicator variable often called "indicator" ($\omega(x)$) (Webster, 2007):

$$\omega(x) = \begin{cases} 1, z(x) \leq z_c \\ 0, otherwise \end{cases}$$

3.6.1.2.2 Sequential Indicator Simulation

Sequential indicator simulation (SIS) is based on a sequential simulation approach. This includes all data available within a neighborhood, including the original data and all previously simulated values (Figure 27) (Juang et. al, 2004).

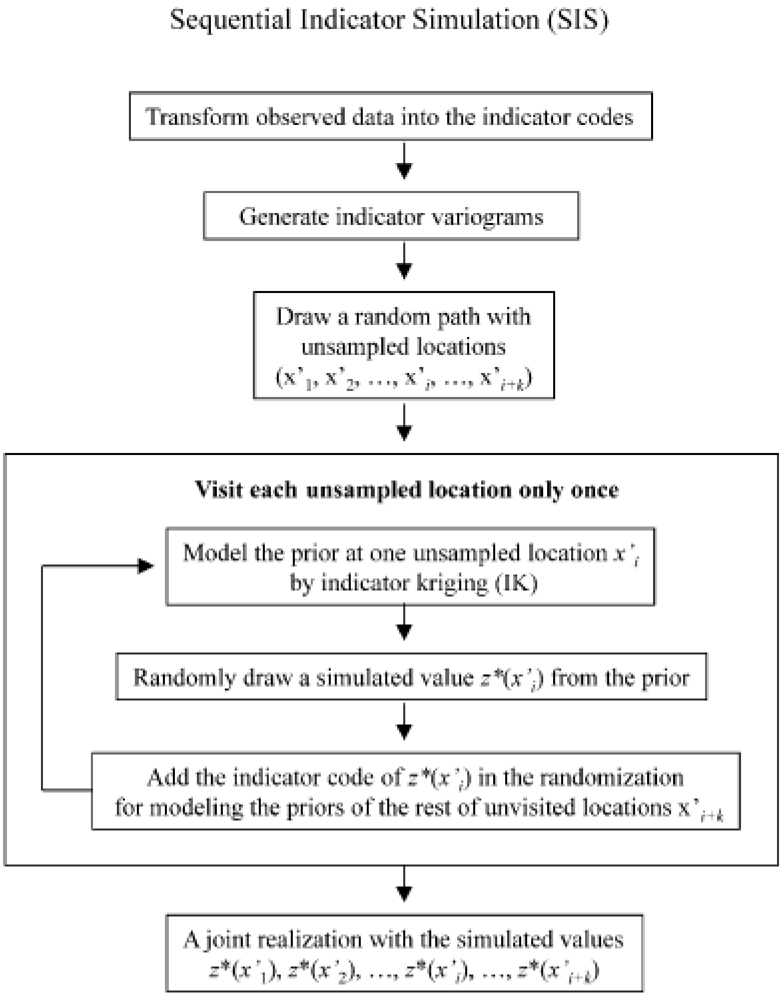


Figure 27: Flow chart illustrating the procedure of Sequential indicator simulation (Juang et. al., 2004).

3.6.1.3 Interpolation

Interpolation method Sequential Indicator Method was used for spatial distribution of hydrofacies at Ljubljansko polje. Hydraulic conductivities were assigned to each lithological unit, which are based on literature data and results of pumping tests. Constructed hydrogeological model enables presentation and extraction of areas, where layers with low hydraulic conductivity appear and can form perched aquifers (Figure 28, Figure 29).

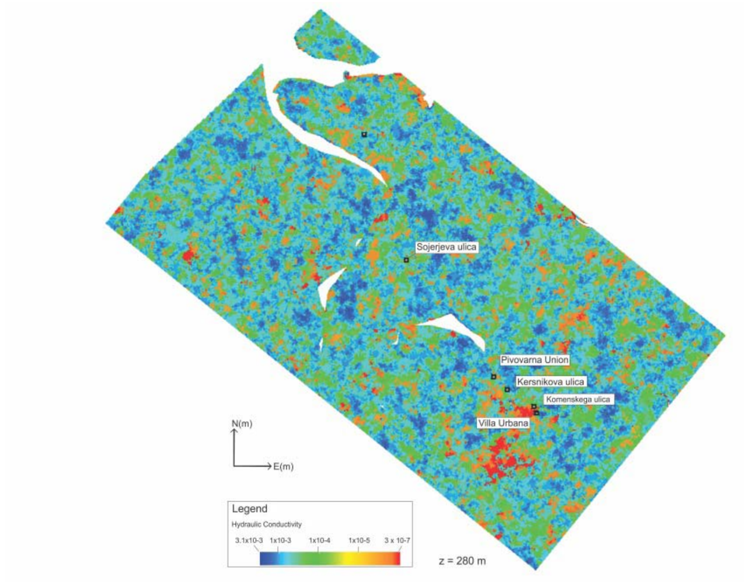


Figure 28: Cross sections from 3D hydraulic conductivity model at Ljubljansko polje.

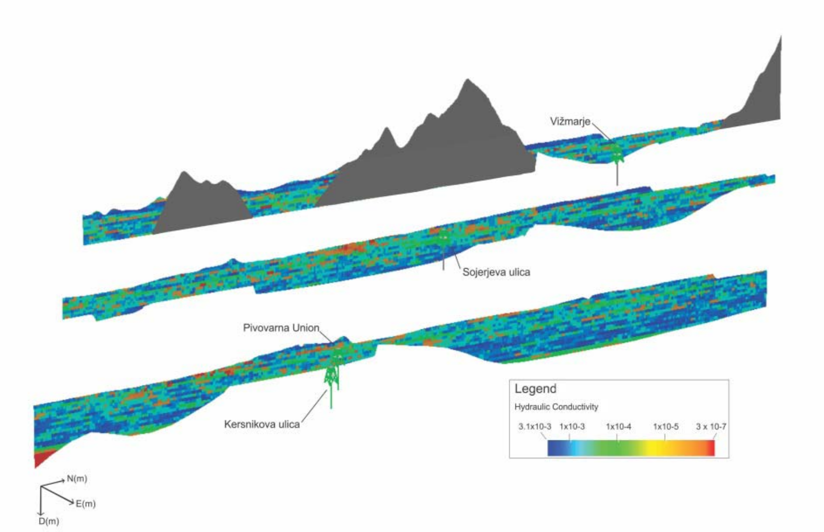


Figure 29: Cross sections from 3D hydraulic conductivity model at Ljubljansko polje (Z exaggeration is 5x).

For determination of areas of potential perched aquifers, two criteria were used:

- cell must have hydraulic conductivity lower than K = 10^{-6} m/s and
- area with low hydraulic conductivity must be larger than 0,07 m^2.

Results of the model show that there are two main areas with higher occurrence of modelled perched aquifers i.e. North side of Šišenski hill and between Šišenski hill and Castle hill. At those areas layers appear at several altitudes, from foot hills to the depth around 30 m. Layers with low hydraulic conductivity but in smaller presence appear also in the other parts of modelled area (Figure 30, Figure 31)

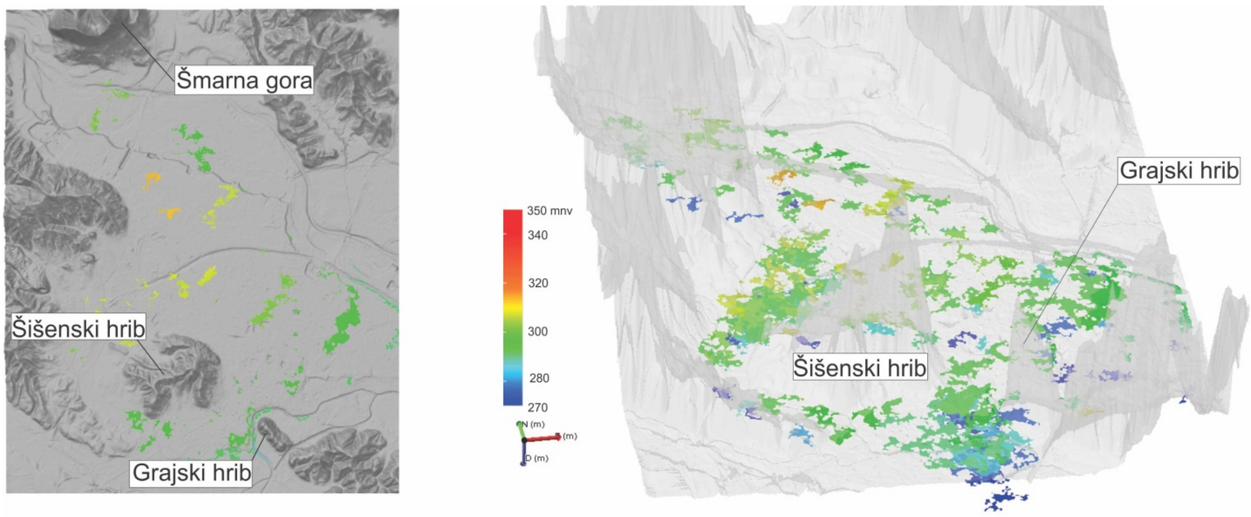


Figure 30: Layers with lower hydraulic conductivity - potential perched aquifers (view 1) (Z exaggeration is 25x).

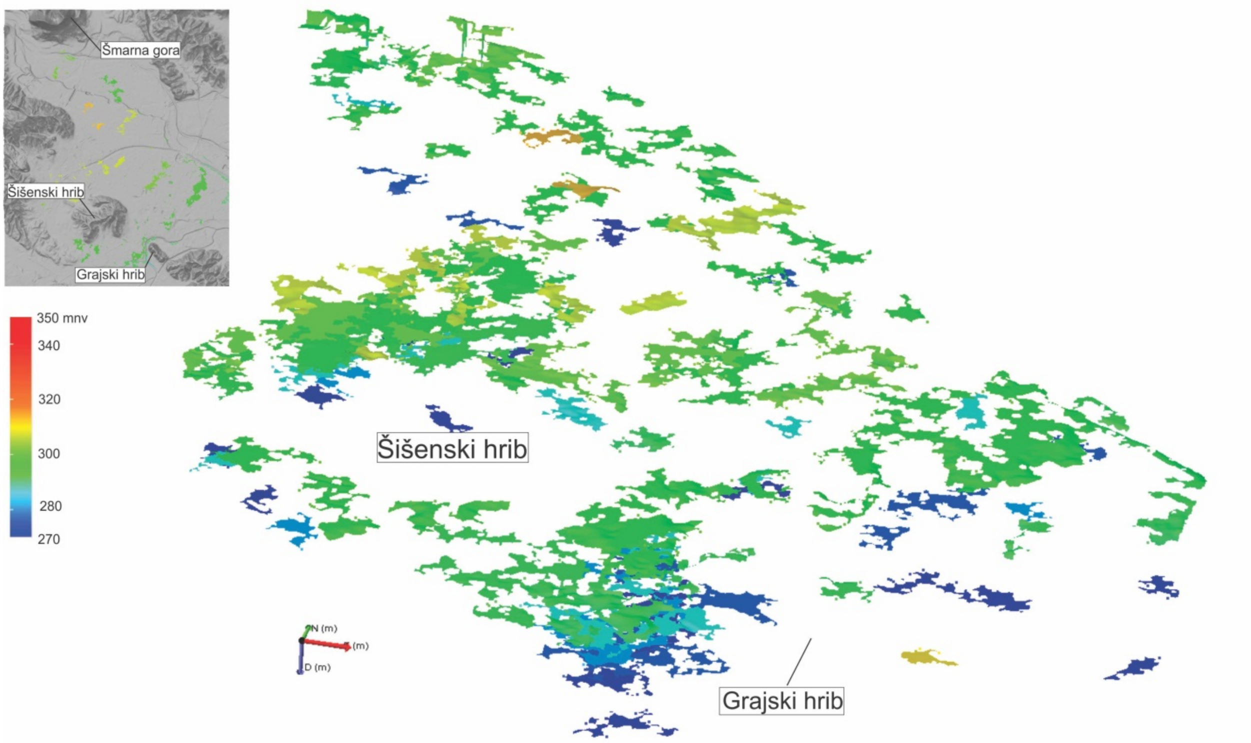


Figure 31: Layers with lower hydraulic conductivity - potential perched aquifers (view 2) (Z exaggeration is 25x).

