Trabajo Fin de Máster

DEVELOPMENT OF EQUIPOTENTIAL HEAD MAPS IN ZAGREB AQUIFER SYSTEM USING DIFFERENT INTERPOLATION METHODS

Intensificación:
ANÁLISIS DE SISTEMAS DE RECURSOS HÍDRICOS

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ABRIL de 2016

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

máster en ingeniería hidráulica y medio ambiente
mihma

Resumen del Trabajo de Fin de Máster

Datos del proyecto
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Fecha de Lectura: abril de 2016

Resumen
En castellano (máximo 2000 palabras)

El gran y rápido crecimiento que ha experimentado la Ciudad de Zagreb durante las últimas decadas ha causado un incremento de la demanda de muchos de los recursos, entre ellos el abastecimiento de agua. Por tanto el sistema acuífero de Zagreb, como única fuente de agua potable de la ciudad, ha experimentado una disminución de los niveles de agua subterránea, generando cambios en la operación del sistema.

Para analizar esta disminución de niveles es necesario estudiar las características del acuífero como las características geográficas, geología, características pedológicas, hidrogeología, características climáticas y meteorológicas, el Río Sava que es el principal factor que influencia al sistema y los ecosistemas dependientes del agua subterránea. A continuación se procedió a realizar una interpolación espacial de los niveles del acuífero utilizando el software ArcGis mediante cuatro métodos: Ponderación de Distancia Media (Inverse Distance Weight), Spline, Kriging y Vecino Natural (Natural Neighbor). De cada uno de estos métodos se han estudiado las opciones y parámetros a modificar para ver cuál se adapta mejor al sistema. Los datos de entrada utilizados en el estudio fueron los de los niveles más bajos y más altos de los últimos 15 años con datos máximos y mínimos diarios y medios mensuales.

Previamente a la interpolación y debido a la gran cantidad de datos iniciales, se ha realizado un “cluster” de los mismos, seleccionando aquéllos que se consideren necesarios hasta obtener una nube de observaciones homogénea a lo largo de toda la extensión del acuífero.

Tras la interpolación se realizó un estudio de precisión de los resultados respecto de los datos de entrada mediante Pearson-Spearman, Error Cuadrático Medio y el t-test para comparar los resultados obtenidos en los diferentes métodos de interpolación y así ayudar a decidir qué método se adapta mejor a este sistema. El resultado de este estudio no ayudó en la toma de la decisión ya que todos los resultados numéricos de todos los métodos tienen una gran precisión. Por tanto la decisión se tomó teniendo en cuenta los resultados gráficos obtenidos en forma de mapas a través de ArcGis, concluyendo que el método del Vecino Natural aporta resultados más precisos.

Con estos mapas obtenidos directamente de la interpolación en el software se dibujaron los cuatro mapas de niveles del acuífero correspondientes a los valores máximos y mínimos diarios y mensuales, corrigiendo los errores locales propios de la interpolación.

También, de la Tesis se puede concluir que la alta conductividad hidráulica del acuífero lo convierte en un sistema muy dinámico, produciendo grandes cambios en la dirección del flujo no sólo cuando éste se encuentra en niveles máximos o mínimos, sino también cuando se utilizan datos diarios o mensuales. Por ello debe tenerse en cuenta este hecho a la hora de decidirse por un tipo de dato u otro dependiendo del tipo de estudio que quiera realizarse.

En valenciano (máximo 2000 palabras)

El gran i ràpid creixement que ha experimentat la Ciutat de Zagreb durant les últimes dècades ha causat un increment de la demanda de molts dels recursos, entre ells el proveïment d'aigua. Per tant el sistema aqüífer de Zagreb, com a única font d'aigua potable de la ciutat, ha experimentat una disminució dels nivells d'aigua subterrània, generant canvis en l'operació del sistema.

Per analitzar aquesta disminució de nivells és necessari estudiar les característiques de l'aqüífer com les característiques geogràfiques, geologia, característiques pedològiques, hidrogeologia, característiques climàtiques i meteorològiques, el Riu Sava que és el principal factor que influencia al sistema i els ecosistemes dependents de l'aigua subterrània. A continuació es va procedir a realitzar una interpolació espacial dels nivells de l'aqüífer utilitzant el software ArcGis mitjançant quatre mètodes: Ponderació de Distància Mitjana (Inverse Distance Weight), Spline, Kriging i Veí Natural (Natural Neighbor). De cadascun d'aquests mètodes s'han estudiat les opcions i paràmetres a modificar per veure quin s'adapta millor al sistema. Les dades d'entrada utilitzades a l'estudi van ser les dels nivells més baixos i més alts dels últims 15 anys amb dades màximes i mínimes diàries i mitjans mensuals.

Prèviament a la interpolació i a causa de la gran quantitat de dades inicials, s'ha realitzat un “cluster” dels mateixos, seleccionant aquells que es considerin necessaris fins a obtenir un núvol d'observacions homogeni al llarg de tota l'extensió de l'aqüífer.

Després de la interpolació es va realitzar un estudi de precisió dels resultats respecte de les dades d'entrada mitjançant Pearson-Spearman, Error Quadràtic Mitjà i el t-test per comparar els resultats obtinguts en els diferents mètodes d'interpolació i així ajudar a decidir que mètode s'adapta millor a aquest sistema. El resultat d'aquest estudi no va ajudar en la presa de la decisió, ja que tots els resultats numèrics de tots els mètodes tenen una gran precisió. Per tant la decisió es va prendre tenint en compte els resultats gràfics obtinguts en forma de mapes a través d'ArcGis, concloent que el mètode del Veí Natural aporta resultats més precisos.

Amb aquests mapes obtinguts directament de la interpolació al software es van dibuixar els quatre mapes de nivells de l'aqüífer corresponents als valors màxims i mínims diaris i mensuals, corregint els errors locals propis de la interpolació.

També, de la Tesi es pot concloure que l'alta conductivitat hidràulica de l'aqüífer el converteix en un sistema molt dinàmic, produint grans canvis en la direcció del flux no només quan aquest es troba en nivells màxims o mínims, sinó també quan s'utilitzen dades diàries o mensuals. Per això ha de tenir-se en compte aquest fet a l'hora de decidir-se per un tipus de dada o un altre depenent del tipus d'estudi que vulgui realitzar-se.

En inglés (máximo 2000 palabras)

The large and quickly development that the City of Zagreb has experienced during the last decades has caused an increment of the demanded of resources, between them, the water supplied. Thus the Zagreb Aquifer System, as the only source of potable water of Zagreb, has experienced a decrease of the ground water levels generating changes in the operation of the system.

To analyze this decrement of levels is necessary to study the characteristics of the aquifer: geographic characteristics, geology, pedologic characteristics, hydrogeology, climatic and meteorological characteristics, the Sava River and ground water dependent ecosystems. Next, it was done the spatial interpolation of the aquifer levels using the software ArcGis through four methods: Inverse Distance Weight, Spline, Kriging and Natural Neighbor. The option and parameters of each one of those methods were studied and modified to check which one fits better to this system. The initial data used were the lowest and highest for 15 years with maximum and minimum daily and average monthly data.

Before to interpolate and due to the large amount of data, it was done a cluster of them, selecting those data which made a homogeny cloud of observation wells.

After the interpolation, it was made an accuracy study using Pearson-Spearman, Root Mean Squared Error and t-test comparing the initial data with the final results of each method. The goal of this study was to help to decide which method was the best one, but it did not work because the result of the four methods was very accurate. So that, the choice was decided through the plots that ArcGis gave, being the Natural Neighbor the method more accurate.

These maps obtained by the interpolation in the software were used for draw the four final maps of aquifer levels: maximum and minimum daily levels and maximum and minimum average monthly; correcting the local errors that the interpolation drew.

Moreover, some conclusions could be gotten. First of all, the very high hydraulic conductivity, become it in a very dynamic system, generating changes in the direction of the flow depending on the level aquifer and if

daily or monthly data are used. Due to, it should be used different kinds of data depending on the scope of the study, because if this is not considered, the yielded results could be wrongs.

Palabras clave (máximo 5): Zagreb Aquifer System, Spatial Interpolation Methods, Ground Water Levels.

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1. INTRODUCTION

1.1 ZAGREB AQUIFER SYSTEM

The Zagreb Aquifer System is the only source of potable water of city of Zagreb. During last years, the water levels have decreased due to Zagreb has increased very quickly its population reaching more than one million of people. This fact, with the climatic change, become pretty important to study it to know how the system works and which has been the impacts of this increment of the demand help to predict the behavior in the future.

This system is influenced by some factors. The most important is the Sava River which crosses the aquifer from west to east. Also there is a river dam in Sava, this building lays up an amount of superficial water that modifies the operation of the aquifer. Finally, the pump fields are very important because they extract the water that supplies the city of Zagreb.

These factors and the high variability of the hydraulic conductivity of the aquifer generate big changes in the movement of the ground water, being completely different with low and high levels or with monthly average and daily data.

1.2 OBJECTIVE OF THE STUDY

This Thesis is going to study different interpolation methods to decide which one gives better results fitting to the reality of the system.

To do the interpolation, it is going to be used the software ArcGis with its Spatial Interpolation tool, which uses four different methods: Inverse Distance Weight, Spline, Kriging and Natural Neighbor. Then, after the interpolation, the results are going to be used to draw maps of equipotential lines with the different data.

Finally, through these maps, the difference between the movements of the flow will be shown when daily and monthly data or low and high level are used. Then it will be able to say when it should be used some data or the others.

2. INVESTIGATION AREA

2.1 GEOGRAPHICAL CHARACTERISTICS

The study is focused in the Zagreb aquifer system, which is situated in the Northwest side of Croatia, with an extension of 350 Km^2, covering the city of Zagreb and part of the Zagreb County (FIG. 2.1).

This region is formed by a large alluvial plain bordered in the north and northwest by a mountain range, Mt. Medvednica and Mt. Žumberak. The study area consists of great diversity of lithological, pedological and land use characteristics. The northern and northwestern side is formed by mountain systems with big differences in topographical elevation, from few hundred meters to over 1000 meters. In the west and southwest, it predominates a region with soft slope and terraced landscape. Regarding to the elevation, it ranges between 150 and 250 meters. Finally, the center part of the study area consists in a floodplain with flat morphology and elevation around 100 m. This area is crossed by Sava River, the longest and most important river in Croatia, which is in direct contact with the aquifer and it is used as main source of supply water of the City of Zagreb.

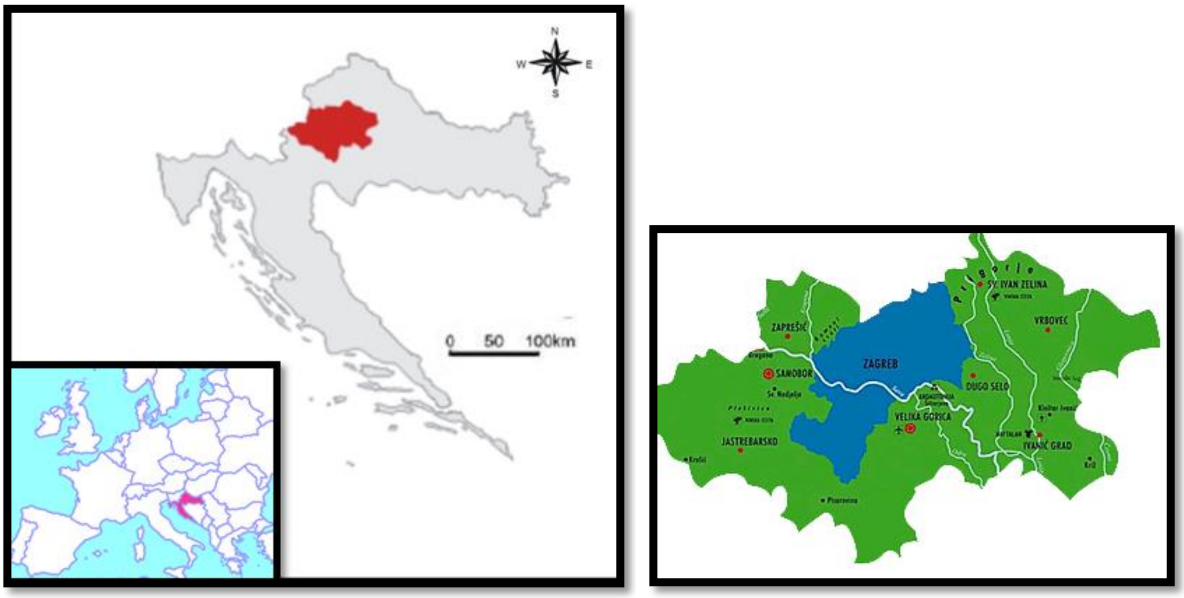


Figure 2.1: Geographical position of Zagreb county and City of Zagreb.

2.2 GEOLOGY

The study area is formed by Quaternary age sediments. The north edge, Mt. Medvednica, is an extension of the Mid-Transdanubian terrain. The northwest area is composed of an extensive Lower Cretaceous magmatic-sedimentary rocks complex. This area is in tectonic contact with a formation of low-grade metamorphic belongs to Middle to Late Palaeozoic from northeast to southeast (ŠIKIĆ et al., 1979; BASCH, 1981).

Tectonically, Mt. Medvenica is an elevated structure where the ENE-striking marginal faults of the Neogene due to recent N-S-directed compression. The tectonic activities have formed local depressions and elevations. The Sava River depression was made by tectonics movement at the end of Pleistocene and beginning of Holocene. Also, Neogene structures started to descend causing breakthrough for water mass and forming the Zagreb depression (ŠIKIĆ et al., 1979) (FIG. 2.2).

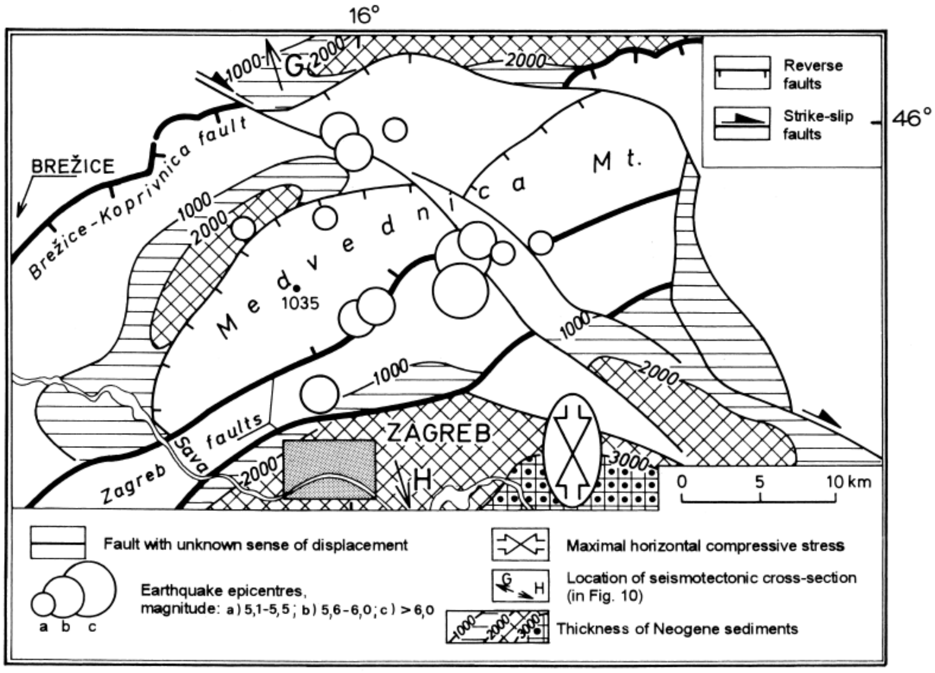


Figure 2.2: Seismotectonic activity of the Medvednica fault zone. The ENE-striking marginal faults delimit a zone where reverse faults are most prominent and where the strongest earthquakes occur (PRELOGOVIĆ et al., 1998).

The Zagreb aquifer system belongs to Quaternary age, specifically the Middle and Upper Pleistocene and Holocene. Firstly, the Middle Pleistocene is characterized by have an uniform composition separates in two zones. On the one hand, the lower and middle part is mainly comprised of grey sands and, on the other hand, the upper part is composed of grey or red to yellowish-brown mottled silt and clay sized particles. The top of these sediments were affected by pedogenic processes during the warm periods (VELIĆ & DURN, 1993; VELIĆ & SAFTIĆ, 1996) (FIG. 2.3).

Secondly, the Upper Pleistocene unit is composed by constant changes of gravel, sands, silts, and clays. The top of this unit is formed by varves, as alternating, millimeter thick light colored, fine-grained sands and dark grey to black silts. The Upper Pleistocene was occupied by lakes and swamps, while the mountains terrain that surround them were exposed to intensive erosion and denudation. Because of this, the worn material, mainly siliciclastics particles, was transported by runoff processes and deposited into lakes and swamps (VELIĆ & SAFTIĆ, 1991) (FIG. 2.3).

Finally, The Holocene unit is formed by gravels, from pale to yellowish-grey, and sands with predominance of limestone blocks. These kinds of materials are situated in the Holocene sediments. In this period was formed the Sava River channel. At that time the river transported particles from the Alpine region, predominantly of carbonate composition (VELIĆ & DURN 1993). The climatic changes had a very important influence in the intensity of the material transported. During the warm and wet period the amount of the material transported was high, but it decreased significantly in dry and cold periods. Moreover this processes varied due to the influence of tectonic movements (VELIĆ et al. 1999). These changes in transport material have made important conditions of heterogeneity and anisotropy in the geological environment of the Zagreb aquifer system (FIG. 2.3).