In the past Sava river has flown at the entire Ljubljansko polje area. In the Figure 32 are shown paleo channels of Sava river which are not older than 200 years. At the entire Ljubljansko polje area are also found gravel sediments transported by Sava in Quaternary. Layer with low hydraulic conductivity can be interpreted as old river channels of river Sava or its flood plains (Figure 32). One of the reasons why layers with low hydraulic conductivity are not continuous is a heterogenic processes developed at the Ljubljansko polje i.e. old flood plain could be eroded or cut by younger channel of Sava river.

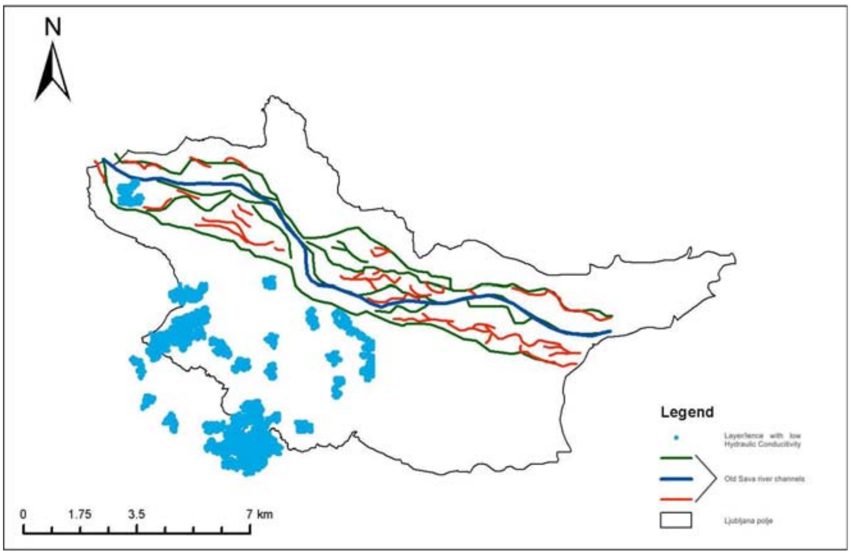


Figure 32: Paleo-channels of river Sava and appearance of layers with low hydraulic conductivity.

3.8 Model Calibration and Validation

In a calibration phase values of parameters which give good agreement of observations and model simulations were defined. The optimised values of the most sensitive model parameters (hydraulic conductivity, specific yield of geounits and river bed leakage coefficient) have been searched with procedure that combines automatic and manual calibration. Time series of piesometric groundwater levels (2004 – 2006) were used as calibration target (Appendix 1).

In the validation procedure the model results were verified with the observations that weren't used in the calibration procedure. Groundwater level time series for the period 2007 – 2009 (Appendix 1), river Sava water level at measuring station Šentjakob (Figure 33) and chemical analysis of TCE pollution in groundwater (Figure 34, Figure 35).

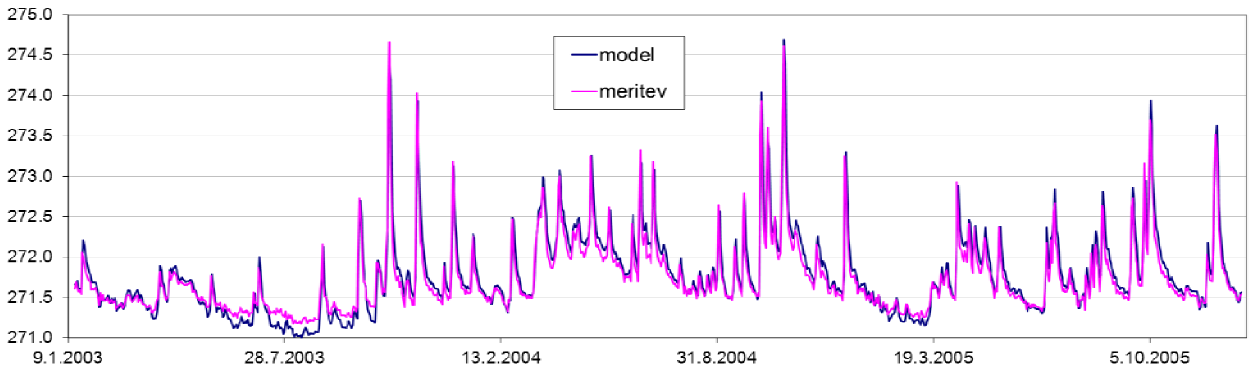


Figure 33:Comparison of river Sava water level at measuring station Šentjakob.

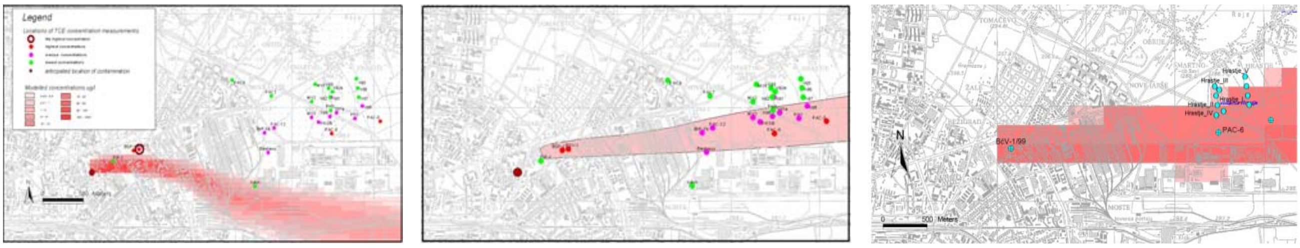


Figure 34: Comparison of observed TCE polution (midle) and simulated with MIKE SHE 2000 (left) and MIKE SHE INCOME (right).

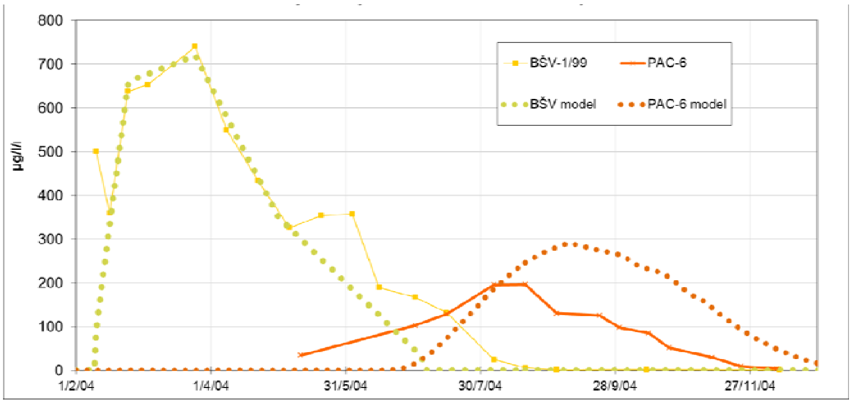


Figure 35: Comparison of observed and simulated (MIKE SHE –INCOME) concentration of TCE.

3.9 Uncertainty assessment

Hydrological and water quality modelling is associated with uncertainty which arises from different sources. One of the most important is related to the spatial variability of the hydrological parameter values. It has been tested with the use of results of geostatistical modelling (Janža, 2009). Four equally probable realisations of heterogeneity of the aquifer, defined by distribution of sedimentological/hydrogeological units were used.

In the calibration phase values of hydrological parameters of hydrogeological units which result reasonable agreement between simulated and observed groundwater levels were defined. Calibrated values assure comparable agreement for all four models, using different geostatistical realisations.

Water movement results of four models were used as a basis for water quality (advection dispersion) simulations. The source of pollution was located in the central part of Ljubljansko polje and concentrations were extracted 3000 m downstream from the source location. Figure 36 shows comparison of simulated concentrations which indicates uncertainty in water quality simulation which is related to heterogeneity of the aquifer. It shows that simulated maximum concentrations differ up to 10 % and time lag increases with time, up to 25 days (8 %).

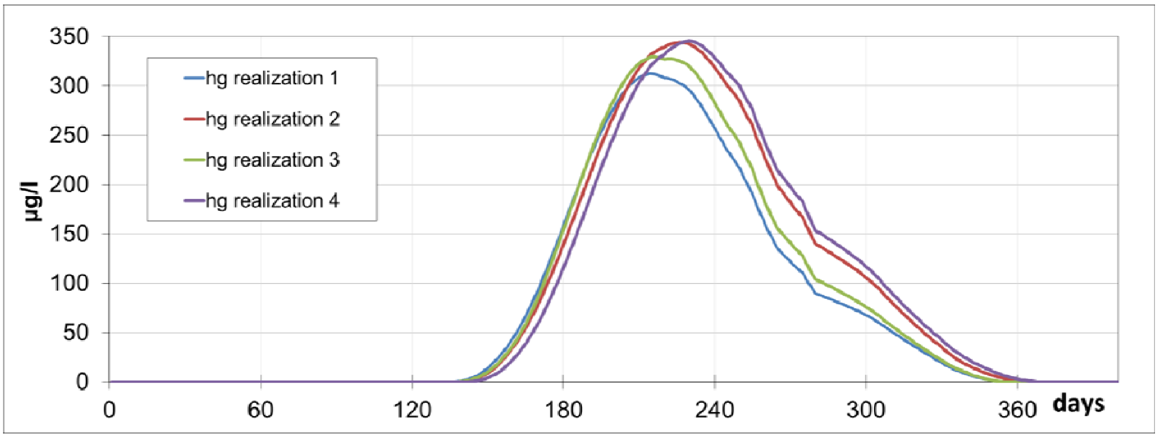


Figure 36: Simulated concentrations (3000 m downstream from source), using four different geostatistical realisations.

Simulated range of spatial distribution of pollution spreading from a constant source is presented on Figure 38 and Figure 39.

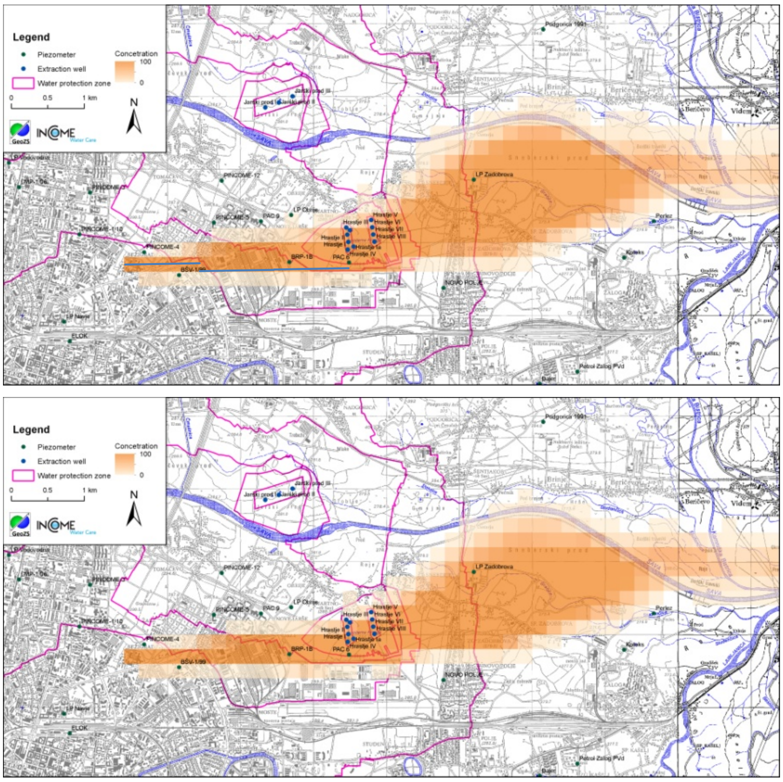


Figure 37: Simulation of pollution spreading from constant source, using four different geostatistical realisations.

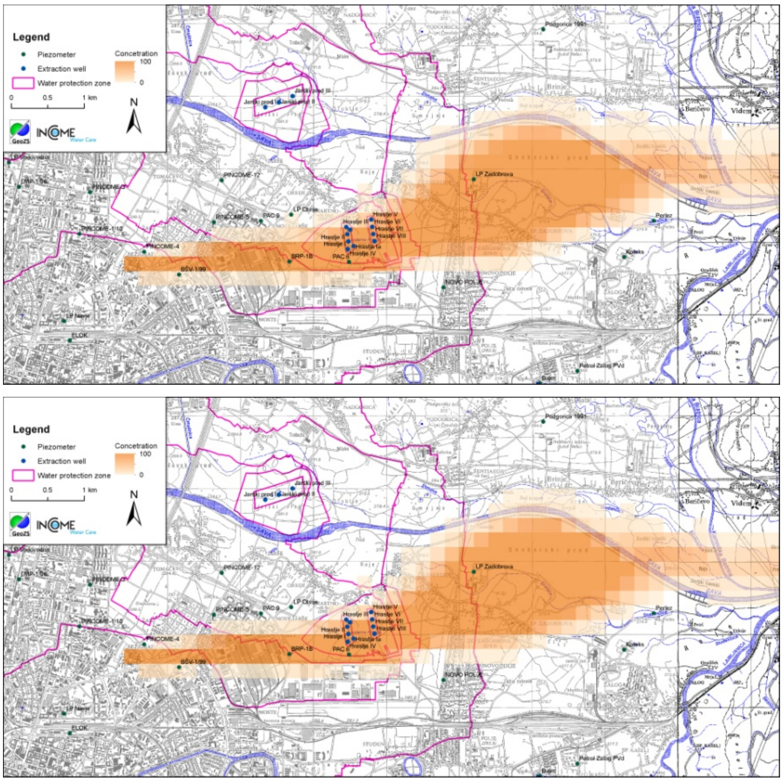


Figure 38: Simulation of pollution spreading from constant source, using four different geostatistical realisations.

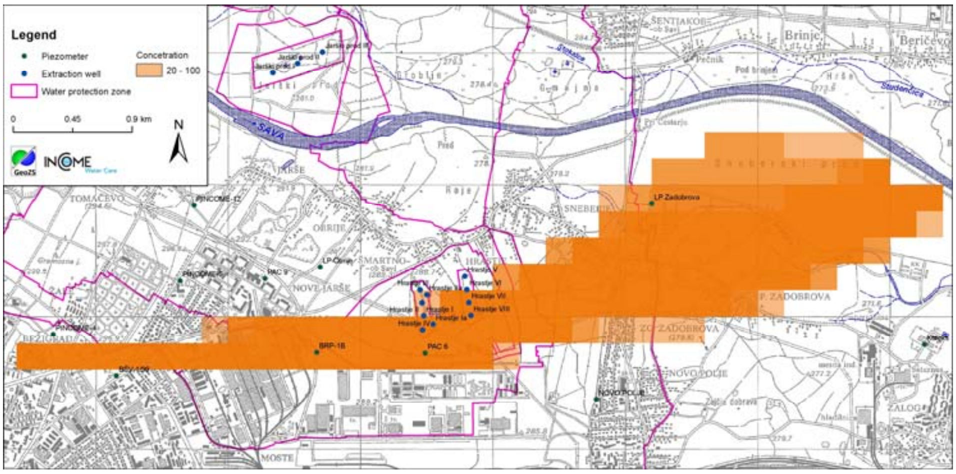


Figure 39: Range of simulated pollution spreading (combination of four different geostatistical realisations).

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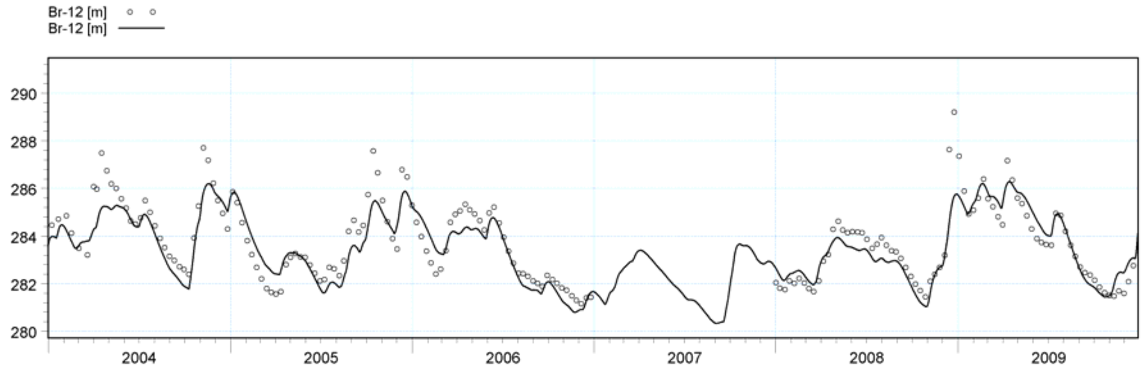
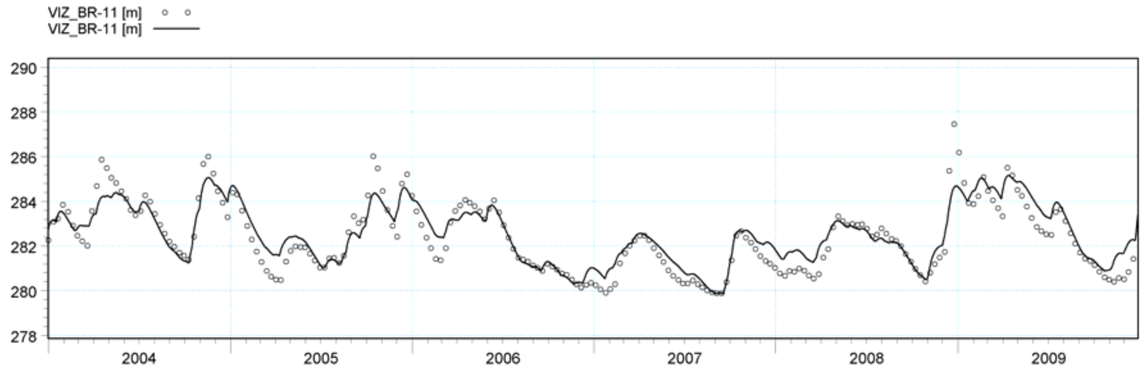
Appendix 1

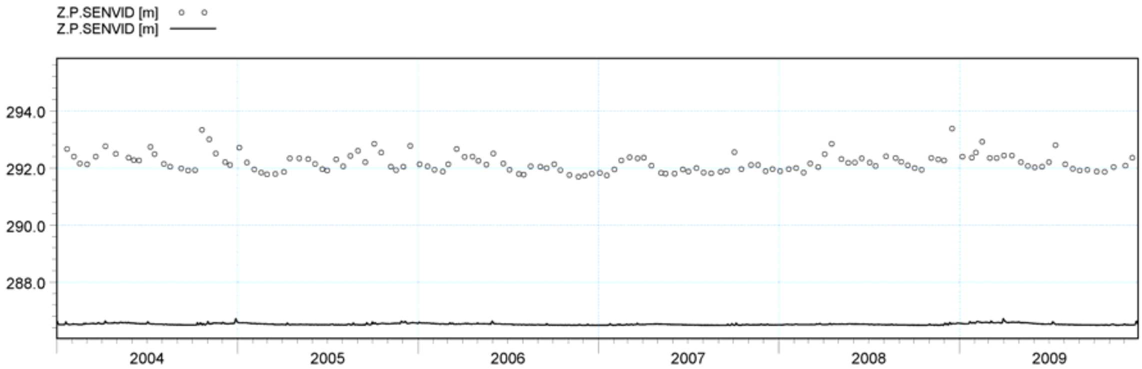
Groundwater level time series for the period 2004 – 2009



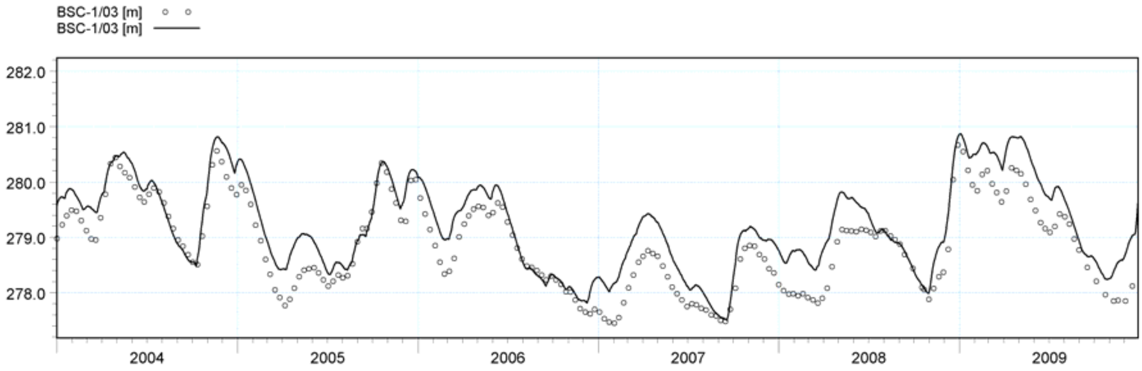
ME=0.212638
MAE=0.554207
RMSE=0.737251
STDres=0.705921
R(Correlation)=0.904048
R2(Nash_Sutcliffe)=0.798733



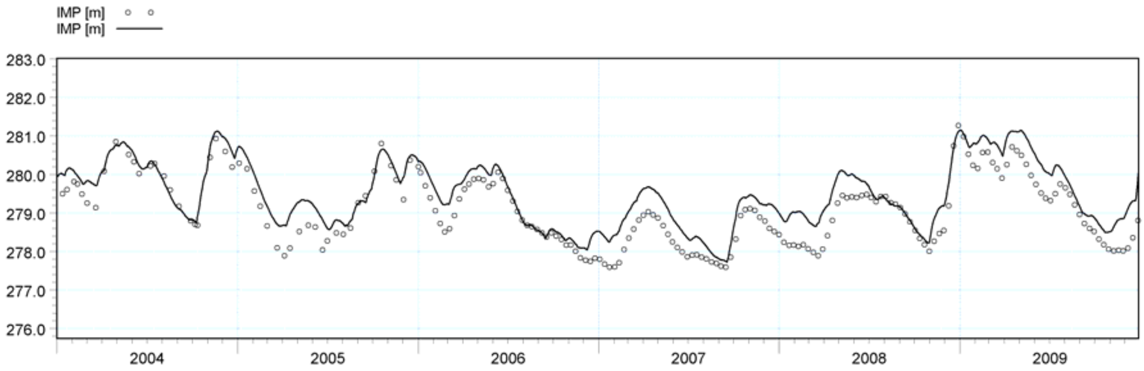
ME=-0.161974
MAE=0.457219
RMSE=0.613912
STDres=0.592159
R(Correlation)=0.931193
R2(Nash_Sutcliffe)=0.843747



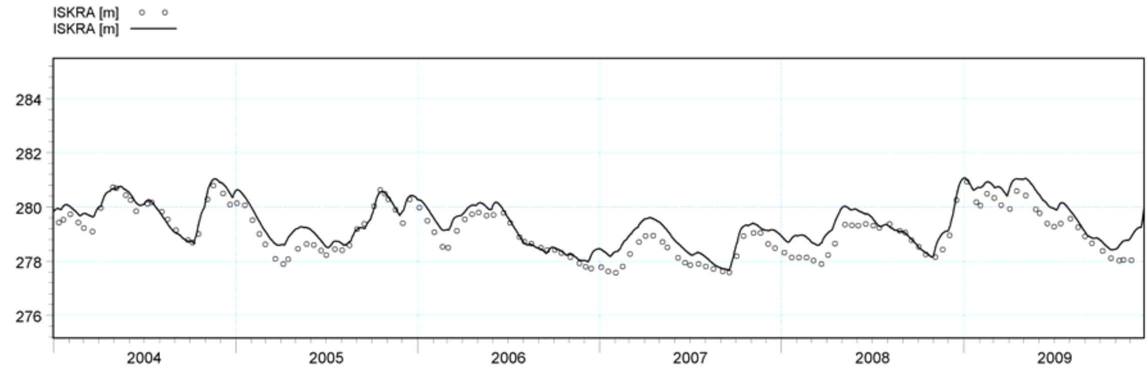
ME=5.65975
MAE=5.65975
RMSE=5.6678
STDres=0.301939
R(Correlation)=0.42473
R2(Nash_Sutcliffe)=-325.393