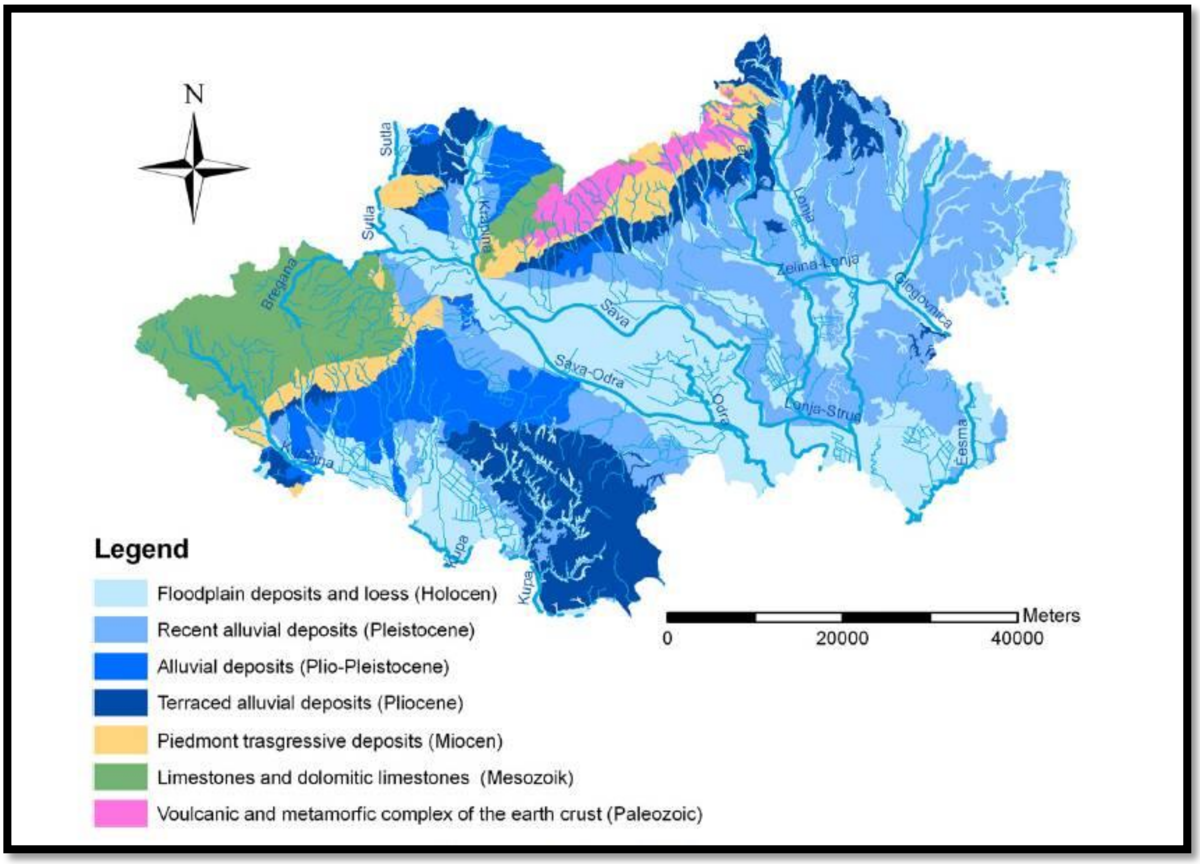


Figure 2.3: Simplified geological and geomorphological map of Zagreb and Zagreb county (SOLLITTO et al., 2010).

2.3 PEDOLOGICAL CHARACTERISTIC

The study area is characterized by a large heterogeneity of the parent material, which joined with the climate characteristics and geomorphology of the surrounding region has caused the creation of a great variety of soil types. The floodplain soils are composed by sediments eroded from the catchment area. Its mineralogical, chemical and textural properties are result of the Sava River flow as well (FIG. 2.4). Since Holocene age, several materials have been developed like Molic Fluvisols, Calcaric Fluvisols, Eutric Cambisols, Eutric and Calcic Gleysols. As well, in Pleistocene terraces predominates Stagnic Podzoluviols and Glayic Podzoluviols.

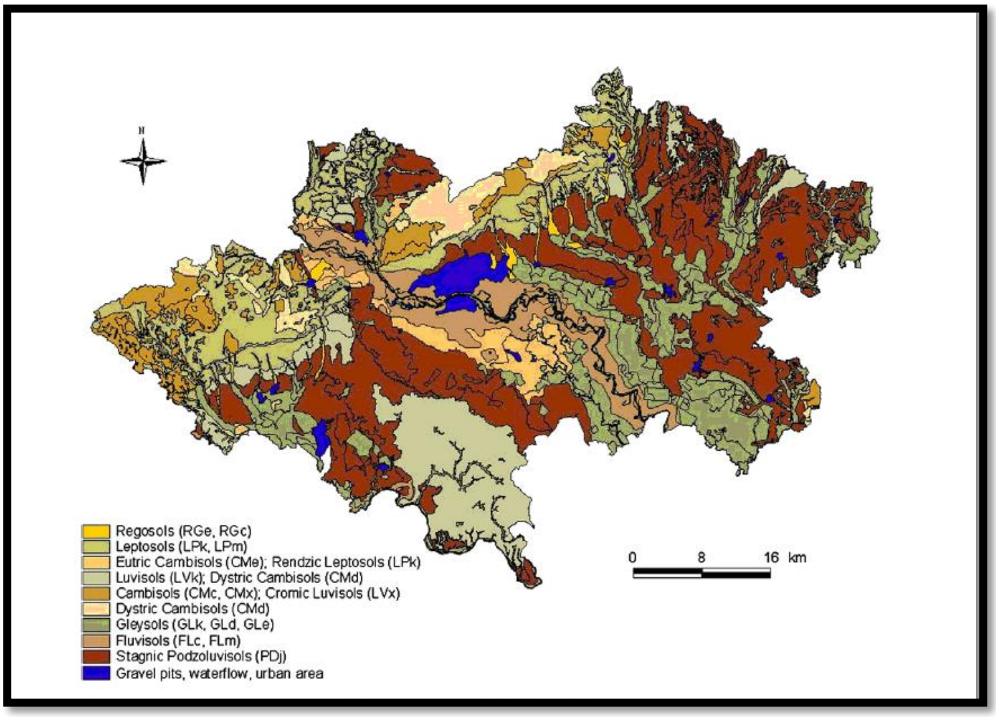


Figure 2.4: Pedological map of Zagreb and Zagreb county area (BOGUNOVIĆ et al., 1998). Simplified by SOLLITTO et al., 2010.

The main pedologic units in the Zagreb aquifer are: Fluvisol, Stagnic Podzoluvisols and Eutric Cambisols (BOGUNOVIĆ et al., 1998).

Fluvisol material is on alluvial plains, river fans and valleys (FAO, 1998). This soils use to be regular. They are wet due to the stagnant groundwater and/or flooded river water. It exits growth of vegetation because there isn't groundwater elevation in rhisosphere zone and the physical, chemical and biological characteristic are positives. The textures of those zones are loam or clayey loam and the structure is crumb to blocky (ROMIĆ et al., 2005).

Stagnic Podzoluvisols is hydromorphic soil which belongs to Stagnosol class. These kinds of soils have water causing redoximorphic features. They are formed in a great kind of unconsolidated materials like glacial till and loamy aeolian, alluvial and colluvial deposits. The process happens in regions with gently slope and in cool temperate to subtropical climes (FAO, 2007). The stagnant rainfall water generates much wetting causing hydromorphic processes. Finally, the texture of this soils is silty-clay-and loam and the structure is granular and very unstable (ROMIĆ et al., 2005).

Eutric Cambisols soils are result of primary minerals decomposition. They mix soils with at least a subsurface soil formation. Cambisols are composed by parent material and illuviated clay, organic matter and Al and/or Fe compounds (FAO, 2007). In Zagreb aquifer area the, Cambisols soil has been development since Holocene deposits. The texture is silty-clay to clay-loam and mainly loamy and the structure is granular and very stable. Moreover this kind of soil is very porous and permeable and it is very favorable for cultivation.

2.4 HYDROGEOLOGY

Below the urban area of Zagreb is situated the aquifer system. It is composed by Upper Pleistocene and Holocene deposits of the Sava River plane, which extends along the river and it is bounded, at the north, for Mt. Medvednica and, by the south, for Vukomeričke Gorice hills.

The Sava River is the longest one in Croatia and it divides the Zagreb water bearing in two parts. This is the most important source of groundwater recharge, connected with the shallow layer with very high levels of hydraulic conductivity. The Zagreb aquifer system is exploited for the water supply of the City of Zagreb and part of Zagreb County. That means that water is extracted for more than one million of citizens. This is the only source of potable water, hence it has a great importance for the city. The water is obtained by pumping of six well fields exceeds the annual renewable groundwater reserves. The average resources has been estimated in 107×10^6 m^3/year from 1997-2007, while 125×10^6 m^3/year were pumped in the same period. This difference was covered by the permanent groundwater reserves, which have decrease from 1.81×10^9 m^3 in 1977 to 1.68×10^9 m^3 in 2007 (BAČANI et al., 2010).

The hydrogeological conditions of the Quaternary materials may be divided in three different units: first of all, a layer composed by clay and silt. Next, a high Holocene aquifer formed by medium-grain gravel mixed with sands. And finally, a deeper aquifer Middle and Upper Pleistocene containing constants lateral and vertical alterations of gravel, sand and clay.

The Zagreb aquifer system is an alluvial aquifer. It contains important semi-permeable silt-clayey deposits, forming a layer called aquitard. This aquitard has a lower thickness in the western side (< 1m), even there are zones no cover or soil is present, while the aquifer advances to the eastern side, the thickness increases until 50-70 meters (FIG. 2.5).

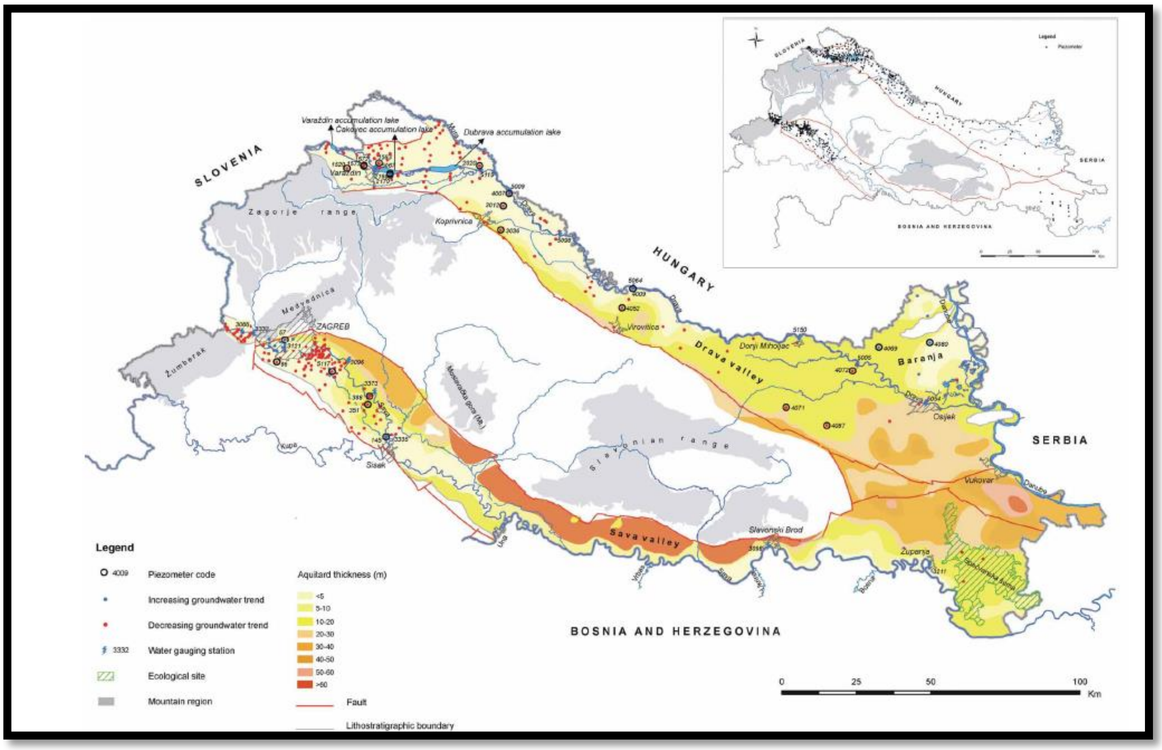


Figura 2.5: Monitoring network for groundwater and surface water levels and thickness of aquitard in northern Croatia (BRKIĆ et al., 2010).

Due to this, the sheet of water of the Zagreb aquifer is subject to atmosphere pressure, that is to say, unconfined aquifer. Hydraulically, the north edge of the aquifer is impermeable formed by clayey deposits, the west and south edges are inflow sides and the east edge is the outflow. Because of this, the main direction flow of the ground water is from west to east and southeast. Posavec (2006) researched the south border of the aquifer through of equipotential maps for annual high, medium and low levels of groundwater, concluding that inflow exists along this edge with different intensity depending of the zone (FIG. 2.6).

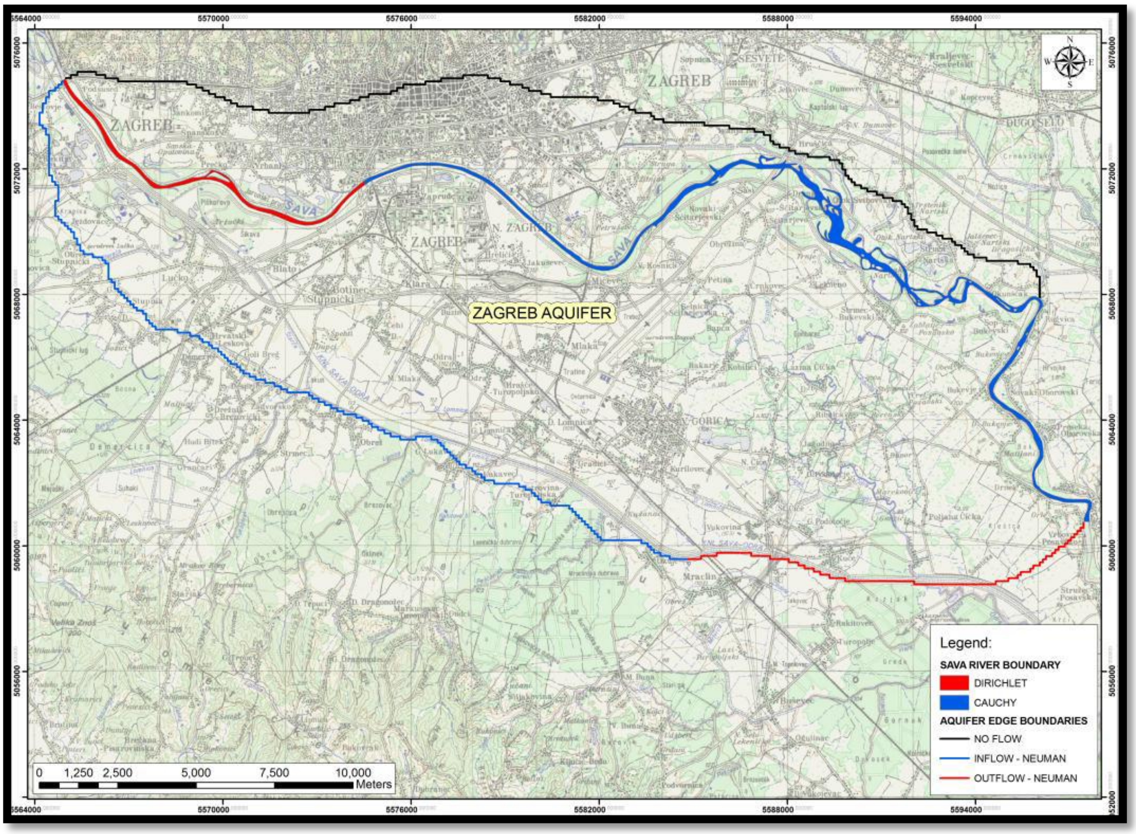


Figure 2.6: Boundary Conditions (Deliverable D4.2 version 2.0, 2011, GENESIS).

The Zagreb aquifer system can be divided in two layers: the first one, composed by alluvial deposits of the Sava River from the Alps during the Holocene age, and the second one, built of sand and gravel from the surrounding mountains, which forms lake or pond layers (FIG 2.7). The impermeable material of the roof can no exist or to increase throughout the aquifer to 15 meters in the south-eastern side and along the edges. The thin impermeable roof was devastated, and then it is not be able to protect the groundwater system of the surface pollution. The bottom of the aquifer system is composed by impermeable deposits, forming the water bearing system bedrock.

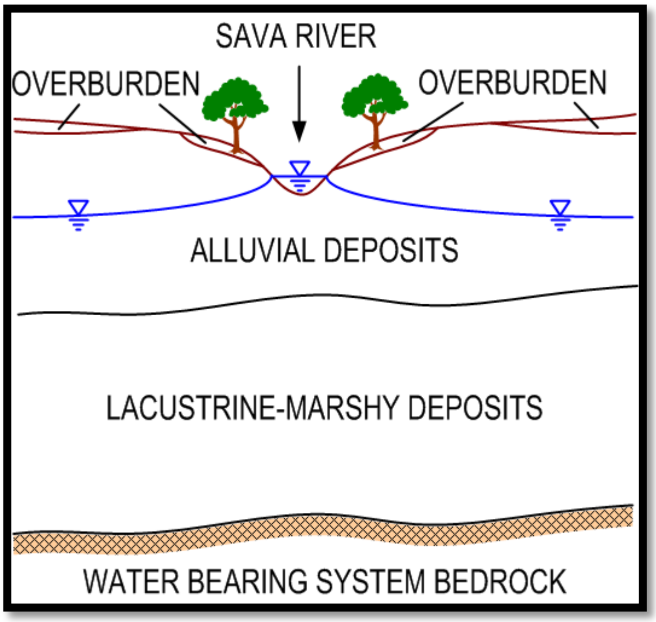


Figure 2.7: Schematic profile of the Zagreb aquifer system (POSAVEC, 2006).