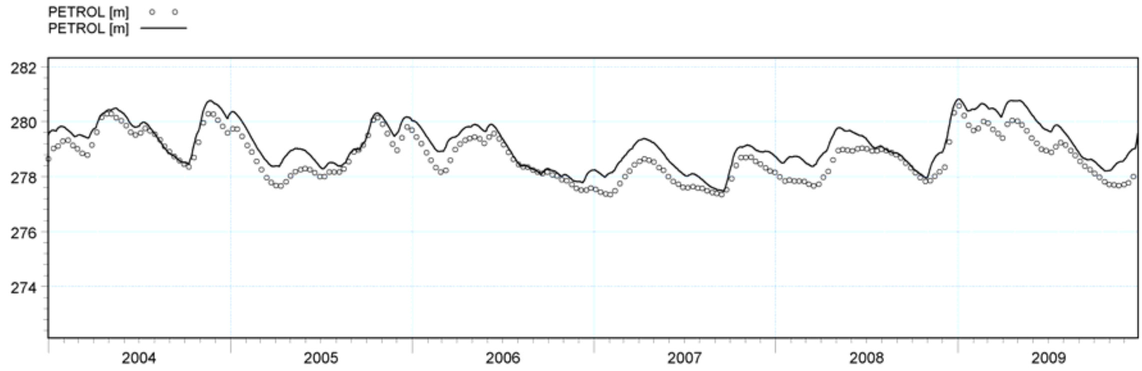
ME=-0.361211
MAE=0.374149
RMSE=0.442761
STDres=0.256055
R(Correlation)=0.950275
R2(Nash_Sutcliffe)=0.701566



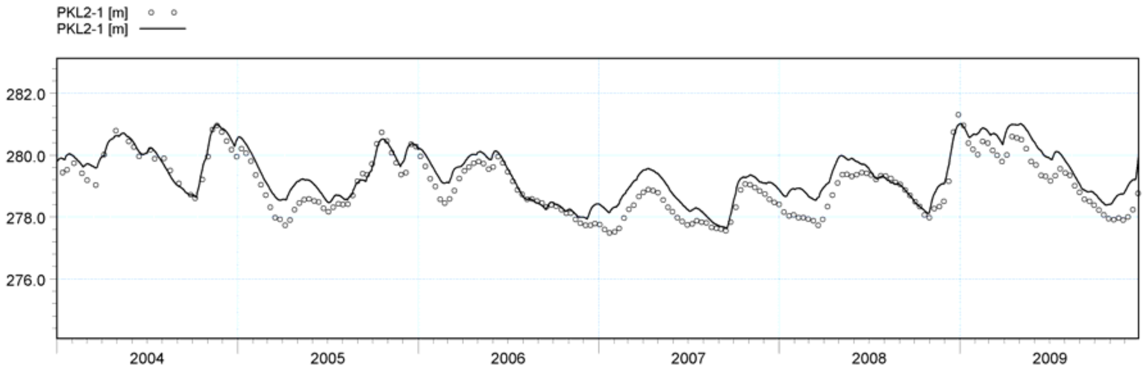
ME=-0.43061
MAE=0.438121
RMSE=0.511726
STDres=0.276475
R(Correlation)=0.947085
R2(Nash_Sutcliffe)=0.644679



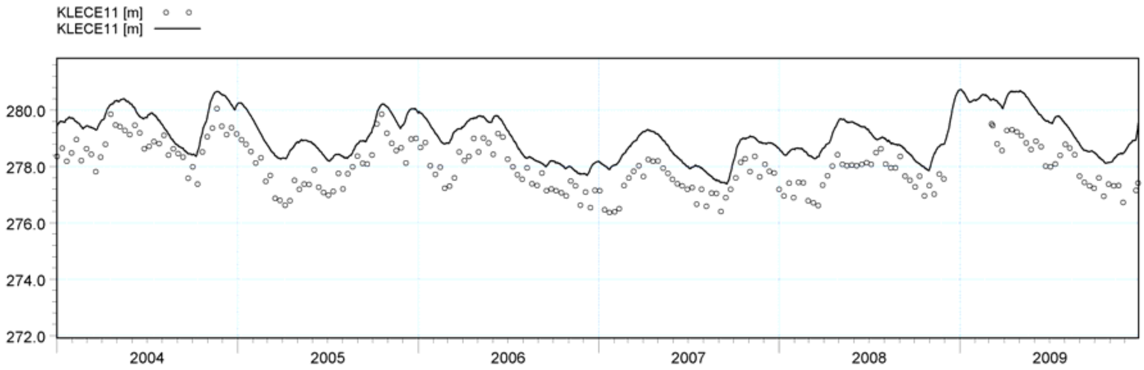
ME=-0.35503
MAE=0.372295
RMSE=0.445791
STDres=0.269599
R(Correlation)=0.949867
R2(Nash_Sutcliffe)=0.732499



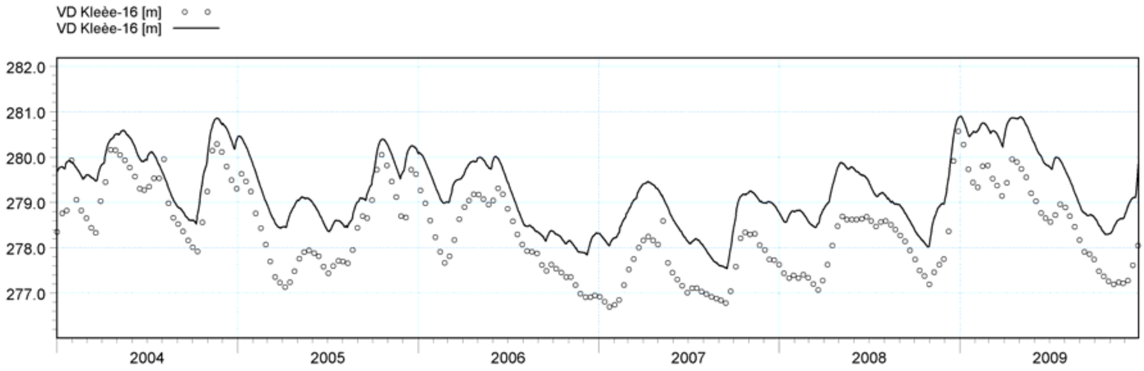
ME=-0.463201
MAE=0.464849
RMSE=0.534715
STDres=0.267142
R(Correlation)=0.944251
R2(Nash_Sutcliffe)=0.54945



ME=-0.380228
MAE=0.40299
RMSE=0.480705
STDres=0.294115
R(Correlation)=0.943368
R2(Nash_Sutcliffe)=0.705747

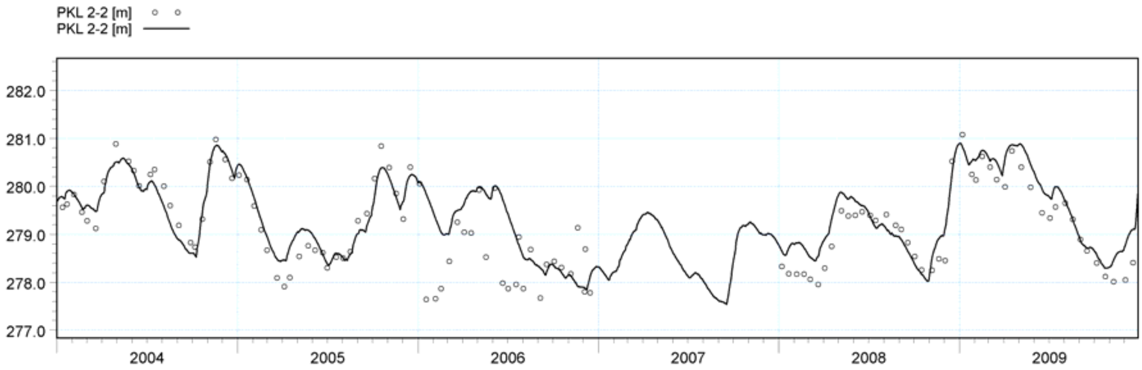


ME=-1.02678
MAE=1.02678
RMSE=1.09636
STDres=0.384357
R(Correlation)=0.888629
R2(Nash_Sutcliffe)=-0.719503

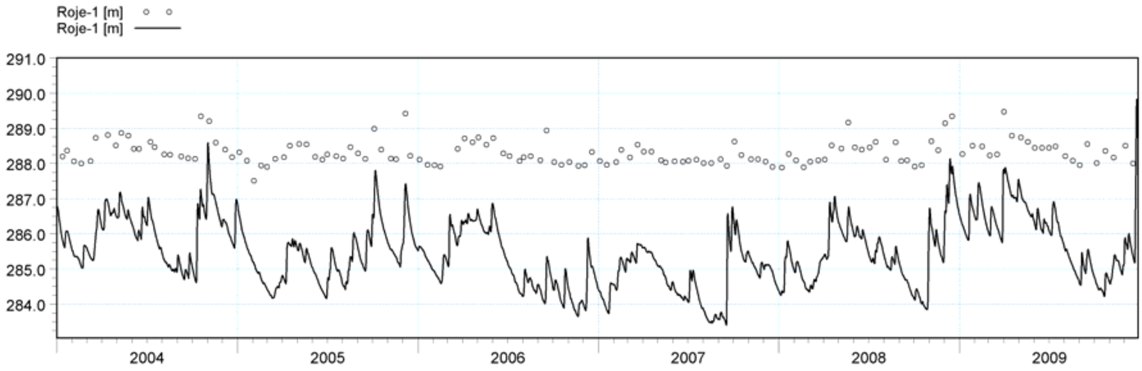


ME=-0.924302
MAE=0.928114
RMSE=0.977868
STDres=0.319205
R(Correlation)=0.943037
R2(Nash_Sutcliffe)=-0.0958705

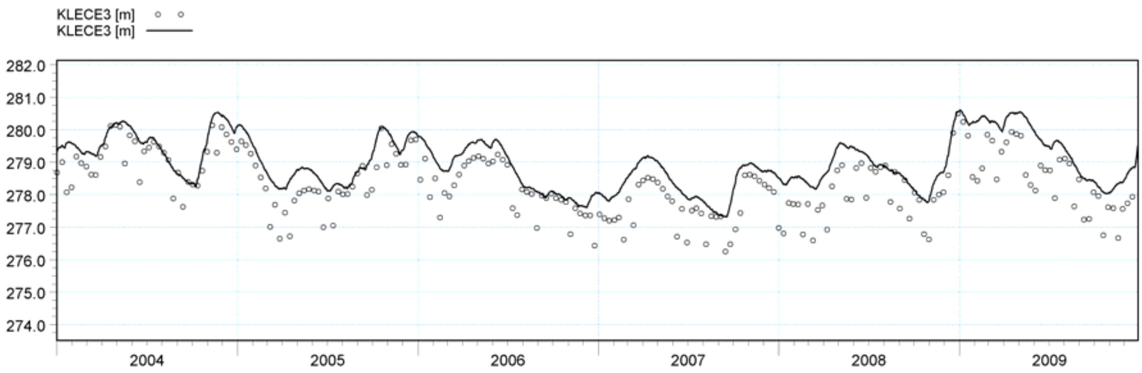
ME=0.297642
MAE=0.407405
RMSE=0.501987
STDres=0.404228
R(Correlation)=0.935502
R2(Nash_Sutcliffe)=0.782297



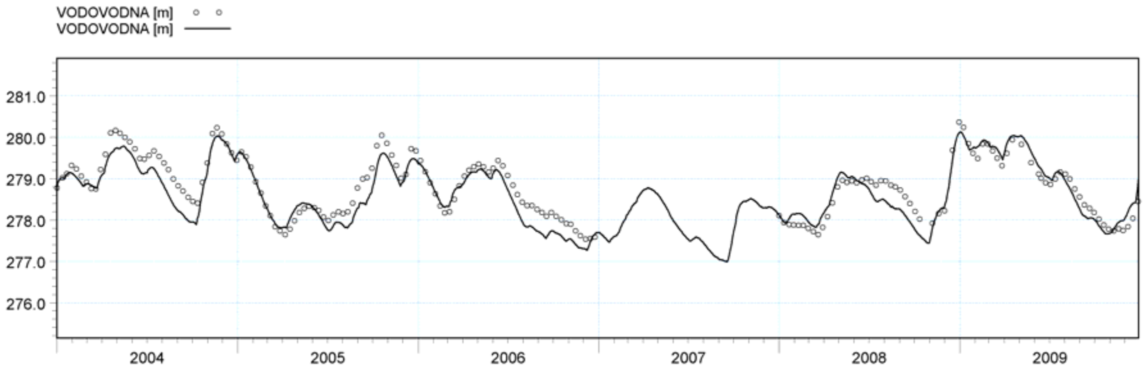
ME=-0.212622
MAE=0.371629
RMSE=0.532859
STDres=0.488601
R(Correlation)=0.836109
R2(Nash_Sutcliffe)=0.639618



ME=2.86027
MAE=2.86027
RMSE=2.94561
STDres=0.703892
R(Correlation)=0.811111
R2(Nash_Sutcliffe)=-73.4858

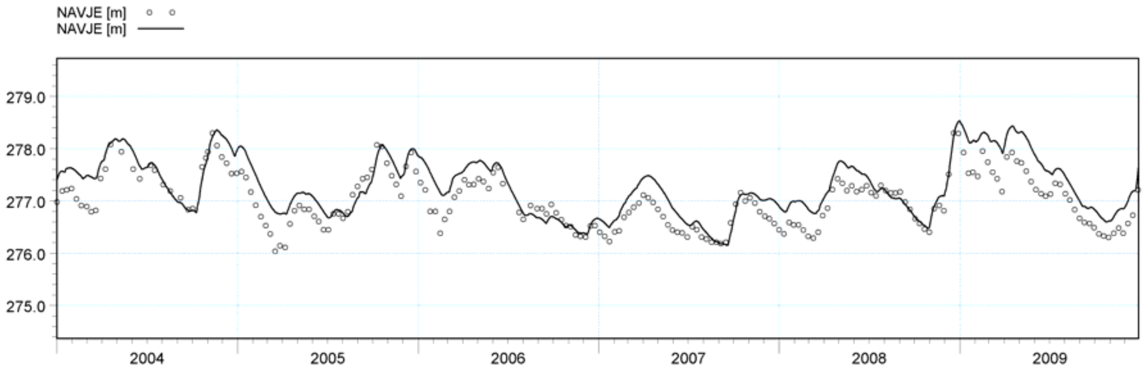


ME=-0.676695
MAE=0.681418
RMSE=0.844953
STDres=0.505994
R(Correlation)=0.832385
R2(Nash_Sutcliffe)=0.140857

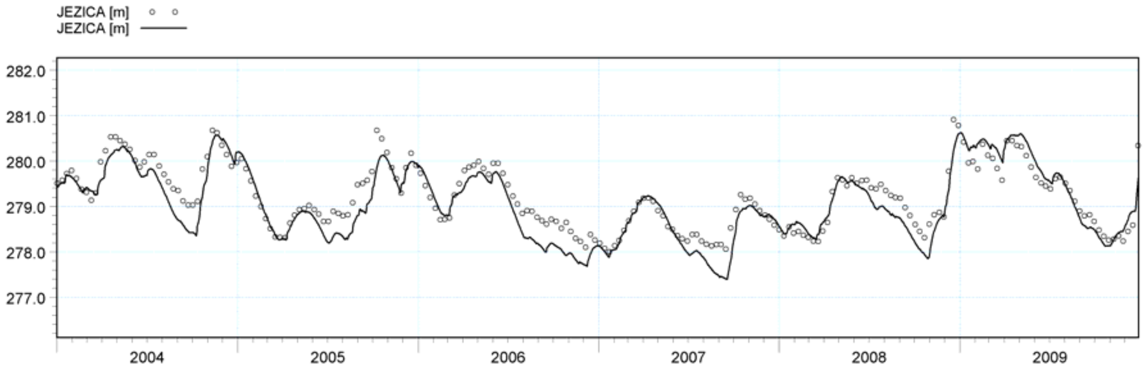


ME=0.146203
MAE=0.24441
RMSE=0.295456
STDres=0.256747
R(Correlation)=0.933166
R2(Nash_Sutcliffe)=0.824098

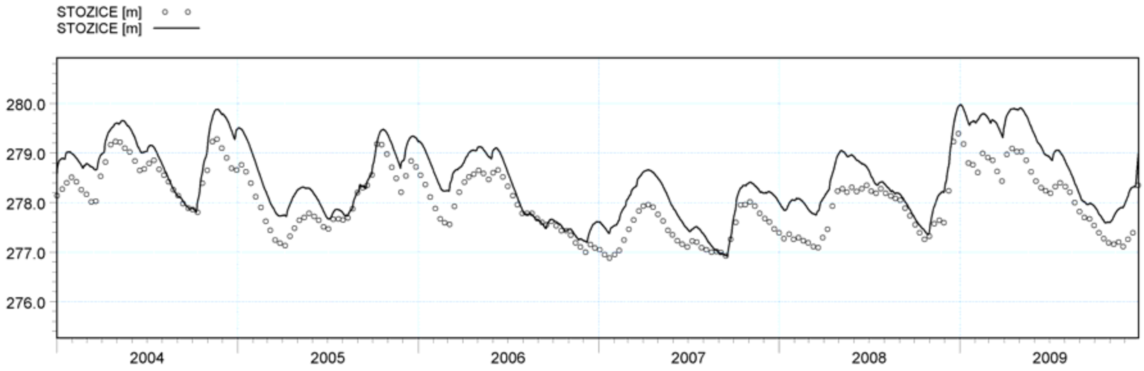
ME=-0.344995
MAE=0.359986
RMSE=0.412458
STDres=0.226054
R(Correlation)=0.933109
R2(Nash_Sutcliffe)=0.44218



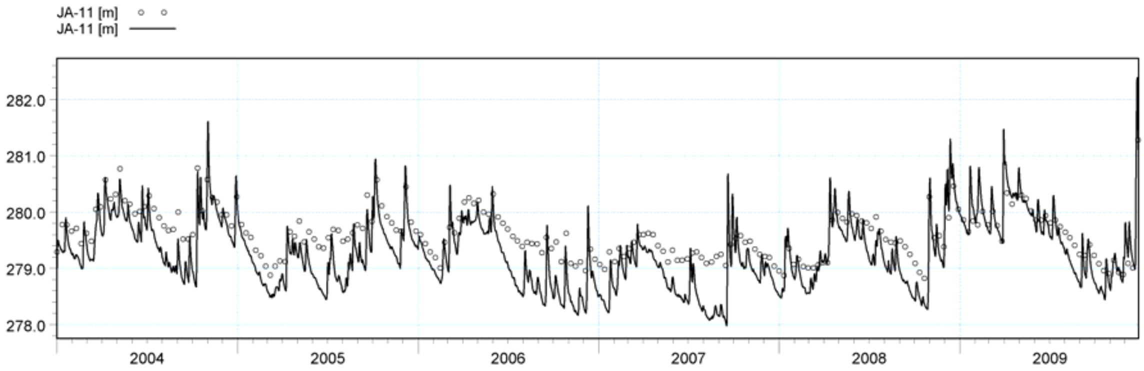
ME=-0.280999
MAE=0.318007
RMSE=0.368244
STDres=0.237999
R(Correlation)=0.901239
R2(Nash_Sutcliffe)=0.467491



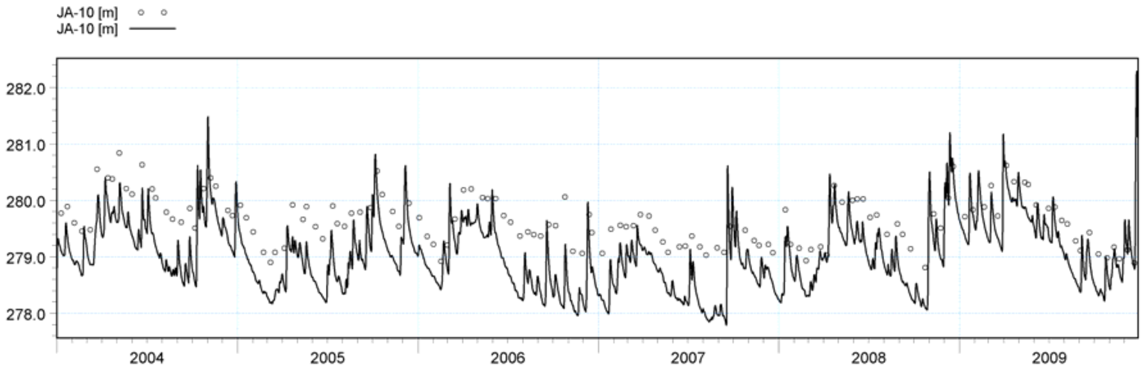
ME=0.160098
MAE=0.260647
RMSE=0.326119
STDres=0.284116
R(Correlation)=0.931599
R2(Nash_Sutcliffe)=0.780238



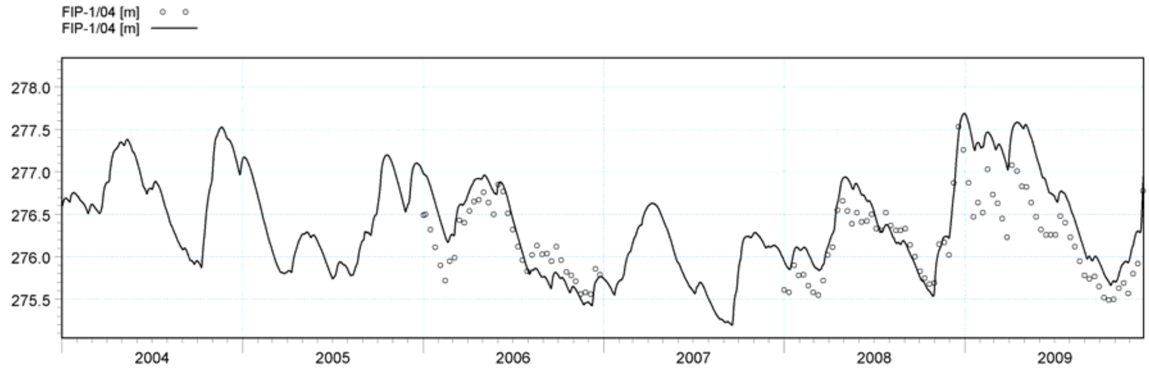
ME=-0.457626
MAE=0.460526
RMSE=0.527202
STDres=0.261763
R(Correlation)=0.934643
R2(Nash_Sutcliffe)=0.301907



ME=0.348729
MAE=0.382488
RMSE=0.451519
STDres=0.286806
R(Correlation)=0.897083
R2(Nash_Sutcliffe)=-0.0885405

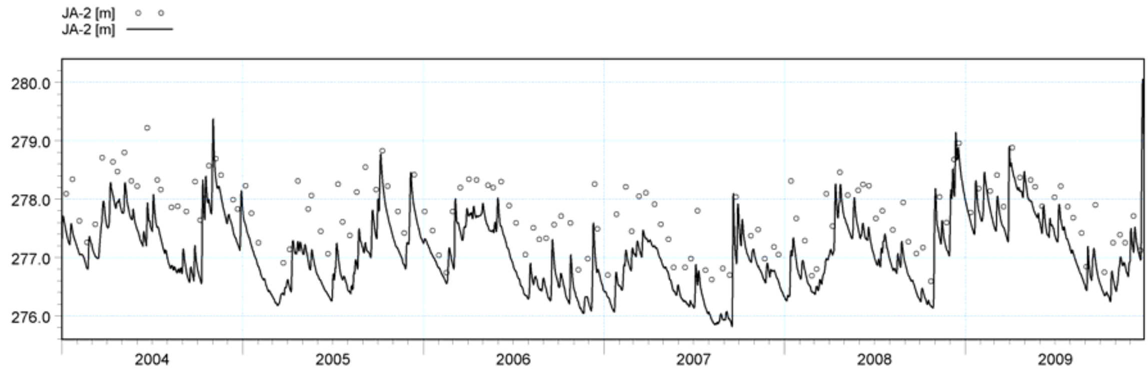


ME=0.608948
MAE=0.609742
RMSE=0.664525
STDres=0.266038
R(Correlation)=0.883164
R2(Nash_Sutcliffe)=-1.30792