Analyzing a map of headequipotentials of the Zagreb aquifer system, the next results are obtained: Sava River is drained by the aquifer along the all course in the study area during high waters period. However, when there are medium and low waters, just in certain zones, the river fills the aquifer, causing negative impacts to the groundwater levels which mean that it decreases the available quantities of groundwater during the drought periods. The Sava's riverbed crosses alluvial deposits that belong to Holocene age. This material is characterized by an exceptionally high hydraulic conductivity, being mainly gravel beds. The hydraulic conductivity decreases from western side of the aquifer to eastern side, varying from 3000 m/day to 1000 m/day (URUMOVIĆ & MIHELČIĆ, 2000). A very strong correlation exists between the water level of Sava River and the groundwater level along the entire course in the study area. This is so strong that the river fills about 73% to groundwater renewal (MILETIĆ & BAČANI, 1999) (FIG. 2.8).

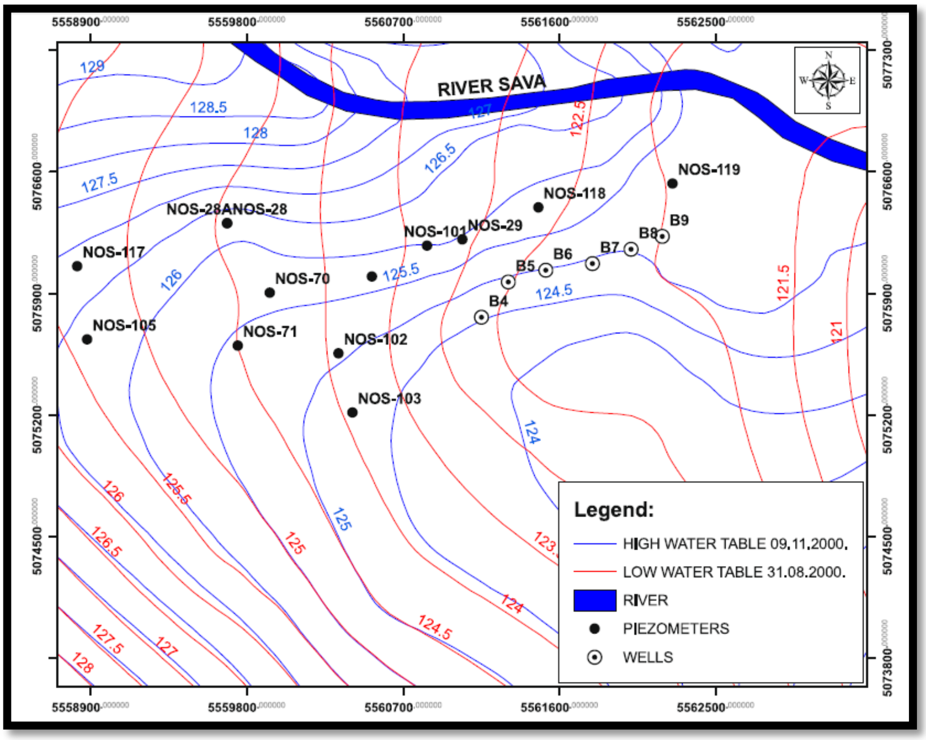


Figure 2.8: Map of Headlines (VLAHOVIĆ, T. et al., 2008).

The main contributors which fill the aquifer are: infiltration from the Sava River, infiltration for precipitation, infiltration for supply and sewage network and inflow from neighboring Samobor aquifer along the western edge and Vukomeričke Gorice hills along southern edge.

Moreover, there are two actions with an important influence in the Zagreb water bearing: the well field catchment and the Dams in Sava River. Since 1983 it has had an increase in catchment by pumping well, from 3300 l/s to 4700l/s. This has been associated with the fast growth of both the city and the population, but also the water supply network that losses around 40%.

The aquifer water levels are also very conditioned by the small river dam. An average drop of the Sava River water level amounts 0,4 m/km while the drop of the water level downstream from the river dam is higher, reaching to 6 m on less distance. This affects the water flow directions and levels in close vicinity of the river dam as is showed in the next figure (FIG. 2.9).

Also there are others reasons that affect to the groundwater levels: extensive riverbed erosion due to upstream Sava River regulation in Republic of Slovenia; the building of an embankment for avoid the occasional flooding the urban area and potential infiltration to groundwater; long drought periods. The consequence has been that the groundwater levels have reached the minimum levels.

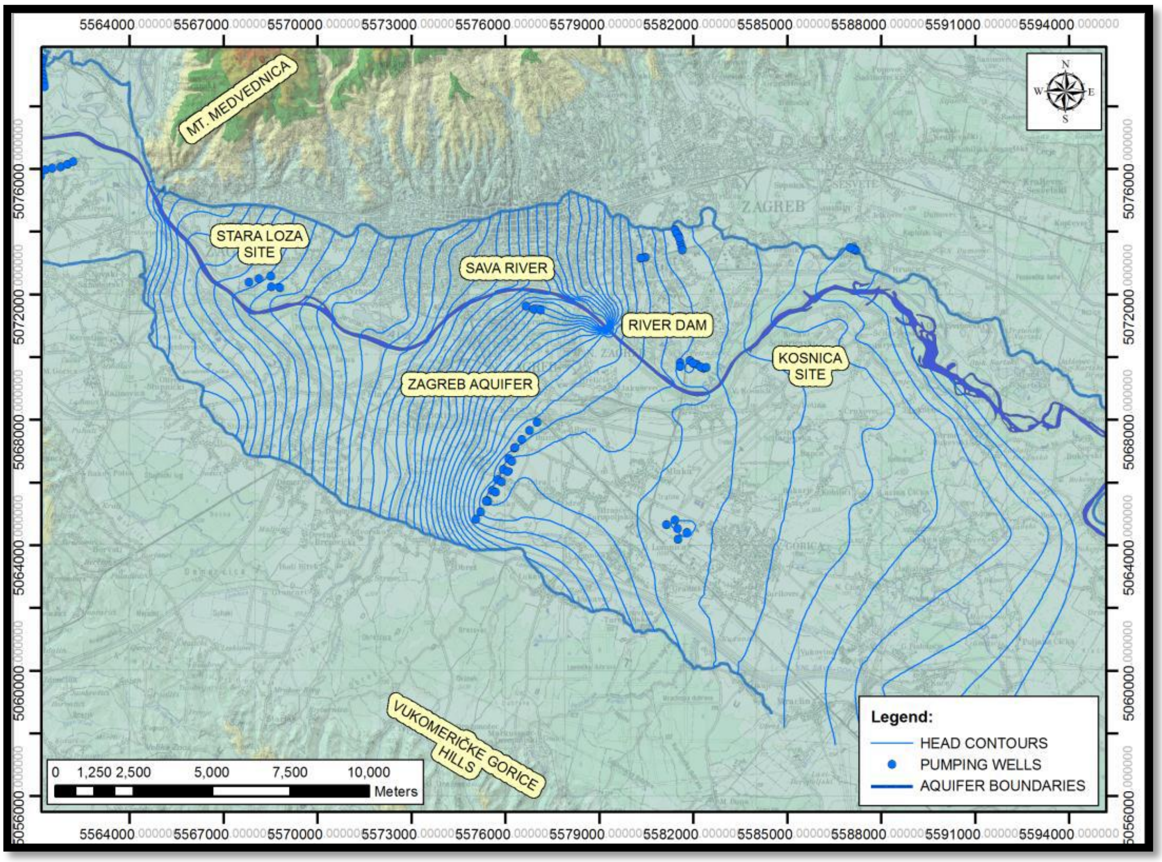


Figure 2.9: River dam location and head contour maps showing impact on ground water flow direction in near vicinity of the river dam. (Deliverable D4.2 Version 2.0, 2011, GENESIS).

Moreover the thickness of the aquifer affects to the regularity of the equipotential lines. The eastern side has higher thickness than the western side, generating more irregularities in the observation wells. This eastern side of the aquifer is highly influenced by the well fields and and river dam and, in the northern side of Sava River, by the city of Zagreb, where the underground buildings and the waterproofing of the soil modify the aquifer flow (FIG 2.10).

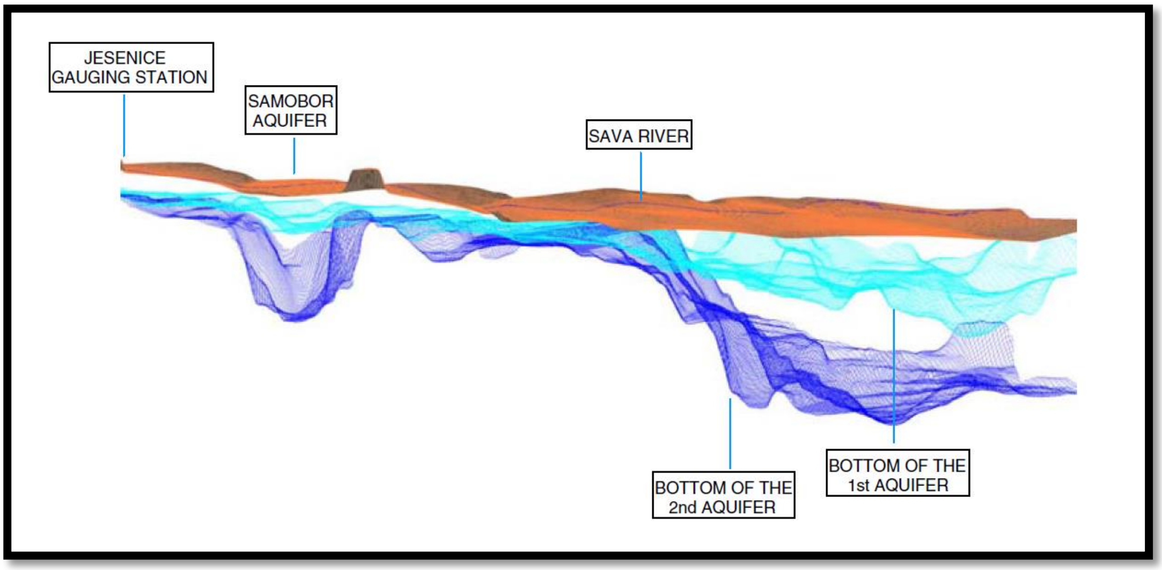


Figure 2.10: Three-Dimensional Model of Zagreb Water-Bearing System (VLAHOVIĆ et al. 2008)

2.5 CLIMATIC AND METEOROLOGICAL CHARACTERISTICS

The region of Zagreb has a climate denominated as a moderately continental climate (Cfwbx in Köppen climate classification system). Each season is different from de other, but without a discernible dry season. The winters are cold and the average temperature is -0.5 ºC, it is in those months when snowfall is more probably. The summers are warm and the average temperature is 20.0 ºC. Moreover, rain and fog are common during the autumn (FIG. 2.11).

Table 1: Average climatic data for Zagreb study area (Croatian Meteorological and Hydrological Service).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C	19.4	22	26	29.4	33.4	37.6	40.4	39.8	32.8	28.3	25.4	22.5	40.4
Average high °C	3.1	6.1	11.3	16.4	21.3	24.6	26.7	26.2	22.3	16.2	9.3	4.4	15.7
Daily mean °C	-0.1	2	6.2	10.9	15.7	19.1	20.8	20	16	10.8	5.7	1.3	10.7
Average low °C	-4	-2.5	0.9	4.9	9.2	12.7	14.2	13.7	10.4	5.8	1.8	-1.9	5.4
Record low °C	-24.3	-27.3	-18.3	-4.4	-1.8	2.5	5.4	3.7	-0.6	-5.6	-13.5	-19.8	-27.5
Precipitation mm	48.6	41.9	51.6	61.5	78.8	99.3	81.0	90.5	82.7	71.6	84.8	63.8	856.1
Avg. rainy days	10.8	10.0	11.2	12.7	13.2	13.6	10.9	10.4	9.8	10.2	12.2	12.1	137.1
Avg. snowy days	6	5	4	1	0	0	0	0	0	0	2	5	23
Sunshine hours	59.4	95.7	140.1	175.4	234.0	243.7	281.0	256.0	186.7	130.8	65.6	44.9	1,913.3

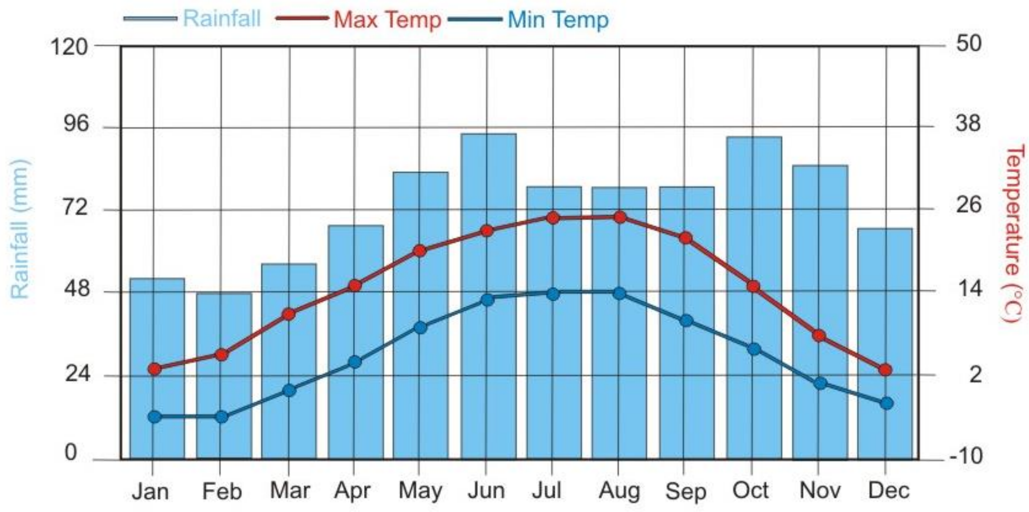


Figure 2.11: Climatic chart of Zagreb with average values for temperature and rainfall (Croatian Meteorological and Hydrological Service).

2.6 SAVA RIVER

The Sava River is the mainly source of water for the Zagreb aquifer system, because of this, it is really important to know how it works. Sava River is the major sub-basin of the Danube River, it cross five countries: Slovenia, Croatia, Bosnia and Herzegovina, Montenegro and Serbia.

The Sava River Basin covers a total area of 97713 Km^2 and its length is 945 Km approximately. The elevation ranges between 2864 m a.s.l. in Slovenia and 71 m a.s.l. in Serbia (FIG. 2.12).

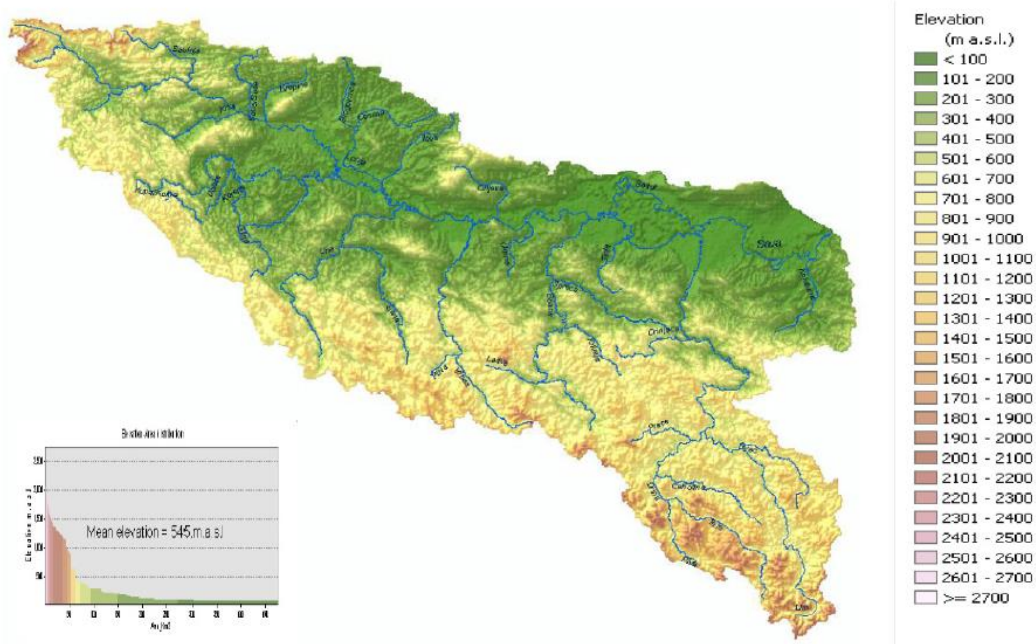


Figure 2.12: Relief of Sava River Basin (BABIĆ-MLADENOVIĆ, M. et al., 2013).

The river course can be divided in three parts: Upper, Middle and Lower Sava. The Upper Sava comprises from the confluence of Sava Dolinka and Sava Bohinjka to Rugvica, it means 658 km of length. The catchment area is composed by mountains and hills. The Middle Sava is 178 km, from Rugvica to the mouth of the Drina River. It is a lowland area with alluvial section of several floodplains and confluence of tributaries. Finally, the Lower Sava, from downstream of Drina River to Danube River, is 100 km of length (BABIĆ-MLADENOVIĆ et al,. 2013).

The average precipitation is estimated about 1100 mm, varying between 2200-2300 mm in mountainous areas and 600-700 mm in northern regions. Most of the rain occurs at the end of summer and autumn, having an important part of the precipitation form of snow. Due to this, in spring there is high runoff. The average discharge from the Sava to Danube is about 1700 m^3/s (BABIĆ-MLADENOVIĆ et al,. 2013) (FIGs. 2.13, 2.14).

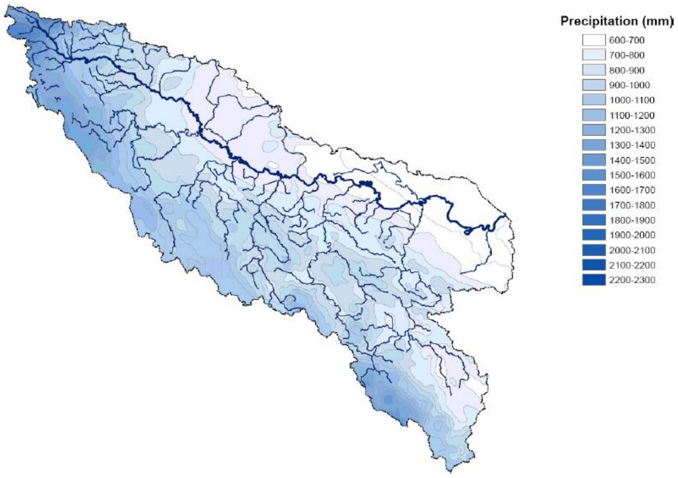


Figure 2.13: Mean annual precipitation in the Sava River Basin (The Danube and its Basin – Hydrological Monograph, 2006).

Figure 2.14: Mean annual runoff in the Sava River Basin (The Danube and its Basin – Hydrological Monograph, 2006).

2.7 GROUND WATER DEPENDENT ECOSYSTEMS

An ecosystem is dependent of the groundwater when its composition, structure and function are, directly or indirectly, connected to the groundwater, even if this connection is seasonal or occasional. Through this connection the aquifer provides water, nutrients, buoyancy and stable temperature (KLOVE et al., 2011).

There are not too much information about this union between the ecosystems and the Zagreb aquifer system but exists a clear relationship between the groundwater and the ecosystems belong to Sava River and phreatophytic ecosystems. Any physical, chemical or biological change in the ecosystem could affect to the environment.

On the interface of aquifer and river is the hyporheic zone. It is formed by alluvial material from bottom and sides of the river channel where there is an exchange between groundwater and river water through interstitial movements. Due to this water exchange, it is an area susceptible of pollution. The typical contaminants in Zagreb aquifer are: the sewage network; agricultural contaminants (pesticides, herbicides and fertilizers); accidental or industrial activity waste; salt introduced by road salting.

Another ecosystem is the riparian zone which is between the river and land. This area extends along the river banks and it is characterized by hydrophilic plants. It has much importance because it works like a natural biofilter, avoiding excessive sedimentation, pollution and erosion. In Zagreb area, the riparian zone is damaged because of the river regulation.

Phreatophytic zone exists when the groundwater is available by vegetation for transpiration. Duo to the shallow and unconfined layer aquifer, plant can extract it just extending their roots. Changes of water bearing regime can affect seriously this zone.

3. METHOD: SPATIAL INTERPOLATION

Interpolation is a tool used for predict values for cells without data from other cells which have sample data points. It is used to calculate unknown values for any geographic point data of many types: elevation, rainfall, chemical concentrations and others, between is groundwater levels (FIGs. 3.1, 3.2).

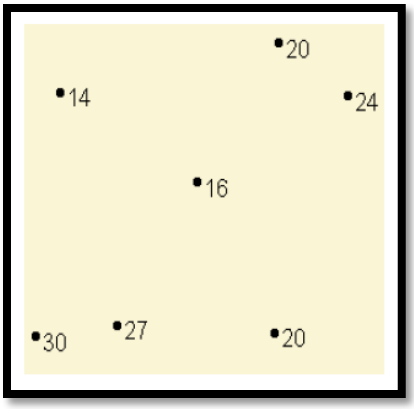


Figure 3.1: Point dataset of known (MCCOY, et al., 2001-2002).

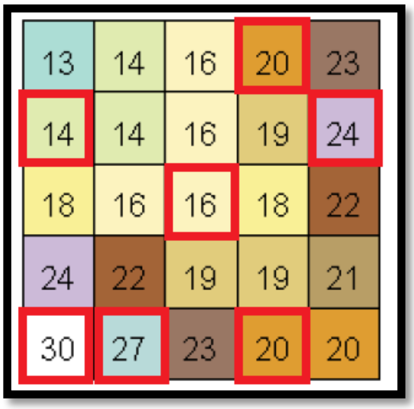


Figure 3.2: Raster Interpolated from the points. Cells highlighted in red indicate the values of the input point dataset (MCCOY, et al., 2001-2002).

The interpolation is really useful because it enables to get a complete map through sample input points dispersed strategically, avoiding visit the study area to measure the height, magnitude or concentration, which usually is difficult or expensive.

The importance of the mistakes made during the interpolation is related with the sample data inputs. It means, it will be a good interpolation if the spatially distributed points are spatially correlated because neighboring points usually have similar characteristics. Because of that, the obtained values of points close to sampled points are nearer to the real values.

Spatial interpolation can be done through deterministic or geostatistical techniques.

- The deterministic interpolation techniques use the measured points to create surfaces, based in similarity between points or the degree of smoothing. These techniques can be divided in global or local. Global techniques interpolate using everything measured data, while the local techniques use the measured points within neighborhoods, it means use smaller areas within the study area. The Inverse Distance Weight, local polynomial and radial basis functions are local interpolators. And global polynomial is a global interpolator. Moreover, the deterministic interpolation can force to a resulting surface to pass or not through the data values. There are exacts techniques, which predict a value identical to the measured, and inexact interpolators that predict a different value. The last one can be used to avoid sharp peaks or troughs in the output surface.
- Geostatistical interpolation techniques create surface using the statistical properties of the measured points. They quantify the spatial autocorrelation among measured points and account for the spatial configuration of the sample points around the prediction location. Due to these are statistical techniques, not only predict the surface, also they calculate the error or uncertainly surfaces. Also these techniques can create probability and quantile output maps. All the geostatistical methods belong to Kriging family.

3.1 INVERSE DISTANCE WEIGHTED

The Inverse Distance Weighted (IDW) interpolation use the reasoning that points closer than others, regarding one point, are more similar. It means that the surrounding measured values will be used to predict the unmeasured point. To predict it, the closest measured points will have more influence that the farther away. Thus, IDW assumes that the measured points have a weight that decrease with distance.

The general formula is (3.1):

$$\hat{\mathbf{Z}}(\mathbf{S_0}) = \sum_{i=1}^{N} \lambda_i \, \mathbf{Z}(\mathbf{S_i}) \qquad (3.1)$$

Where:

- $\hat{Z}(S_0)$ is the value it is trying to predict for location S_0.
- N is the number of measured points surrounding the prediction location that will be used in the prediction.
- λ_i are the weights assigned to each measured point that it is going to use. These weights will decrease with the distance.
- $Z(S_i)$ is the observed value at the location S_i.

The formula to determine the weights is the following (3.2, 3.3):

$$\boldsymbol{\lambda_i = \frac{d_{i0}^{-P}}{\sum_{i=1}^{N} d_{i0}^{-P}}} \tag{3.2}$$

$$\boldsymbol{\sum_{i=1}^{N} \lambda_i = 1} \tag{3.3}$$

Where:

- As the distance becomes larger, the weight is reduced by a factor of p.
- The quantity d_{i0} is the distance between the prediction location S_0 and each of the measured locations S_i.

The power parameter p marks the differences of weighting between the measured values regarding the location value of the prediction. It means that the influence decrease exponentially when the distance increases. The weights of the measured values used for the prediction will have to sum 1.

3.1.1- THE POWER FUNCTION

The optimal p value is determined by minimizing the Root-Mean-Square Prediction Error (RMSPE). In cross-validation, the measured point is removed and compared to the predicted value for that location. To identify the optimal power it tries with several values of p to find the minimum RMSPE. As show below, the RMSPE is plotted with several values of p and the optimal will be the minimum RMSPE (FIG. 3.3).

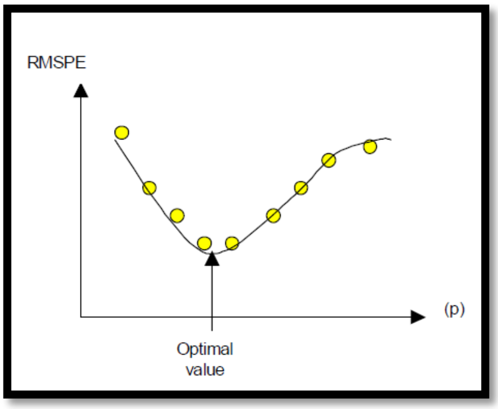


Figure 3.3: Minimum RMSPE (Using ArcGis Geostatistical Analyst, 2001).

The weights are inversely proportional to the distance raised. As show in the figure below, when the distance raised, the weights decreases exponentially. If p = 0, the weight does not decrease with the distance, but if p increases, just the immediate few surrounding points will influence the prediction (FIG. 3.4).

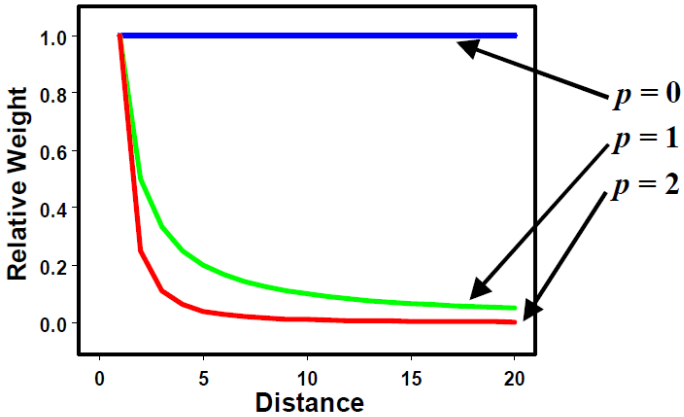


Figure 3.4: Diagram of inverse proportion between Weight and Distance (Using ArcGis Geostatistical Analyst, 2001).

3.2.2- THE SEARCH NEIGHBORHOOD

The things closer are more similar than those farther away, because of that the farther measured points will have little relationship. Thus, to calculate the prediction, it can to discount to zero the farther measured points with little influence, making a neighborhood with the important measured values inside. This shape restricts how far and where to look for the values used in the prediction (FIG. 3.5).

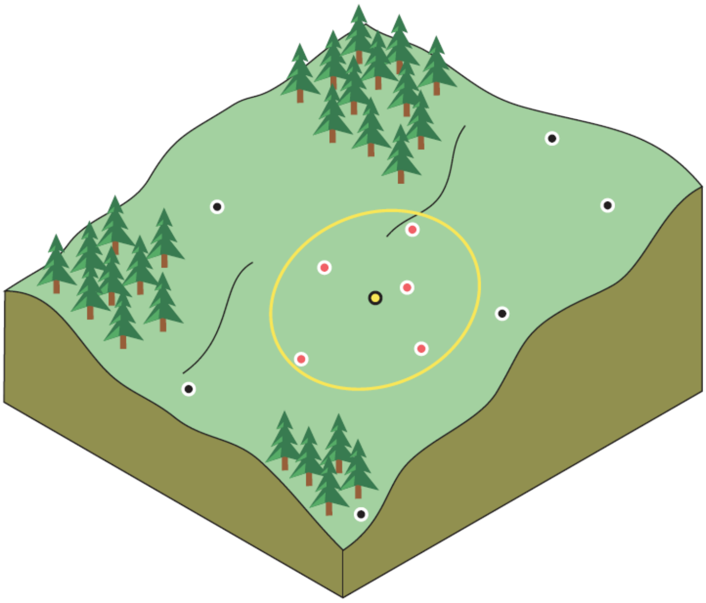


Figure 3.5: The neighborhood of the unknown value (yellow point) (Using ArcGis Geostatistical Analyst, 2001).

The shape of neighborhood can be of different ways depending of the input data and the surface that will be created. For example, this shape can be a circle if there are not directional influences, it means equal points in all directions. However, if there is directional influences, like groundwater flow, maybe is better use an ellipse, which adjusts to the change if it is put with the major axis parallel with the main flow. In this kind of situations is a good decision use an ellipse, because, usually, the directions are known and the shape will have better adjustment.

Moreover, the shape of neighborhood could restrict the points that will be used inside it. Also it is possible define the maximum and minimum number of points to use and divide the neighborhood in sectors. In this case, the maximum and minimum will be applied to each sector.

Summarizing, the main factors, that have to be studied when IDW is used, are the selection of power parameter (p) and the neighborhood shape. IDW is an exact interpolator, the interpolated surface present maximum and minimum just in the sample values. The surface calculated is varies with clustering and presence of outliers. Also IDW assumes that the surface is being driven by the local variation, which can be captured through the neighborhood (FIG. 3.6).

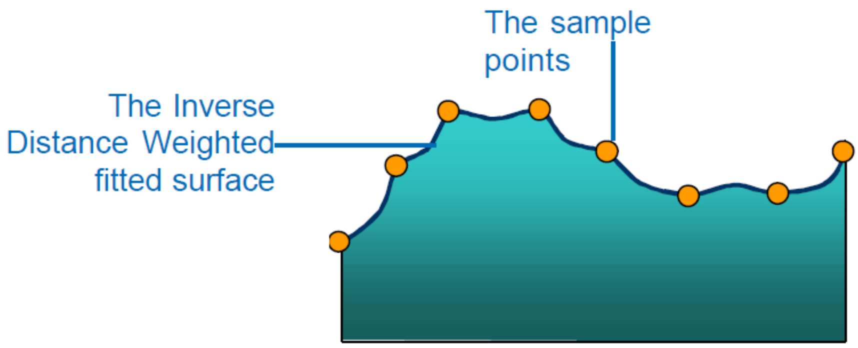


Figure 3.6: Surface with maximum and minimum points (Using ArcGis Geostatistical Analyst, 2001).

3.2 SPLINE

Spline belongs to Radial Basis Functions (RBF) methods. These are exact interpolation techniques, it means that the calculated surface must pass through each input point. Spline method calculates surface using a mathematical function that transforms the surface curvature in a smoother surface. This method uses a mathematical function for fit the nearest input points passing through of them. It is useful for gently varying surface like water table heights (FIG. 3.7).

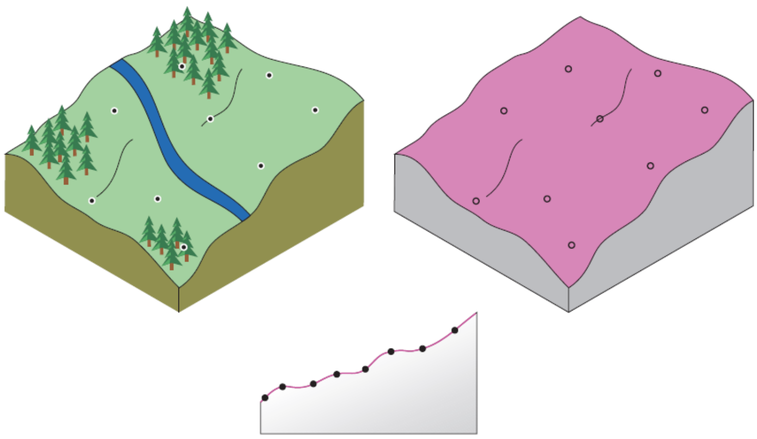


Figure 3.7: Surface fits through sample values (Using ArcGis Geostatistical Analyst, 2001).

There are two Spline methods:

- <u>Regularized method</u>: it estimates a smooth and changing surface, but the calculated values may lie outside the sample data range (3.4).

$$\psi(\mathbf{d})=\ln(\frac{cd}{2})^2+E_1(cd)^2+\gamma \qquad (3.4)$$

Where:

- d is the distance from sample to prediction location.
- c is a smoothing factor.

- Tension method: it varies the calculated surface according to the modeled phenomenon. This surface is less-smooth if the values are closely constrained by the sample data range (3.5)

$$\psi(\mathbf{d})=\ln\left(\frac{cd}{2}\right)+I_0(cd)+\gamma \qquad (3.5)$$

Where:

- d is the distance from sample to prediction location.
- c is a smoothing factor.
- I_0 is the modified Bessel function.

WEIGHT

In regularized method, weight marks the importance of the third derivatives of the surface in the curvature minimization expression. When the weight is higher, the surface is smoother. The value has to be equal or greater than zero.

For tension method, it defines the importance of the tension. If the weight is high, the surface is coarse. The value has to be equal or greater than zero.

NUMBER OF POINTS

It is used for calculate how many points there are in each interpolated cell. When more inputs points are specified, more influence has the distant in each cell and the surface is smoother.

IDW VS SPLINE

IDW and SPLINE are exact interpolators that mean the calculated surface has to pass through the measured points. While IDW does not estimate values above the maximum or below the minimum measured values, the Spline method do predict values over the maximum and under the minimum measured values, as it is shown in the figure below (FIG. 3.8).