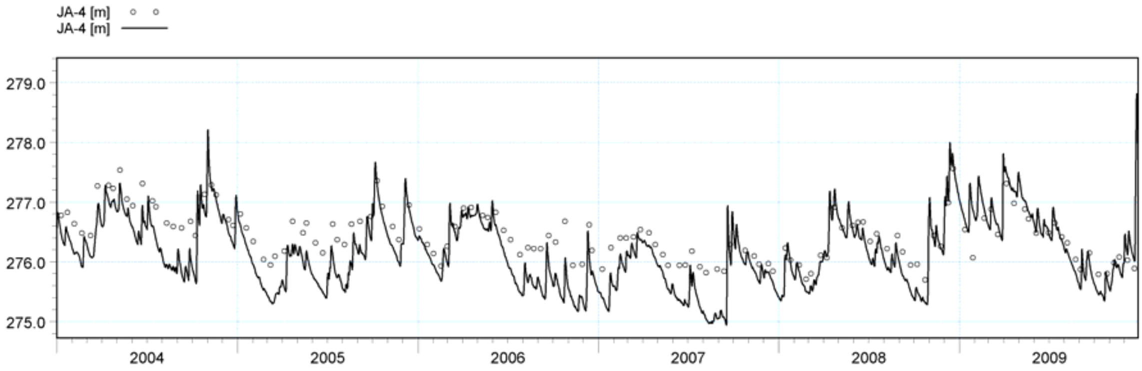


ME=-0.218284
MAE=0.297098
RMSE=0.361232
STDres=0.287821
R(Correlation)=0.88321
R2(Nash_Sutcliffe)=0.315864

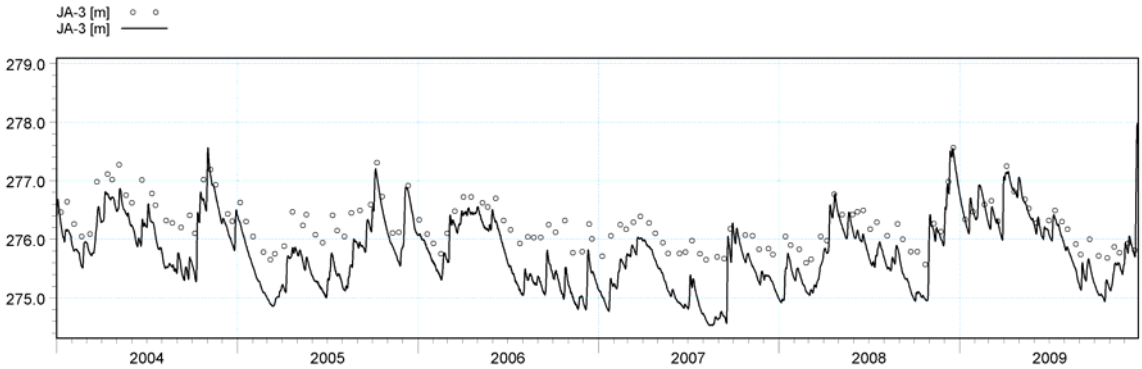
ME=-0.27216
MAE=0.323645
RMSE=0.402295
STDres=0.296261
R(Correlation)=0.867538
R2(Nash_Sutcliffe)=0.208483



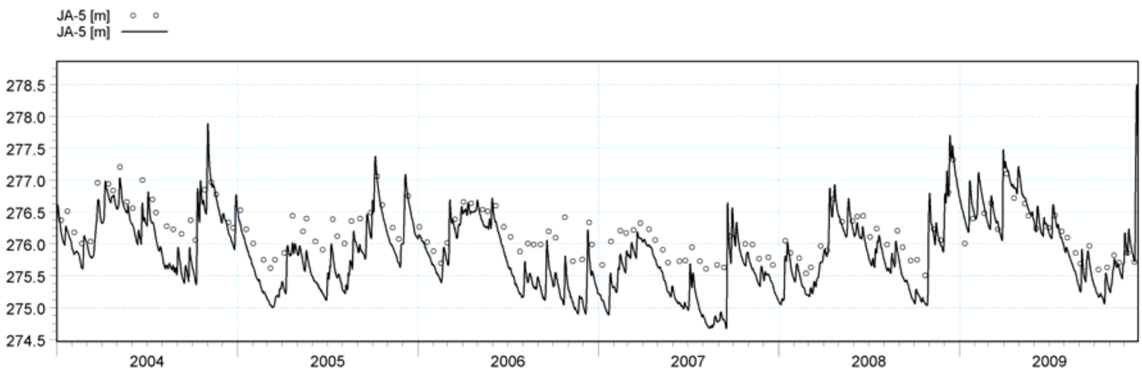
ME=0.666195
MAE=0.666195
RMSE=0.714552
STDres=0.258395
R(Correlation)=0.898904
R2(Nash_Sutcliffe)=-0.521865



ME=0.284891
MAE=0.327309
RMSE=0.393755
STDres=0.271809
R(Correlation)=0.879129
R2(Nash_Sutcliffe)=0.0961814

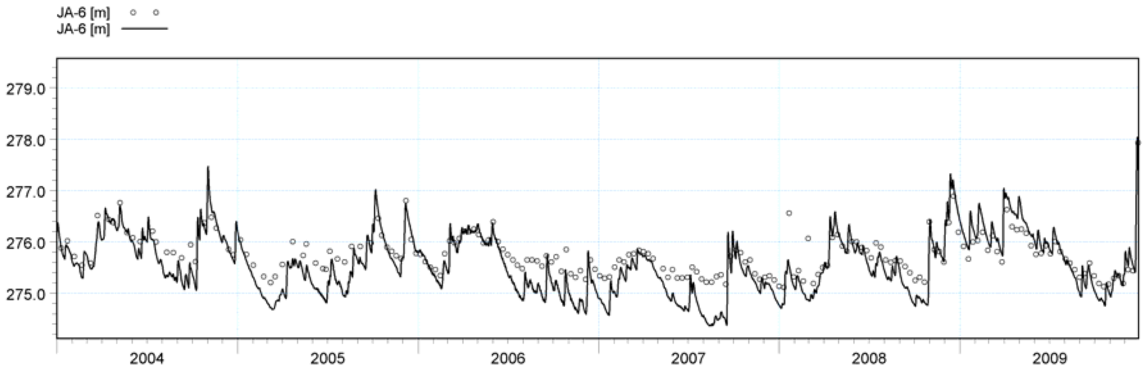


ME=0.469828
MAE=0.471
RMSE=0.534286
STDres=0.254409
R(Correlation)=0.920731
R2(Nash_Sutcliffe)=-0.700712



ME=0.317709
MAE=0.340207
RMSE=0.40288
STDres=0.247737
R(Correlation)=0.91813
R2(Nash_Sutcliffe)=-0.097675

ME=-0.106862
MAE=0.204467
RMSE=0.238439
STDres=0.213152
R(Correlation)=0.945658
R2(Nash_Sutcliffe)=0.729576

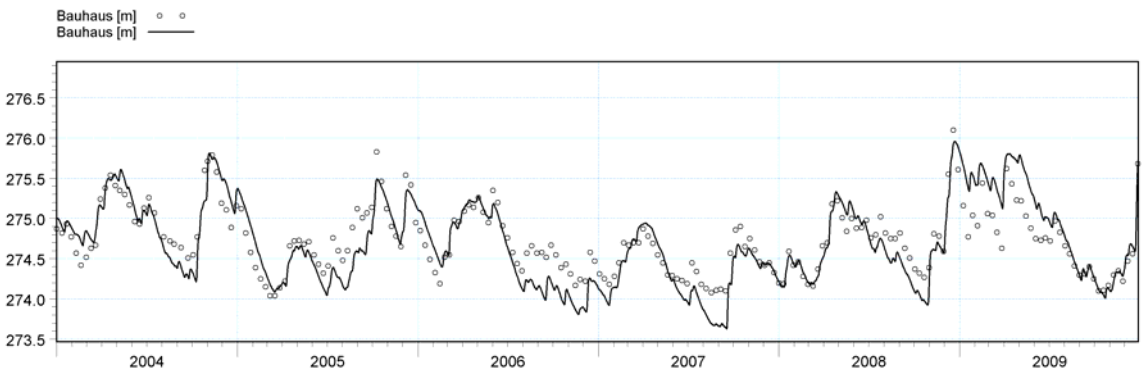


ME=0.202711
MAE=0.275669
RMSE=0.349574
STDres=0.284798
R(Correlation)=0.899068
R2(Nash_Sutcliffe)=0.225152

ME=0.424027
MAE=0.433384
RMSE=0.508958
STDres=0.281495
R(Correlation)=0.858729
R2(Nash_Sutcliffe)=-0.64118

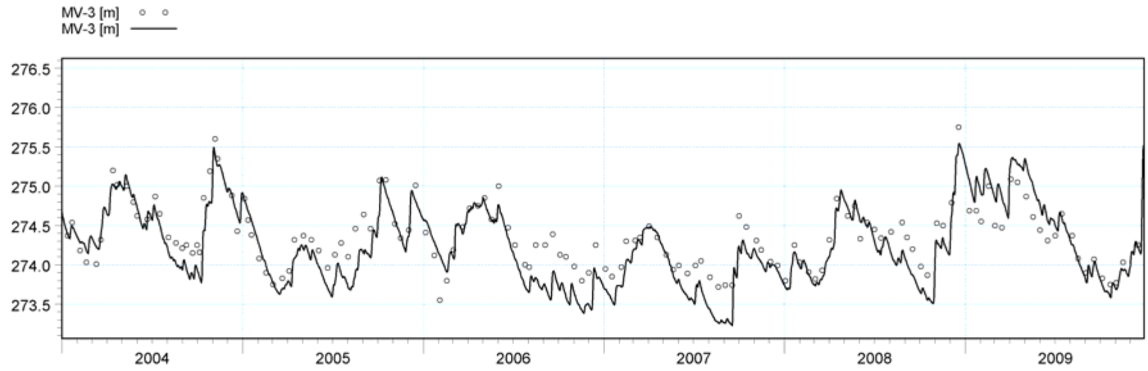
ME=-0.0260058
MAE=0.212178
RMSE=0.267247
STDres=0.265979
R(Correlation)=0.8808
R2(Nash_Sutcliffe)=0.523414

ME=0.0102261
MAE=0.210808
RMSE=0.2614
STDres=0.2612
R(Correlation)=0.875152
R2(Nash_Sutcliffe)=0.559519



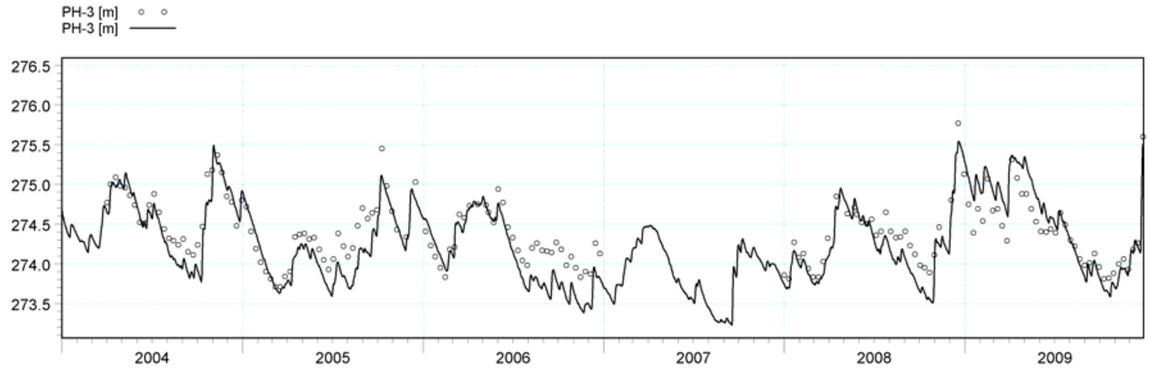
ME=0.02999
MAE=0.202014
RMSE=0.25271
STDres=0.250924
R(Correlation)=0.880136
R2(Nash_Sutcliffe)=0.612608

ME=0.125271
MAE=0.207268
RMSE=0.250198
STDres=0.216578
R(Correlation)=0.903528
R2(Nash_Sutcliffe)=0.593247