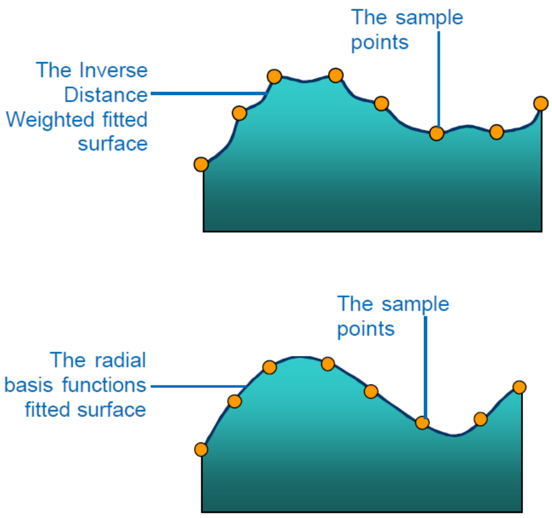


Figure 3.8: Difference between IDW and Spline Methods (Using ArcGis Geostatistical Analyst, 2001).

3.3 KRIGING

While IDW and Spline belong to Deterministic Interpolation Methods, Kriging is a Geostatistical Interpolation Method. Kriging methods use statistical models, including autocorrelation; it means the statistical relationships among the measured points, unlike the deterministic methods that use specified mathematical formulas. Due to statistical models, kriging provides predicted surfaces and also measure of the certainty or accuracy of the predictions.

As IDW does, Kriging works whit the weights of surrounding measured points to predict the value of an unmeasured location. Then the formula used consists in weighted sum of data (3.6):

$$\hat{\mathbf{Z}}(\mathbf{S_0})=\sum_{i=1}^{N} \lambda_i \, \mathbf{Z}(\mathbf{S_i}) \tag{3.6}$$

Where:

- $\hat{Z}(S_0)$ is the value it is trying to predict for location S_0.
- N is the number of measured points surrounding the prediction location that will be used in the prediction.

- λ_i is an unknown weight for the measured value at the location.
- $Z(S_i)$ is the observed value at the location S_i.

It is the same formula that IDW weight, but the difference is in λ_i. IDW λ_i depends only to the distance among measured value and prediction location. However, in Kriging, the weight is also influenced by spatial arrangement between the measured points and their values. It is necessary to quantify the spatial autocorrelation. Thus, the weight is influenced by a fitted model to the measured points, the distance and the spatial relationships among the location and the surrounding measured points.

Kriging needs two tasks to make a prediction: to know the dependency rules and to make the prediction. And these two tasks are gotten doing two-steps process: estimating spatial autocorrelation through variograms and covariance function, which depend on the model of autocorrelation. And predict the unknown values. Thus, Kriging uses the data twice: firstly, to estimate the spatial autocorrelation and finally to predict the unknown data.

3.3.1- VARIOGRAPHY

Variography is called structural analysis or fitting a model as well. First of all, it has to do a graph of the empirical semivariogram of the structure of the measured points, computed as (3.7):

Semivariogram (distancia h) = 0.5 * Average [(value at location i – value at location j)^2]
(3.7)

That is calculated for all the pairs separated by distance h. Then this formula calculates the difference squared between the values of the paired locations. This process is repeated for each measured point. The next figure shows the pairing of one point with the other measured locations (FIG. 3.9).

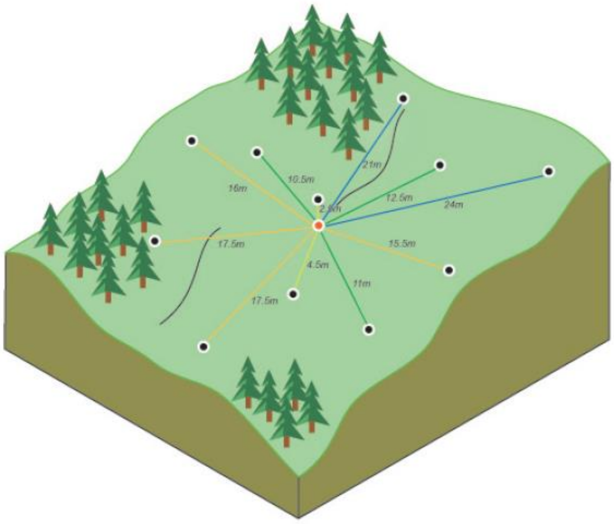


Figure 3.9: The pairing of one point with the other measured locations (MCCOY et al., 2001-2002).

Usually, each pair has a unique distance and there are many pairs of points, because of that to make a graph with all pairs quickly is unmanageable. Thus, it is easier to group the pairs by values of distance. For example, plot the average semivariance for all pairs of points between 40 and 50 meters of distance. Then the empirical semivariogram becomes in a graph of the averaged semivariogram on the y-axis and distance on the x-axis (FIG. 3.10).

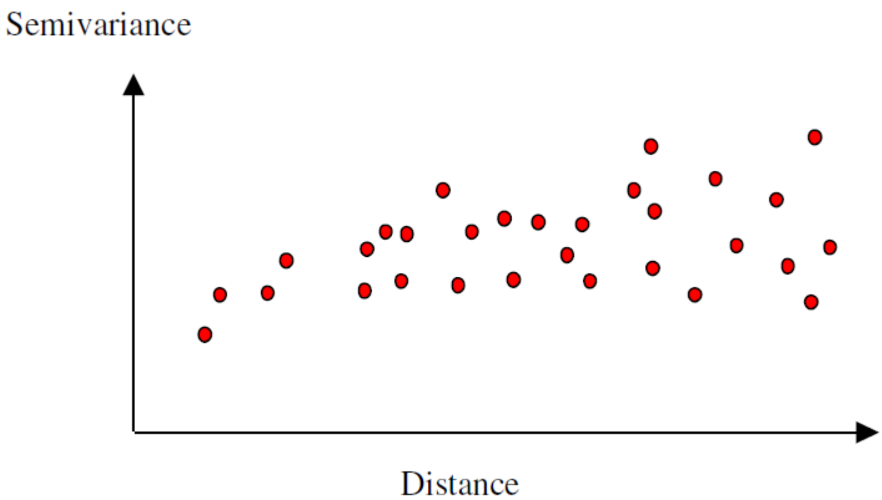


Figura 3.10: Graph of averaged semivariogram (MCCOY et al., 2001-2002).

A basic principle of geography says “things that are closer are more alike than things farther apart”, so spatial autocorrelation tries to quantify this principle. It means, pairs of points that are closer (left side of the x-axis) would have more similar values (lower side of the y-axis). On the contrary, if the pairs are more separated (right side of the x-axis), the values will be more dissimilar and have a higher squared difference (higher side of y-axis).

3.3.2- FITTING A MODEL TO THE EMPIRICAL SEMIVARIOGRAM

Now it has to fit a model in the empirical semivariogram. This model is a key step between spatial description and spatial prediction. Because of that, the main application of Kriging is predict values in unmeasured locations. As it has seen before, the empirical semivariogram calculates the spatial autocorrelation of datasets, but it has not information about all directions and distances. Due to this reason, a model, continuous function or curve, is fitted to the empirical semivariogram.

There are deviations between the model and the points, some of them are above the function and other below. But the distance among the points above and the model will be similar to the distance between the below points and the model. There are lots of kinds semivariograms models to choose from.

3.3.3- DIFFERENT TYPES OF SEMIVARIOGRAM MODELS

The selection of the kind of model has a great influence in the prediction of the unknown values, mainly if the origin differs significantly. Near to the origin, the curve is steeper. As a result, the surface estimated will be less smooth. Because of that, each model is made to fit different types of phenomenon. To see the differences between models, two types will be explained below.

The Spherical Model (FIG. 3.11)

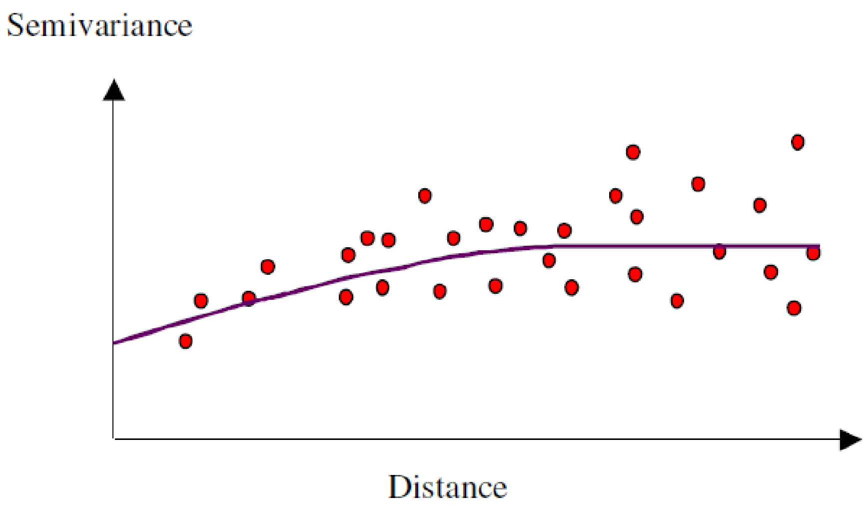


Figure 3.11: The Spherical Model (MCCOY et al., 2001-2002).

The Spherical Model is one of the most commonly used. In this model the spatial autocorrelation decreases with an increase of semivariance. It happens until some distance when the autocorrelation is zero.

The Exponential Model (FIG. 3.12)

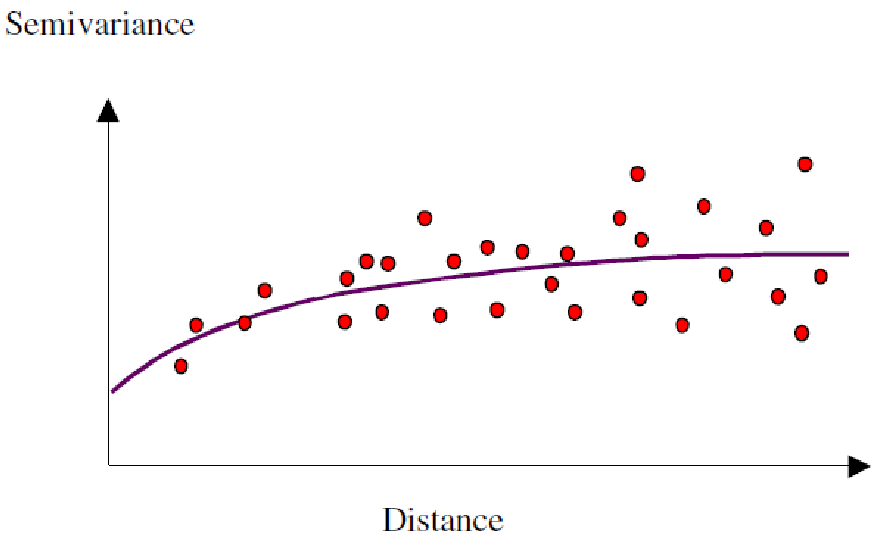


Figura 3.12: The Exponential Model (MCCOY et al., 2001-2002).

The Exponential Model, as its name says, is used when the spatial autocorrelation decreases exponentially with increasing distance. Just in the infinite the autocorrelation is zero.

3.3.4- UNDERESTANDING A SEMIVARIOGRAM: THE RANGE, SILL AND NUGGET

As it has been explained, the semivariogram shows the spatial autocorrelation betwenn measured points. And as a basic principle of geography says “things that are closer are more alike than things farther apart”, the closer measured points have smaller difference squared. Once the points have been binned and plotted, a model is fit through them. There are characteristic that are used to describe these models.

The range and sill

Looking at the model of a semivariogram, it notices that a certain distance the model becomes horizontal, so the distance among the origin and this point is called Range. The points that are within this range are spatially autocorrelated, while outside points are not (FIG. 3.13).

The value in y-axis that the range reaches is known Sill. Also exist the Partial Sill which is the Sill minus the Nugget (FIG. 3.13).

The Nugget

Theoretically, when the distance is zero, the semivariogram should be zero as well. However, there is a really small separation between Zero and the model interception with y-axis. This small distance is called Nugget (FIG. 3.13).

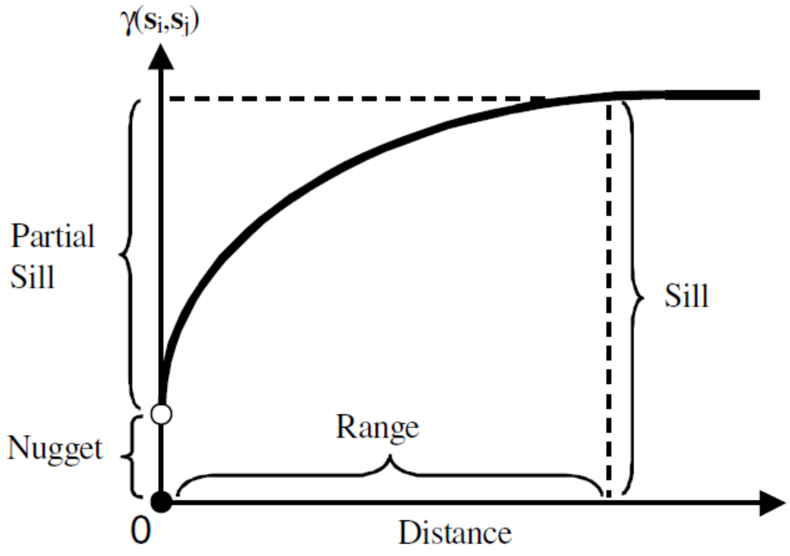


Figure 3.13: Characteristics of models: Range, Sill and Nugget (MCCOY et al., 2001-2002).

The Nugget happens due to measurement errors, spatial sources of variations at distances smaller than the sampling interval or both. The measurement errors appear because the natural phenomena can vary spatially over range of scales. Due to, before work with this data, it is necessary understand the scale of spatial variation.

3.3.5- MAKING A PREDICTION

Once it has been uncovered the dependence, the autocorrelation has been accomplished. It means that it has finished with the first use of the data. The next step is to predict using the fitted model.

In the second tasks, the data are used again to make predictions. Like IDW interpolation, Kriging forms weight from surrounding measured points to predict the unknown location. Also the weight will have more influence in the closest values. The difference is that IDW use a simple algorithm based on distance and Kriging use the semivariogram developed to look at the spatial nature. To create the surface, each location (cell) will have a prediction based on the semivariogram model and the spatial arrangement of measured values that are nearby.

3.3.6- SEARCH RADIUS

As a basic principle of geography says “things that are closer are more alike than things farther apart”, it can assume that the farther points from prediction location have less autocorrelation, thus, it can be eliminated. On reason is that these farther locations may have negative influence if they are in a much different location. Another reason is for computational speed, because the smaller the search neighborhood, the faster the prediction can be made. As a result, usually the number of points is limited using a specific shape that restricts how far and where to look for the measured values to be used in each prediction. Other restriction may be defining the maximum and minimum number of measured points to use within the neighborhood.

There are two types of neighborhood: fixed and variable.

Fixed search radius

To use this type is required a distance and a minimum number of points. The distance will be used to mark the radius of the circle of the neighborhood. It will be constant because for each interpolated cell, the radius of the circle used to find input points is the same. The Minimum number of points dictates the minimum number of measured point to use for the prediction within the neighborhood. Then all the measured points that are inside the circle will be used in the prediction. If the number of points is less than the minimum, the radius of the circle increases until it can encompass this minimum number.

Variable search radius

It has to specify the number of points that are going to be used in the interpolation, then, the distance of the radius varies for each cell to reach the specified number of inputs points. Thus, the size of the neighborhoods will change depending on the density of measured points near the interpolated cell. Also the maximum distance of the radius can be specified, so if the radius reaches this maximum before obtaining the number of measured, the interpolation will be performed with the number of points within the maximum radius.

3.3.7- KRIGING METHODS

Ordinary Kriging

Ordinary Kriging is the most commonly method used of the Kriging Methods. It assumes the constant mean is unknown. It is a good way to solve the problem unless there is some scientific reason to reject the assumption.

Universal Kriging

Universal Kriging is based in a predominant trend in the data and it can be modeled by a deterministic function or polynomial. This polynomial is subtracted from the original measured points and the autocorrelation is modeled from the random errors. When the model is fitted to the random errors, the polynomial is added back, before to predict, to give meaningful results. Universal Kriging just may be used when the trend in the data is known and it is possible give a scientific justification to describe it.

3.4 NATURAL NEIGHBOR

The Natural Neighbour method is related to the concepts of the Voronoi diagram and the Delaunay triangulation. It permits represent the simplest element in a given space like a triangle in 2 dimensions and a polyhedron in 3 dimensions. This method can be used to work with topographic, bathymetric, geophysical and soil data.

To estimate unknown values of a location, this method uses the sampled points situated around of this. Different weights are assigned according to the natural neighbour coordinate of this location with respect to this neighbour (FIG. 3.14). The weights will depend of the areas or volumes rather than distances. Then if each data point in the surface has an attribute a_i, the natural neighbour interpolation formula is (3.8):

$$\mathbf{f(x)= \sum_{i=1}^{k} w_i\,(x)a_i} \tag{3.8}$$

Where:

- $f(x)$ is the interpolated function value at the location x.
- $w_i\,(x)$ is the natural neighbour coordinate of the location with respect to a point.
- k is the number of sampled points.

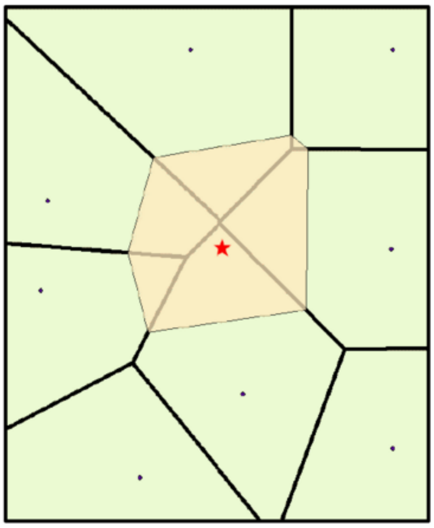
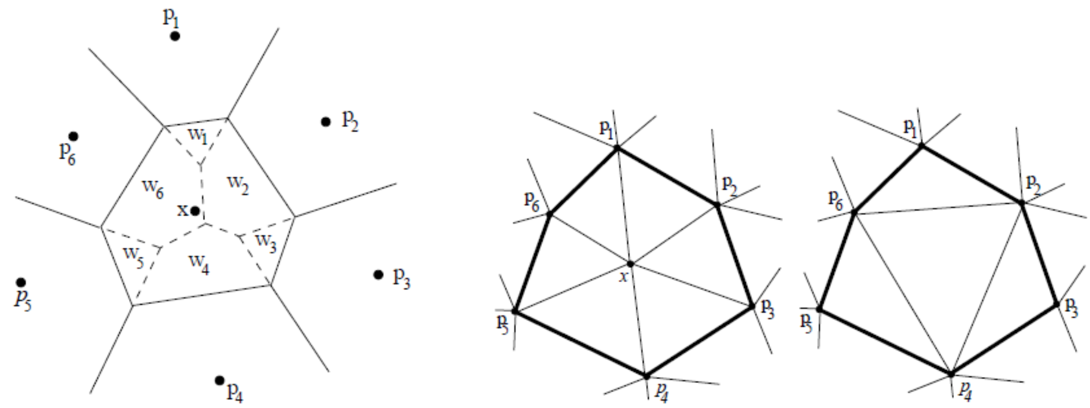


Figure 3.14: Estimation of the surrounded weights (resources.arcgis.com)

Natural Neighbour linear interpolation estimates a surface like a rubber-sheet. Moreover, the surface can be made smooth everywhere and tautness due to the addition of blended gradient information. The characteristic will change according to the modeled phenomenon. The value of tautness depends of two parameters which modify the shape of the blending functions. As a result, Natural Neighbour makes a surface that pass through the data points, with smoothly changing gradients, blended from natural neighbor local trend and variable tautness.

3.4.1- NATURAL NEIGHBOR COORDINATES

This method is used to calculate the natural neighbours of an unknown point in a surface with more sampled points. Its natural neighbours are those that Voronoi cell would be modified if the searched point were inserted in the Voronoi Diagram of this surface. The insertion of this point generates another Voronoi cell for this point that “steals” area from the surface of the natural neighbours (FIG. 3.15).



(a) Natural neighbour coordinates of x in 2D. (b) 2D DT with and without x.

Figure 3.15: Natural Neighbour Coordinates of a point X (LEDOUX et al., 2004)

To estimate the surface steals from each natural neighbour when one Voronoi cell is generated, it is used the next formula (3.9):

$$\mathbf{w_i(x)} = \frac{\mathbf{Vol\ (V_{pi} \cap V_x^+)}}{\mathbf{Vol\ (V_x^+)}} \tag{3.9}$$

Where:

- $w_i(x)$ is the Natural Neighbour Coordinate of searched point with respect to a point p_i.
- $Vol\ (V_{pi})$ represents the volume of V_{pi}.
- V_{pi} represents the value of Voronoi cell of a point.
- $Vol\ (V_x^+)$ represents the sum of all the volumes stolen from each point.

Then, the value of $w_i(x)$ will be 0 when p_i is not a natural neighbor of the searched point (x), and it will be 1 when (x) be at the same location as p_i. The higher value of $w_i(x)$ or weight, is the strongest influence among p_i on x. Thus, the Natural Neighbor Coordinates will be influenced by both the distance from x to p_i and the spatial distribution of the p_i around x.

3.5 ACCURACY OF THE RESULTS

To validate the results given for each of these methods and to help to decide which one has the best behavior in the Zagreb aquifer system, it has been used different statistical methods that compare the initial data with the final results.

3.5.1- PEARSON

The Pearson Method or linear correlation coefficient is the most commonly-used measure of correlation. The value of r of Pearson will be r = 1 when the data lie exactly along a straight line with positive slope. Pearson's r uses nonresistant measures (mean and standard deviations) assuming that the data follow a bivariate normal distribution. Then not only do the individual variables x and y follow a normal distribution, but their joint variation also follow a specified pattern (HELSEL & HIRSCH, 2002).

This method is invariant to scale changes because the dimensionless properties are obtained by standardizing, as is shown in the next formula (3.10) (HELSEL & HIRSCH, 2002):

$$\boldsymbol{r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{x_i-\bar{x}}{S_x}\right)-\left(\frac{y_i-\bar{y}}{S_y}\right)} \tag{3.10}$$

Where:

- x and y are the individual variables.

3.5.2- SPEARMAN

The Spearman Method is a rank correlation coefficient, it works with the differences between data values ranked further apart are given more weight. It is easy to understand as the linear correlation coefficient computed on the ranks of the data. The two variables have to be ranked independently among themselves (3.11) (HELSEL & HIRSCH, 2002):

$$\boldsymbol{rho = \frac{\sum_{i=1}^{n}(Rx_iRy_i)-n\left(\frac{n+1}{2}\right)^2}{n(n^2-1)/12}} \tag{3.11}$$

Where:

- $\boldsymbol{Rx_i}$ and $\boldsymbol{Ry_i}$ are the ranks of the variables x and y.

If the correlation is positive, the higher rank of x and y will be paired and their product will be large and for a negative correlation the higher rank of x will be related to lower ranks of y, giving a smaller product. If there is no correlation rho will be close to zero with a random pattern in the association between both ranks (HELSEL & HIRSCH, 2002).

It is easier to rank the two variables and compute the hypothesis test for r of Pearson, the rank transform method. It will work better if there is a large sample sizes, when n > 20 (HELSEL & HIRSCH, 2002).

3.5.3- Root Mean Squared Error

The Root Mean Squared Error (RMSE) calculates the accuracy of the results combining the bias and the lack of precision. This method compares the mean of x with the true population value. The equation is shown below (3.12). The methods whose estimates $\bar{\boldsymbol{x}}$ are closer to the true value result lower RMSE and have better accuracy (HELSEL & HIRSCH, 2002):

$$\boldsymbol{RMSE} = \sqrt{\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \frac{(\bar{\boldsymbol{x}}-\boldsymbol{\mu})^{\boldsymbol{2}}}{\boldsymbol{\mu}} \Big/ \boldsymbol{N}} \tag{3.12}$$

Where:

- $\bar{\boldsymbol{x}}$ is the mean of x.
- $\boldsymbol{\mu}$ is the value of true population (initial data).

3.5.4- T-Test

The T-Test is the most used method for comparing two independent groups of data, very used in water resources scientist. When T-Test is used some assumptions are accepted like that both groups of data are normally distributed and the have the same variance. According to that both groups have the same distribution varying only in their central location. So that, these are strong assumptions rarely satisfied with water resources data.

4. APPLICATION: INTERPOLATION OF HEADS IN THE ZAGREB AQUIFER

4.1 PREVIOUS WORK

The second part of this Thesis describes construction of equipotential maps for high and low waters at the Zagreb aquifer system through four different interpolation methods. Those methods are Inverse Distance Weighted, Spline, Kriging and Natural Neighbor, which have been explicated previously. To carry out this work, it has used the interpolation functions that are situated in “Spatial Analyst Tools” of ArcMap, belonging to the software ArcGis.

The first step, before starting the interpolation, was to prepare the data regarding groundwater observation wells (coordinates, high and low levels and dates), river water levels (coordinates, high and low levels and dates), the situation of the well fields and the boundaries of the Zagreb Aquifer.

At the beginning, the available information was associated with the groundwater levels distributed for all the aquifer and several water levels along the Sava River. On the one hand, there were too many observation points of the ground water levels and, sometimes, they were close to each other. Therefore it has been necessary to choose which of these points are going to be used. And, on the other hand, there were not enough measured points in the river. Thus it was done a linear interpolation between each two measured points to get values of the river level each one kilometer approximately (4.1 and 4.2). Finally, after the choosing the ground water level observation wells, it has passed from 280 to 105 points focused in Zagreb aquifer and the measured points of the river level from 7 to 39 along the Sava River.

Table 2: Measured River Water Level Data

NAME	LOW	HIGH	DISTANCE
Podsused-Zicara	116.66	120.24	-
Zagreb	109.47	113.11	11
Toplana g.v.	105.24	107.69	5
Toplana d.v.	101.67	105.78	0
Kosnica	98.70	102.64	6
HE-Drenje	98.70	102.64	5
Rugvica	93.26	102.2	10

(4.1)

$$\mathbf{H}=\frac{(\mathbf{H_0}-\mathbf{H_1})}{\mathbf{d}} \quad (4.1)$$

Where:

- H: difference of river water levels between two observation points per kilometer.
- H_0: river water level of initial point.
- H_1: river water level of next point.
- d: distance between 2 measured points in kilometers.

(4.2)

$$\mathbf{H_x}=\mathbf{H_{x-1}}-\mathbf{H} \quad (4.2)$$

Where:

- H_x: river water level calculated.
- H_{x-1}: previous river water level.
- H: difference of river water levels between two measured points per kilometer.

Table 3: Final River Water Level Data

NAME	LOW	HIGH
Podsused-Zicara	116.66	120.24
P1	116.01	119.59
P2	115.35	118.94
P3	114.70	118.30
P4	114.05	117.65
P5	113.39	117.00
P6	112.74	116.35
P7	112.08	115.70
P8	111.43	115.05
P9	110.78	114.41
P10	110.12	113.76
Zagreb	109.47	113.11
P11	108.62	112.03
P12	107.78	110.94
P13	106.93	109.86
P14	106.09	108.77
Toplana g.v.	105.24	107.69
Toplana d.v.	101.67	105.78
P15	101.18	105.26
P16	100.68	104.73
P17	100.19	104.21
P18	99.69	103.69
P19	99.20	103.16
Kosnica	98.70	102.64
P20	98.34	102.61
P21	97.97	102.58
P22	97.61	102.55
P23	97.25	102.52
HE-Drenje	96.89	102.49
P24	96.52	102.46
P25	96.16	102.43
P26	95.80	102.41
P27	95.44	102.38
P28	95.07	102.35
P29	94.71	102.32
P30	94.35	102.29
P31	93.99	102.26
P32	93.62	102.23
Rugvica	93.26	102.20

Moreover, after some interpolations, results showed that some measured samples are incoherent with the rest of them because they show values too much lower or higher than the surrounding samples. Then those samples were changed for other close ones that adjust better to the rest points. The result is shown below (FIGs. 4.1, 4.2).

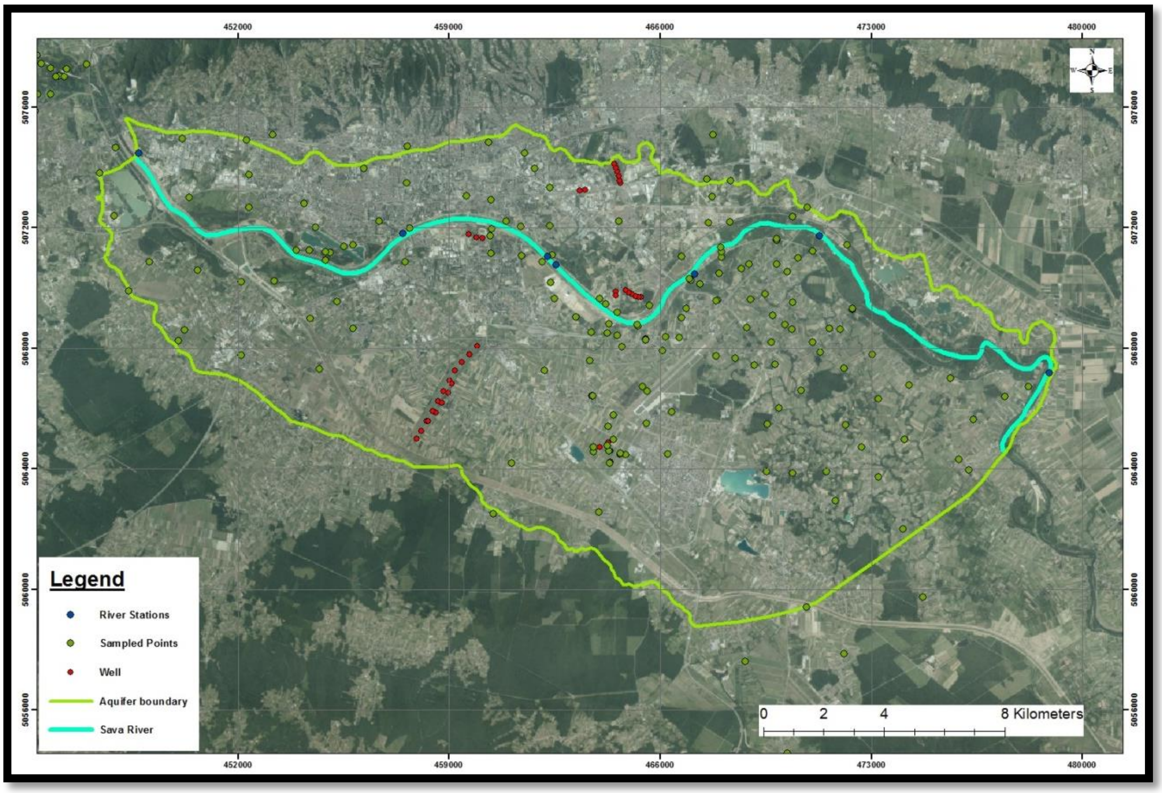


Figura 4.1: Initial data

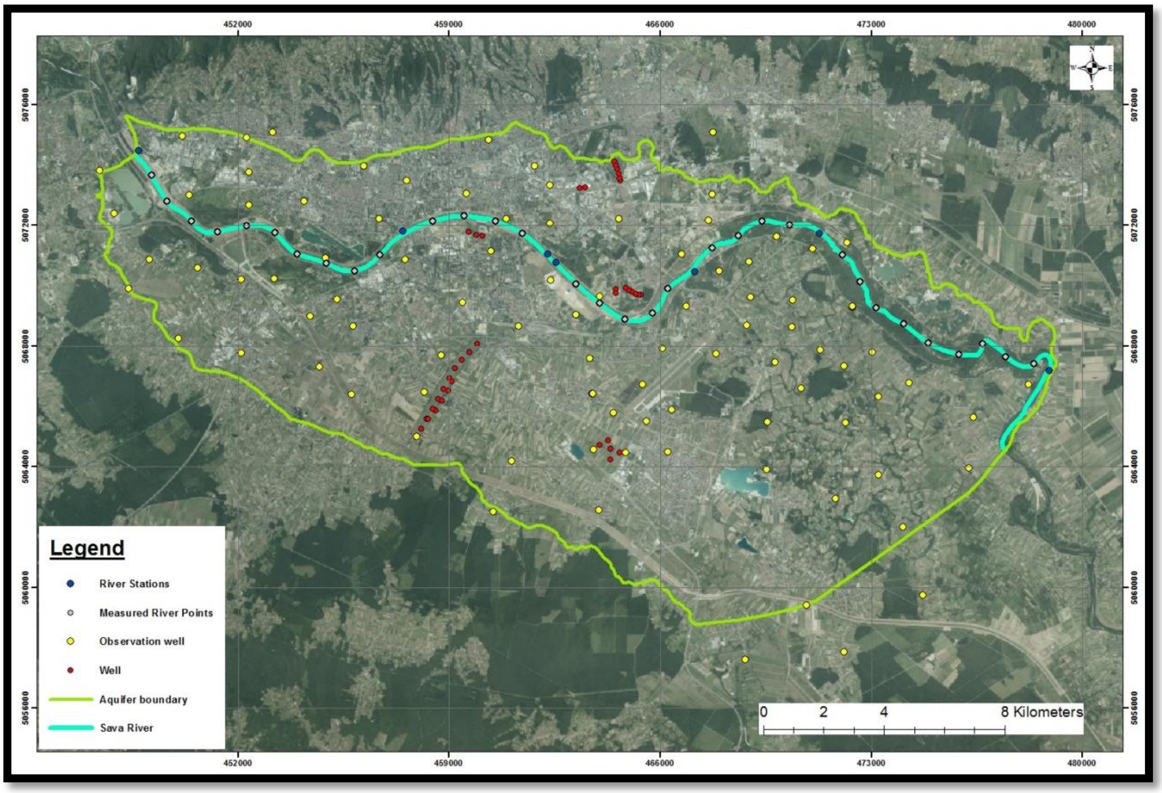


Figura 4.2: Selected data

After that, it has looked for the day with the maximum and minimum level of ground water. For low waters, the date in March and April of 2012 and for high waters, March and April of 2013 (Hruška, 2015) (FIG. 4.3).