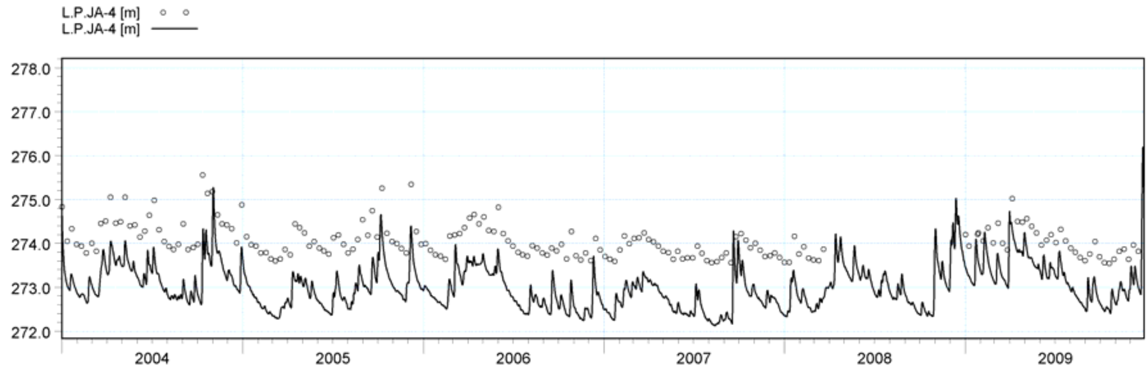


ME=0.111706
MAE=0.210849
RMSE=0.255213
STDres=0.229468
R(Correlation)=0.890944
R2(Nash_Sutcliffe)=0.607563

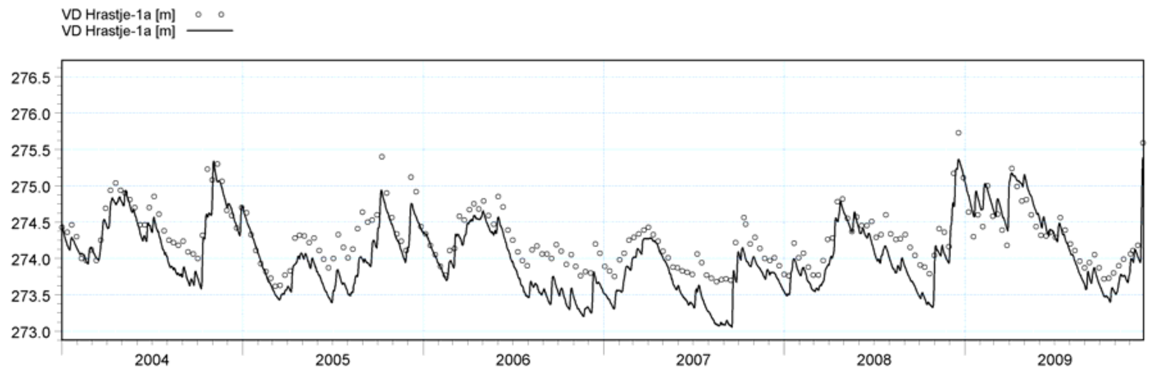
ME=-0.248228
MAE=0.266049
RMSE=0.326591
STDres=0.212237
R(Correlation)=0.908245
R2(Nash_Sutcliffe)=0.283855



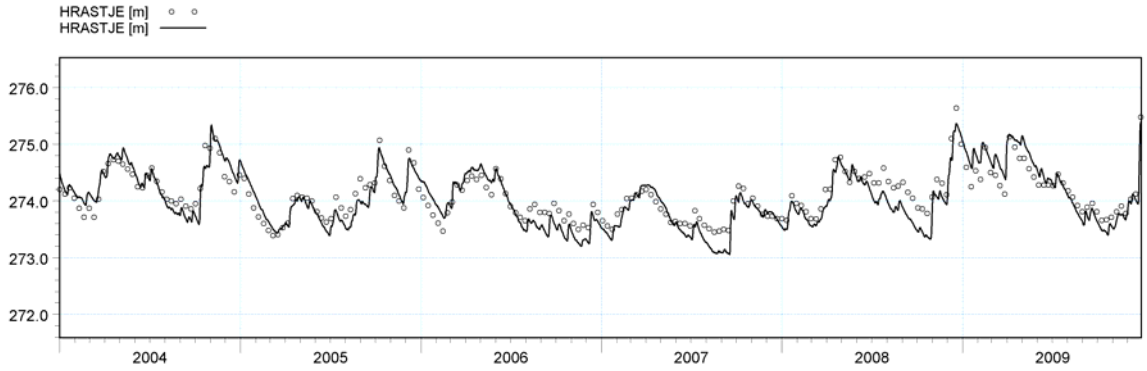
ME=0.108334
MAE=0.20733
RMSE=0.249086
STDres=0.224294
R(Correlation)=0.896124
R2(Nash_Sutcliffe)=0.576585



ME=1.07196
MAE=1.07196
RMSE=1.08902
STDres=0.191957
R(Correlation)=0.916899
R2(Nash_Sutcliffe)=-6.84737



ME=0.23587
MAE=0.26939
RMSE=0.316274
STDres=0.2107
R(Correlation)=0.906173
R2(Nash_Sutcliffe)=0.347998

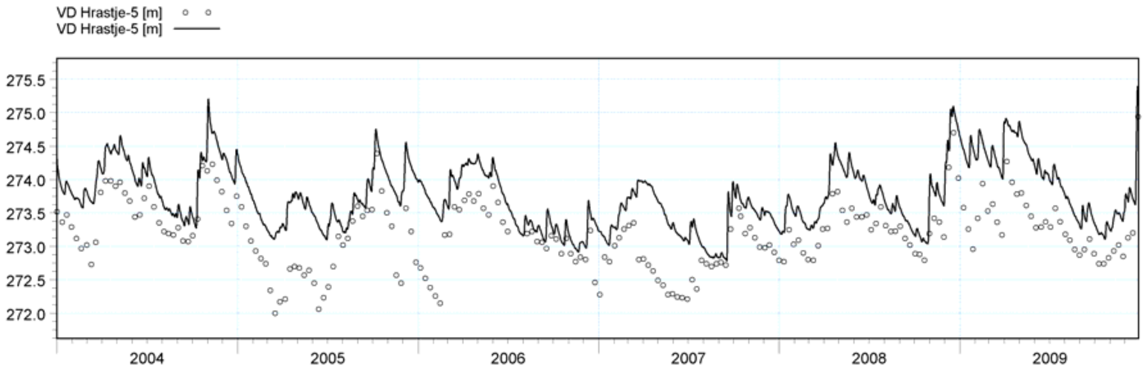


ME=0.05394
MAE=0.180357
RMSE=0.212915
STDres=0.205969
R(Correlation)=0.906987
R2(Nash_Sutcliffe)=0.726101

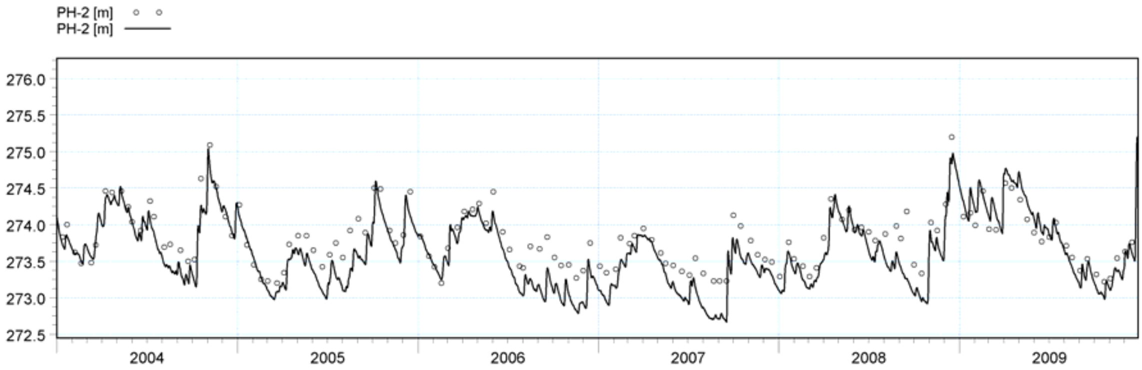
ME=-0.137228
MAE=0.183508
RMSE=0.230667
STDres=0.185407
R(Correlation)=0.931901
R2(Nash_Sutcliffe)=0.637292

ME=-0.0320673
MAE=0.223266
RMSE=0.27411
STDres=0.272228
R(Correlation)=0.891551
R2(Nash_Sutcliffe)=0.579151

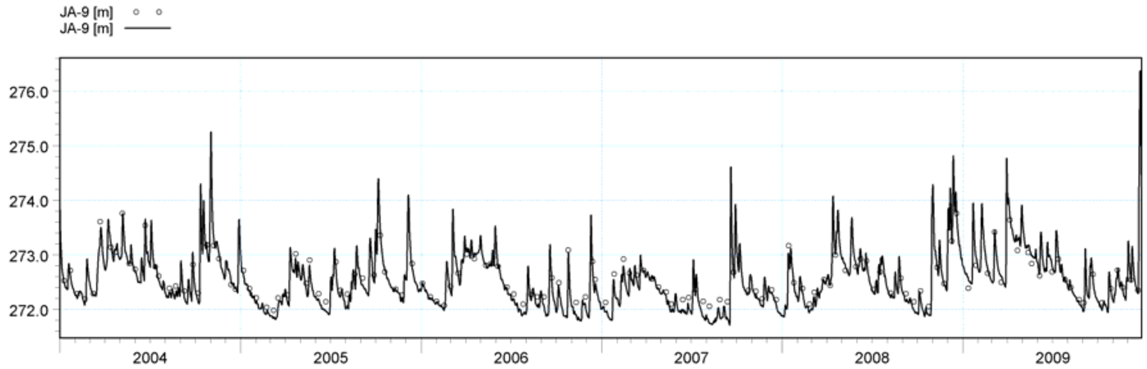
ME=0.0367846
MAE=0.199132
RMSE=0.247725
STDres=0.244979
R(Correlation)=0.875271
R2(Nash_Sutcliffe)=0.585405



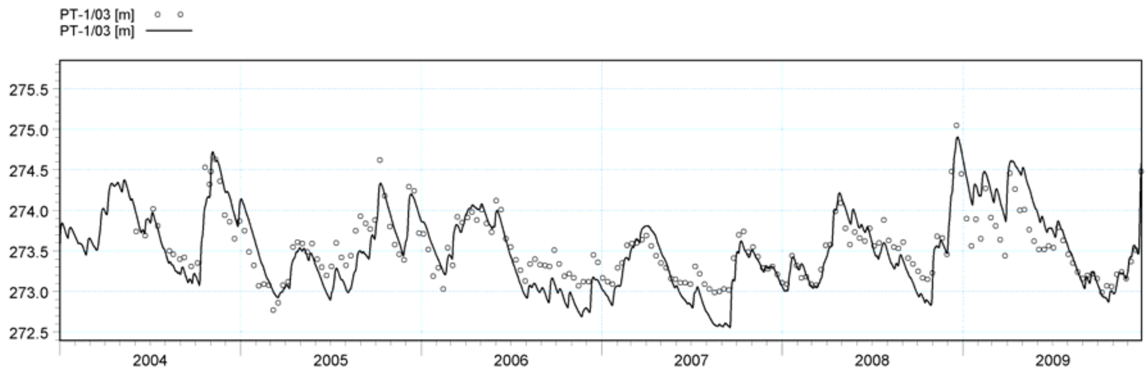
ME=-0.579907
MAE=0.579907
RMSE=0.655379
STDres=0.305335
R(Correlation)=0.80101
R2(Nash_Sutcliffe)=-0.763905



ME=0.188783
MAE=0.229611
RMSE=0.276976
STDres=0.202674
R(Correlation)=0.909477
R2(Nash_Sutcliffe)=0.501034

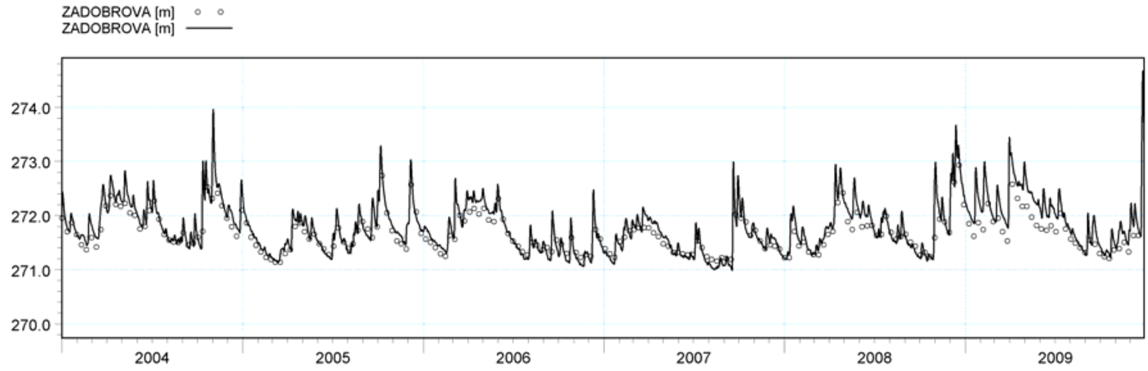


ME=0.0514339
MAE=0.0977006
RMSE=0.123135
STDres=0.111879
R(Correlation)=0.97053
R2(Nash_Sutcliffe)=0.893604