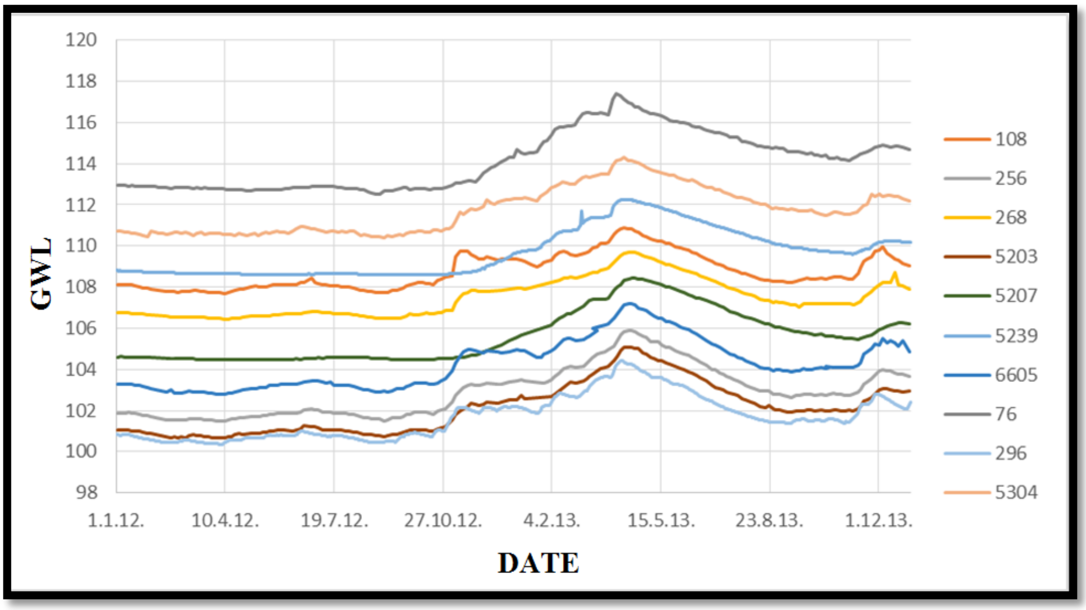


Figure 4.3: Groundwater Levels at observation wells (Hruška, 2015)

In these date ground water level reached the minimum and the maximum in the last 15 years respectively. Furthermore, the same range of dates was in the measured points of the river water level. Then the days with lowest and highest groundwater level were chosen counting the times that those lowest or highest data happened at the same day. After that, the data of those months were used to calculate the average of each month. The Figure 4.4 shows the amount of observation wells that reached the maximum or minimum in each date. The final result was for low water the day 05/04/2012 and the month of April 2012, and for high water the day 04/04/2013 and the month of April 2013 (FIG. 4.4).

DATE	AMOUNT
01/03/2012	7
05/03/2012	3
08/03/2012	0
12/03/2012	4
15/03/2012	3
19/03/2012	10
22/03/2012	3
26/03/2012	9
29/03/2012	10
02/04/2012	17
05/04/2012	73
09/04/2012	23
12/04/2012	8
16/04/2012	6
19/04/2012	4
23/04/2012	3
26/04/2012	7
30/04/2012	13

DATE	AMOUNT
04/03/2013	0
07/03/2013	0
11/03/2013	0
14/03/2013	2
18/03/2013	2
21/03/2013	2
25/03/2013	1
28/03/2013	1
01/04/2013	22
04/04/2013	61
08/04/2013	28
11/04/2013	14
15/04/2013	2
18/04/2013	4
22/04/2013	1
25/04/2013	0
29/04/2013	1

Figure 4.4: Result of Calculate of Lowest and Highest Day

Finally, the last step was to build a spreadsheet for the results of low and high waters which were introduced in the software ArcGis. This sheet must have the water levels of the aquifer and the river with the next distribution in rows and files (FIG. 4.5):

- Code or name of the point.
- Coordinate X.
- Coordinate Y.
- Water level, coordinate Z.

	A	B	C	D
1	CODE	X	Y	GWL
2	2	464632	5072206	104.16
3	4	449058	5070854	120.16
4	10	471802	5062935	100.01
5	11	478198	5066739	101.67
6	22	476227	5063956	99.82
7	24	476389	5065640	101.2
8	25	475626	5066995	101.79
9	28	474702	5059753	99.83
10	29	455282	5069551	113.85
11	44	444135	5073673	127.16
12	45	442131	5073391	132.54
13	50	442075	5074571	132.13
14	51	461075	5064195	104.56
15	52	460470	5062519	104.8
16	55	460306	5074835	108.36

Figure 4.5: Building of the Spreadsheet to ArcGis

Once completed the previous work with the spreadsheet, the file was uploaded in ArcMap and transformed in a "shape file" to be used in the interpolation methods. Therefore it has to carry out three steps. The first one is to upload the spreadsheet to the software like a Excel table. The second step, to display the data of the table specifying which values of the table are the coordinates X, Y, Z. And finally, the last step consists in transform it in a shape file (FIG. 4.6). The same process has to be done for low and high waters and repeat it each time that the values of the spreadsheet change.

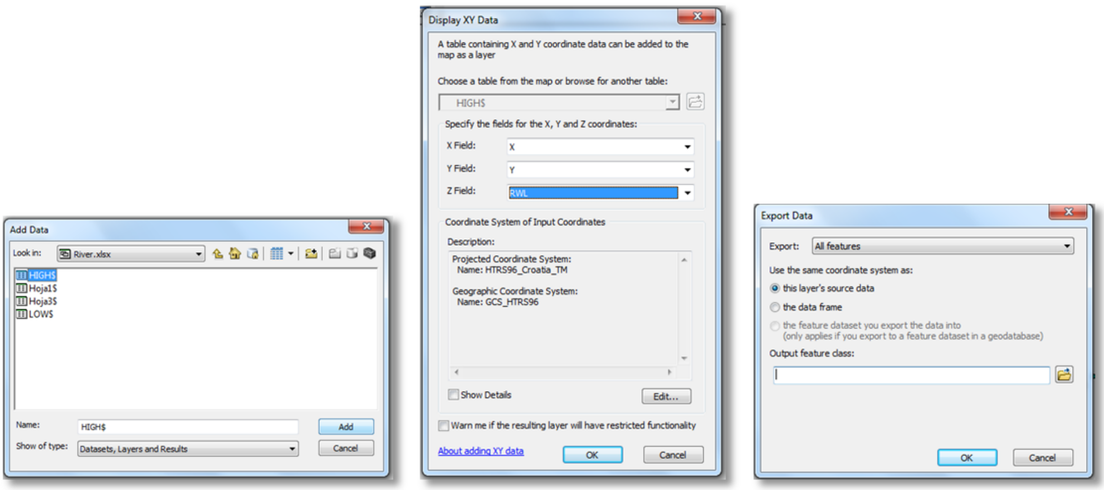


Figure 4.6: Transformation of Spreadsheet to "Shape File"

4.2 METHOD OF INTERPOLATION

Four methods were used to interpolate the data of the levels of ground water. Those methods are in Spatial Analyst Tools of the software ArcGis.

4.2.1 Inverse Distance Weight

The IDW estimates cell values by averaging the values of sample points around each cell. It uses the reasoning that the points closer than others, regarding one point, are more similar. To use this method in ArcGis is necessary choose and fill some options and parameters as is show in the figure below (FIG. 4.7).

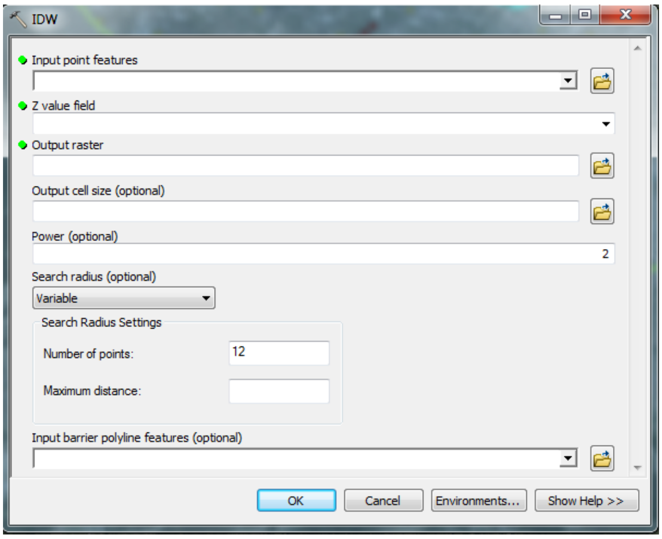


Figure 4.7: Inverse Distance Weight Options

First of all it has to choose the raster file that it is going to be interpolated, that means choose the file of low or high waters. After that it is necessary to select the value of the ground water level as Z value field. Then it is time to change the default parameters established:

- **Power**: as it has been explicated previously, it controls the significance of surrounding points on the interpolated value. The resources of ArcGis recommend that this parameter is between 0.5 and 3. A lower value of it gives more significance to farther points and a higher value to closer points. Considering this reasoning three interpolations were done, with p = 1, 2, 2.5.
- **Search radius**: defines which of the input points will be used to interpolate the value for each cell. There are two options to do it; Variable gives better results for

points randomly placed and Fixed, better for regularly spaced points. Since the sampled points do not follow any order, Variable method was chosen.

With these considerations the next maps have been generated for low and high waters (FIGs. 4.8, 4.9, 4.10, 4.11, 4.12, 4.13):