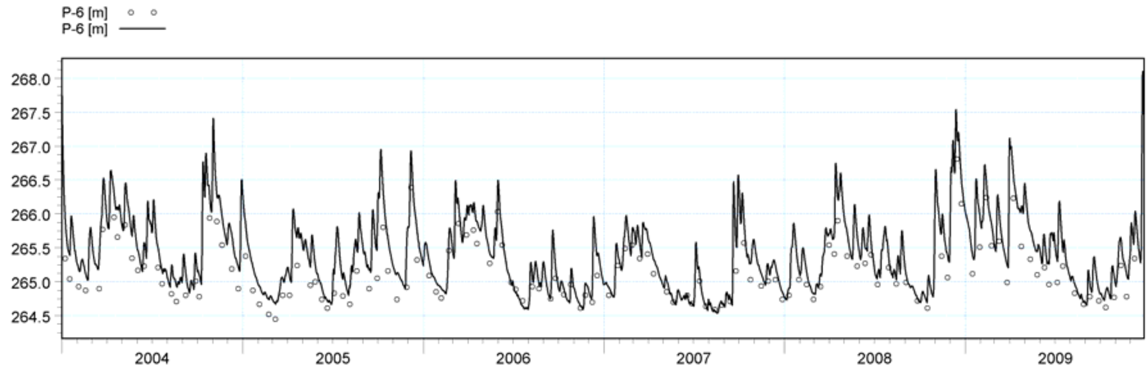


ME=0.0325354
MAE=0.195287
RMSE=0.238568
STDres=0.236339
R(Correlation)=0.883745
R2(Nash_Sutcliffe)=0.600486

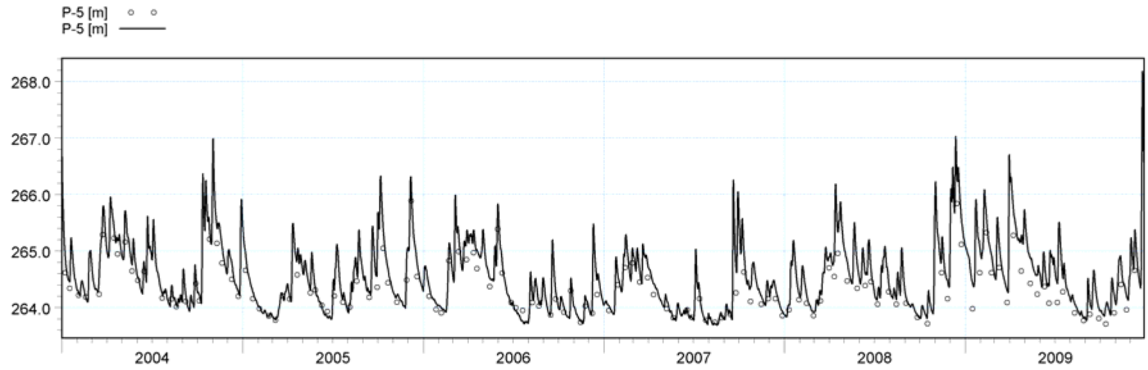
ME=-0.0848839
MAE=0.175636
RMSE=0.219577
STDres=0.202507
R(Correlation)=0.908232
R2(Nash_Sutcliffe)=0.677087



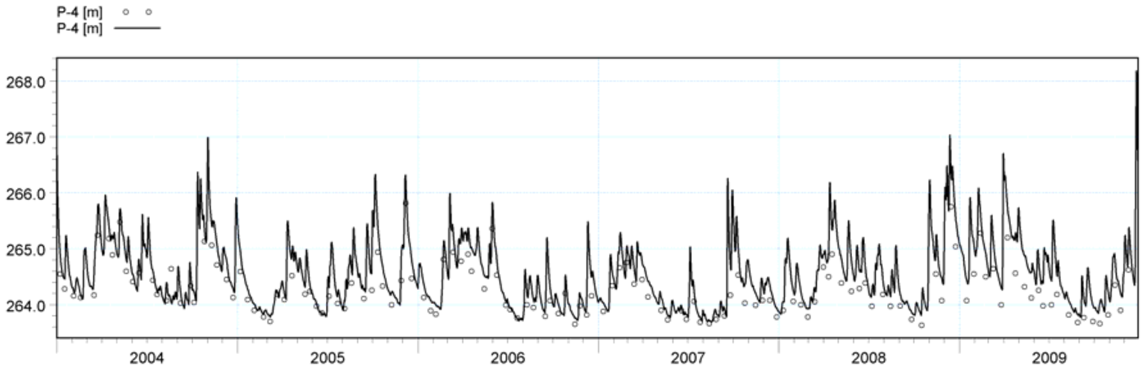
ME=-0.121415
MAE=0.155329
RMSE=0.21437
STDres=0.176671
R(Correlation)=0.931771
R2(Nash_Sutcliffe)=0.622301



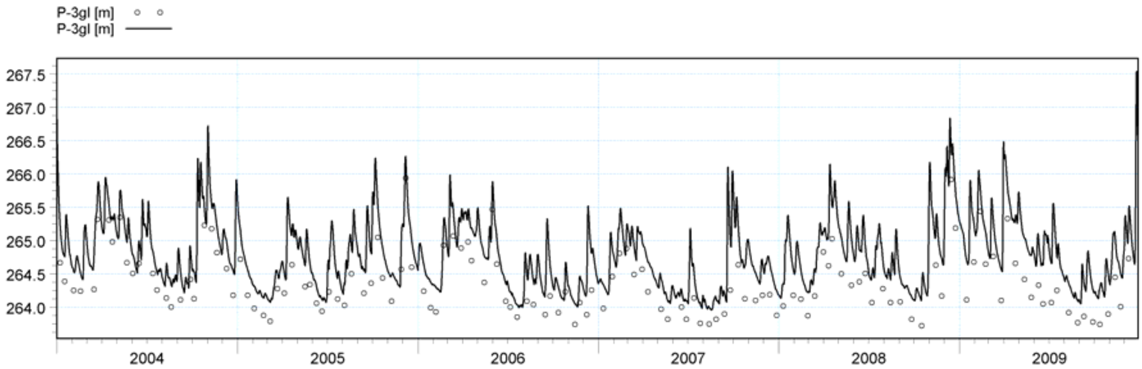
ME=-0.26591
MAE=0.268096
RMSE=0.304281
STDres=0.147914
R(Correlation)=0.971627
R2(Nash_Sutcliffe)=0.48234



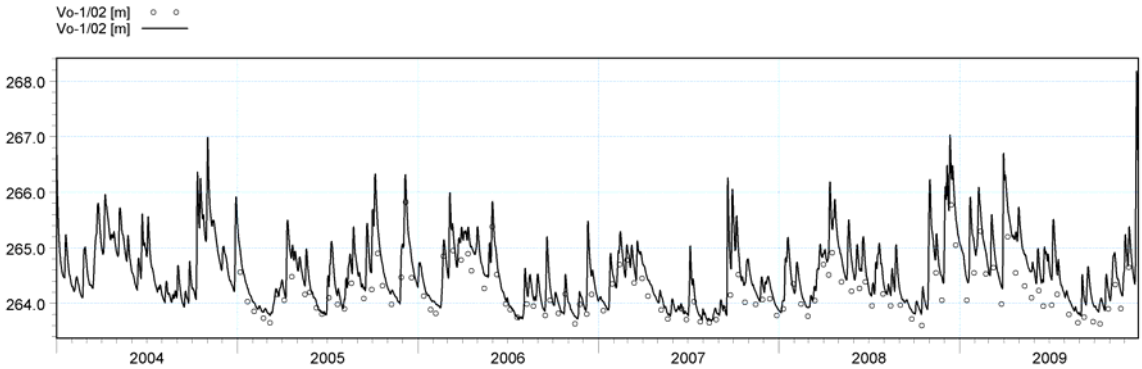
ME=-0.203964
MAE=0.21021
RMSE=0.253754
STDres=0.150963
R(Correlation)=0.977463
R2(Nash_Sutcliffe)=0.656986



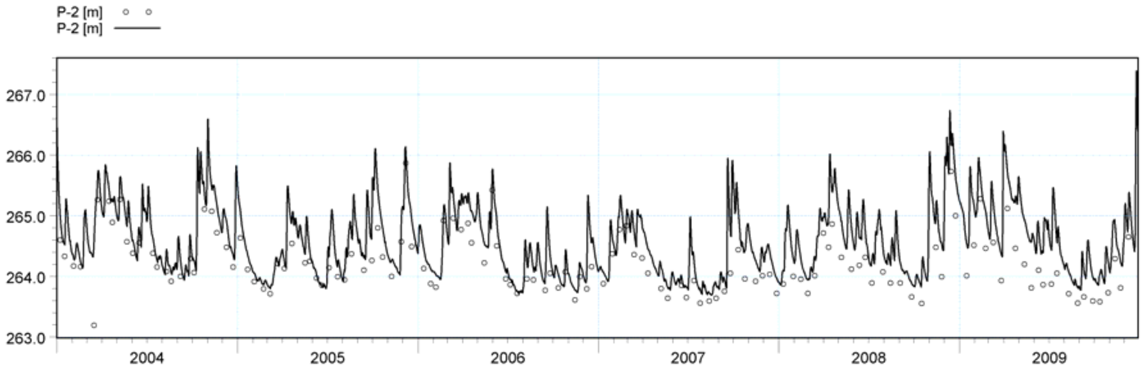
ME=-0.272294
MAE=0.280834
RMSE=0.317667
STDres=0.163609
R(Correlation)=0.964207
R2(Nash_Sutcliffe)=0.488672



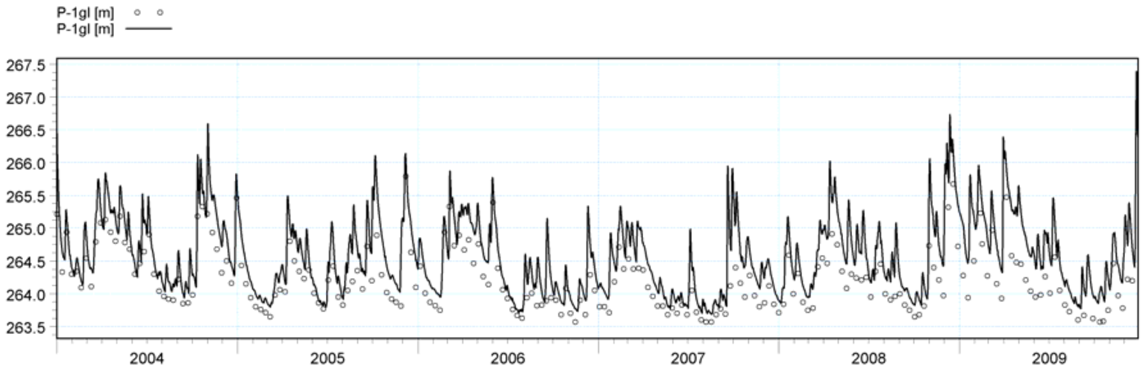
ME=-0.417639
MAE=0.417639
RMSE=0.432659
STDres=0.113013
R(Correlation)=0.972358
R2(Nash_Sutcliffe)=0.0837258



ME=-0.291259
MAE=0.292696
RMSE=0.329061
STDres=0.15313
R(Correlation)=0.973331
R2(Nash_Sutcliffe)=0.431877



ME=-0.35451
MAE=0.354625
RMSE=0.40488
STDres=0.195578
R(Correlation)=0.933305
R2(Nash_Sutcliffe)=0.263858



ME=-0.367948
MAE=0.369093
RMSE=0.406359
STDres=0.172458
R(Correlation)=0.960889
R2(Nash_Sutcliffe)=0.202979