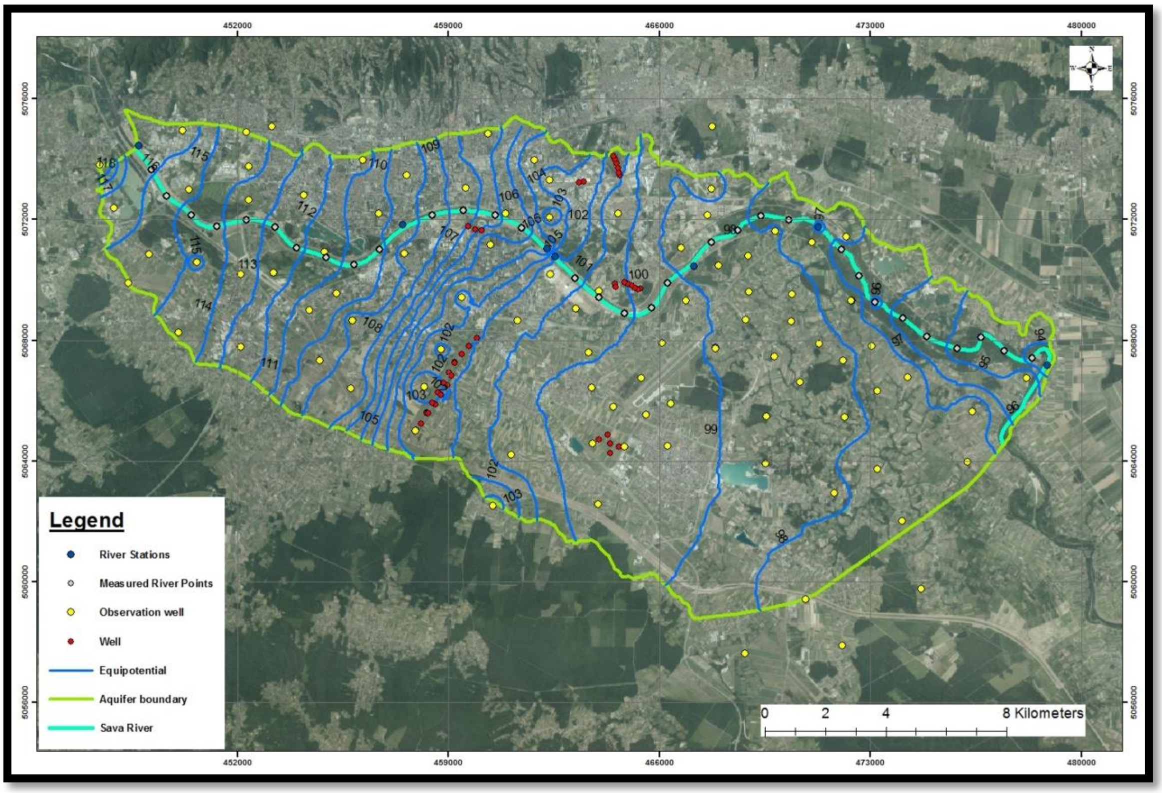


Figure 4.8: IDW, Low Water Levels, Power = 2

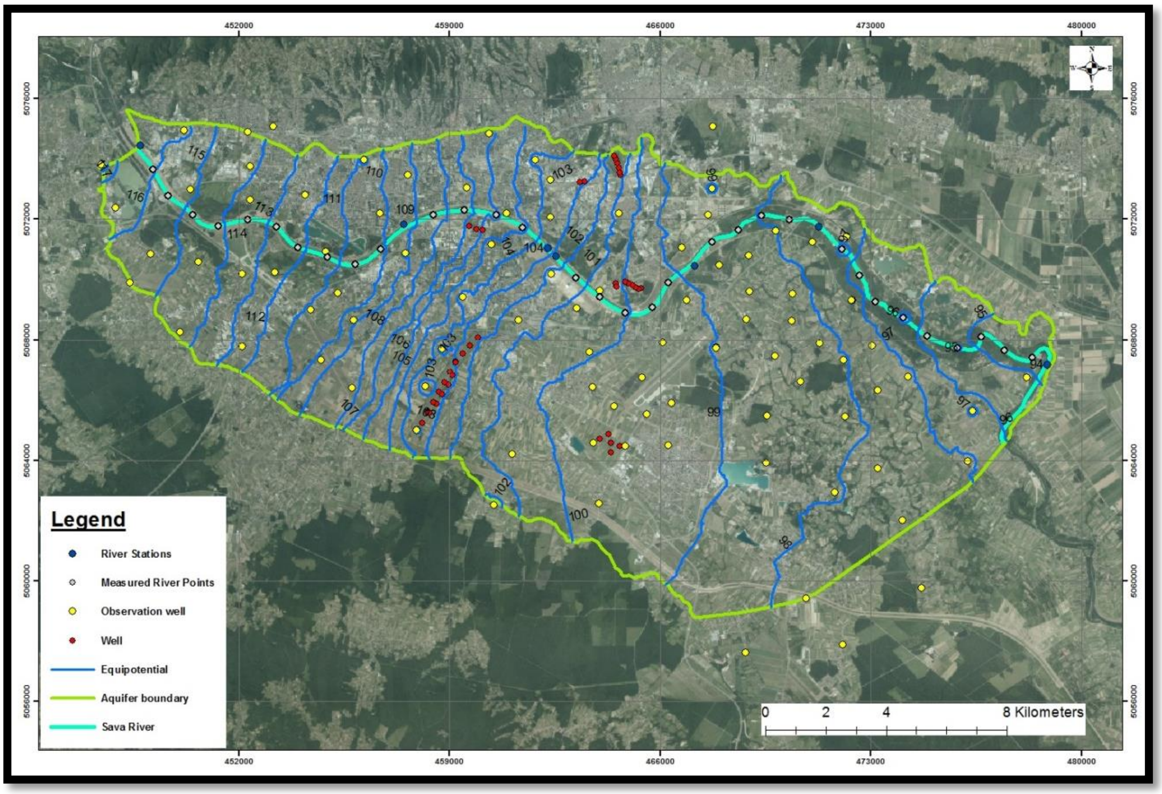


Figure 4.9: IDW, Low Water Levels, Power = 1

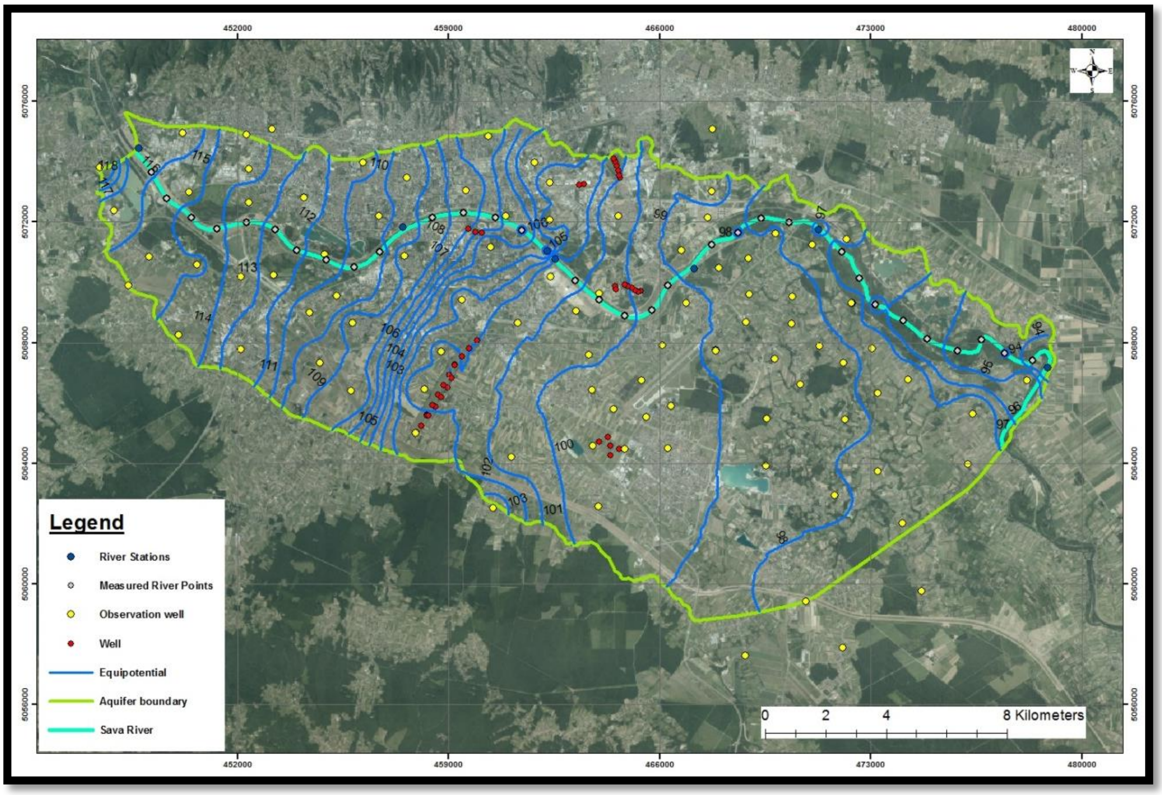


Figure 4.10: IDW, Low Water Levels, Power = 2.5

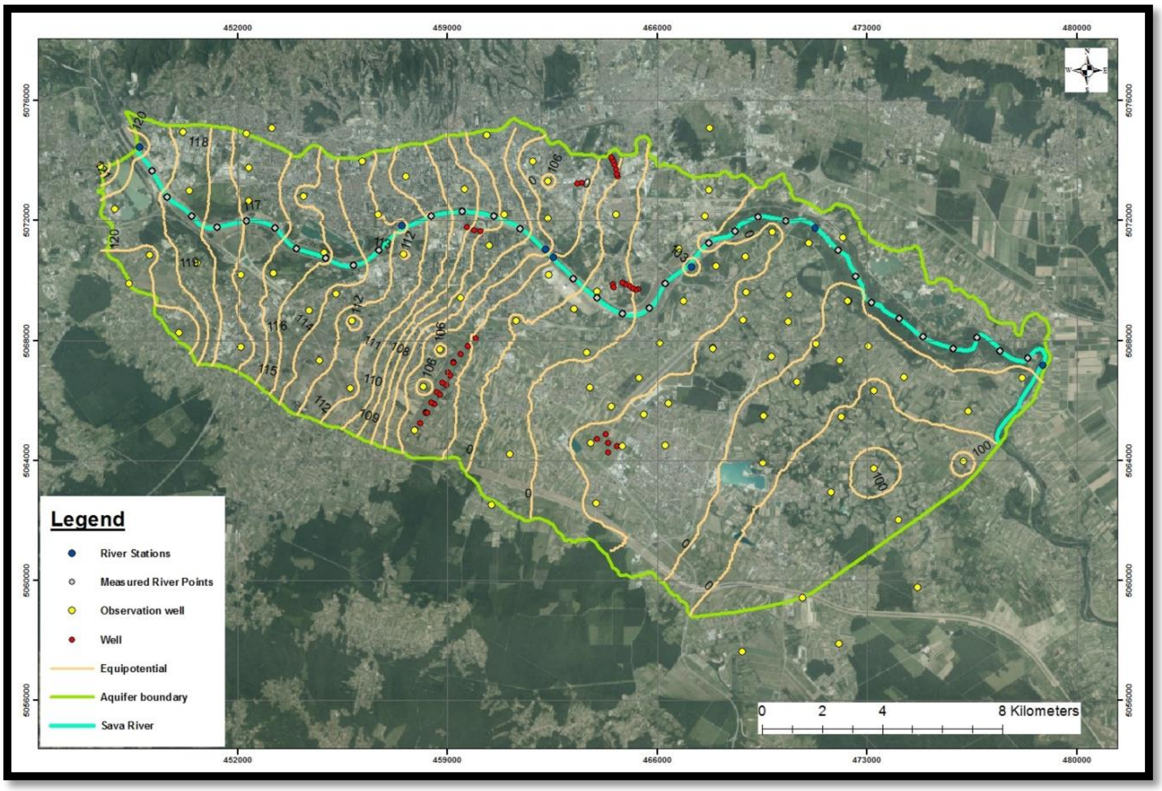


Figure 4.11: IDW, High Water Levels, Power = 2

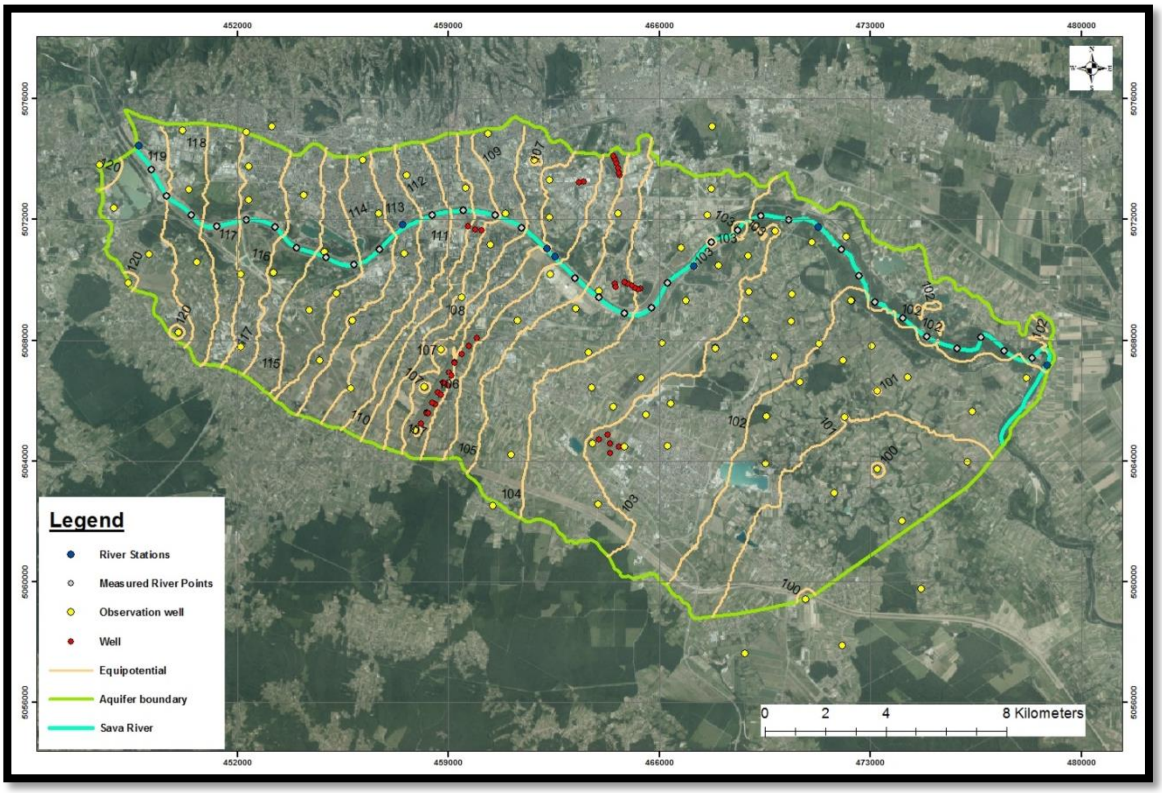


Figure 4.12: IDW, High Water Levels, Power = 1

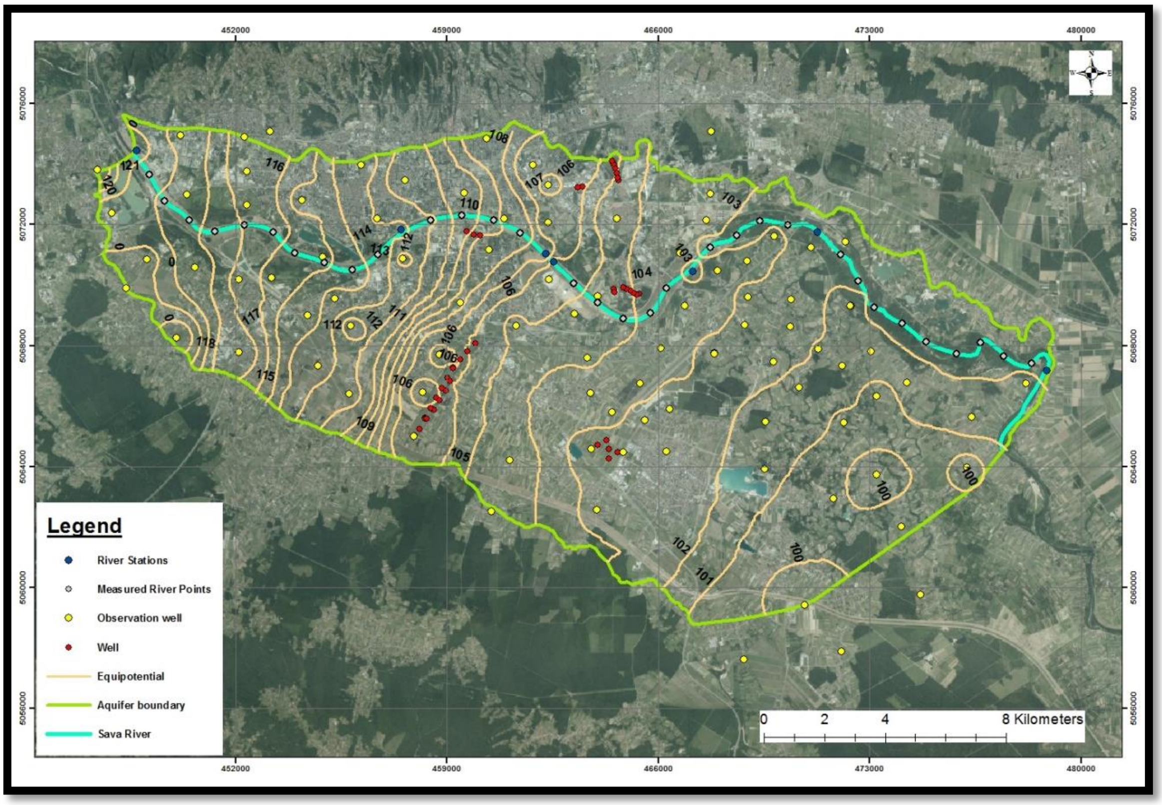


Figure 4.13: IDW, High Water Levels, Power = 2.5

Looking at these pictures, it can be seen differences between them depend on the value of Power. Using lower values of Power, small local points appear in the maps, which can be considered wrongs because this is a smooth aquifer (FIGs 4.9, 4.12). When higher values of Power are used, some of those local points keep appearing (FIGs 4.10, 4.13). However, for the same reason with low values of Power, those points should not appear, because of that the Inverse Distance Weight Method does not work correctly in this aquifer.

After that, Inverse Distance Weight was used with the monthly average for knowing the behavior of this method with other data as well (FIG. 4.14, 4.15).

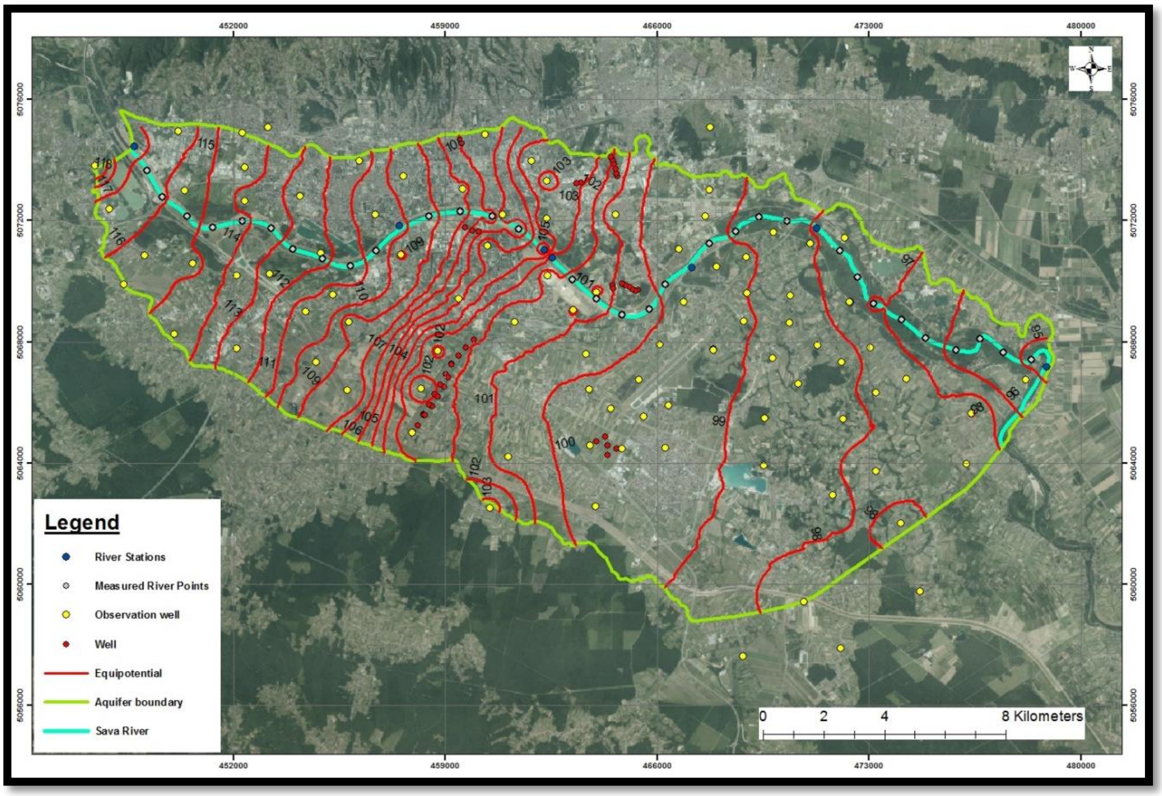


Figure 4.14: IDW, Low Water Levels, Monthly

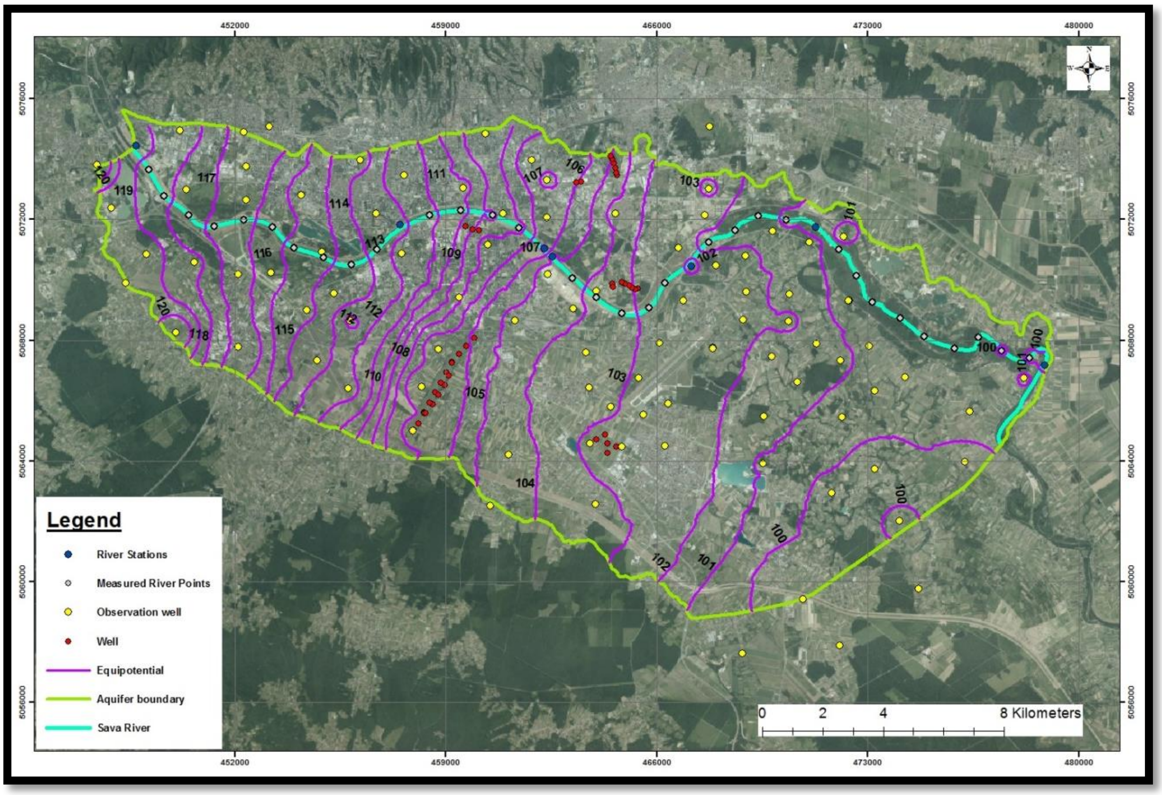


Figure 4.15: IDW, High Water Levels, Monthly

The results are very similar to the previous one. Irregular equipotential lines and small local areas are drawn, so this method cannot be considered appropriated for this aquifer.

4.2.2 Spline

The Spline method uses a mathematical function for fit the nearest input points through of them and transforms the surface curvature in a smoother surface. A priori this method should give good results in gently varying surface like ground water levels. Spline also has some options to choose and parameters to fill (FIG 4.16).

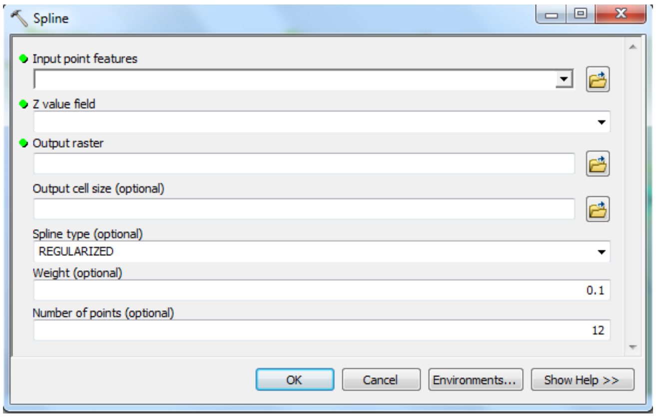


Figure 4.16: Spline Options

As the previous one, first of all it has to choose the raster file that it is going to be interpolated, that means choose the file of low or high waters. After that it musts select the value of the ground water level as Z value field. Then it is time to change the default parameters established:

- **There are two types of Spline**: Regularized method gives results with values may lie outside the sample data range. And Tension method with values inside the data sample range.
- **Weight**: is the parameter that influences the character of the surface. This is in both types of Spline. In Regularized a higher weight results a smoother surfaces, however in Tension a lower weight gives smoother surfaces.
- **Search radius**: it can be Variable or Fixed. For all the methods it has been used the Variable due to the sampled points are situated randomly so that the points have not got the same number of sampled points closer to them.

Due to that, Tension method was chosen because the sampled values points are the only which can be considered rights. Thus it has interpolated using Tension method changing the value of weights (FIGs. 4.17, 4.18, 4.19, 4.20).

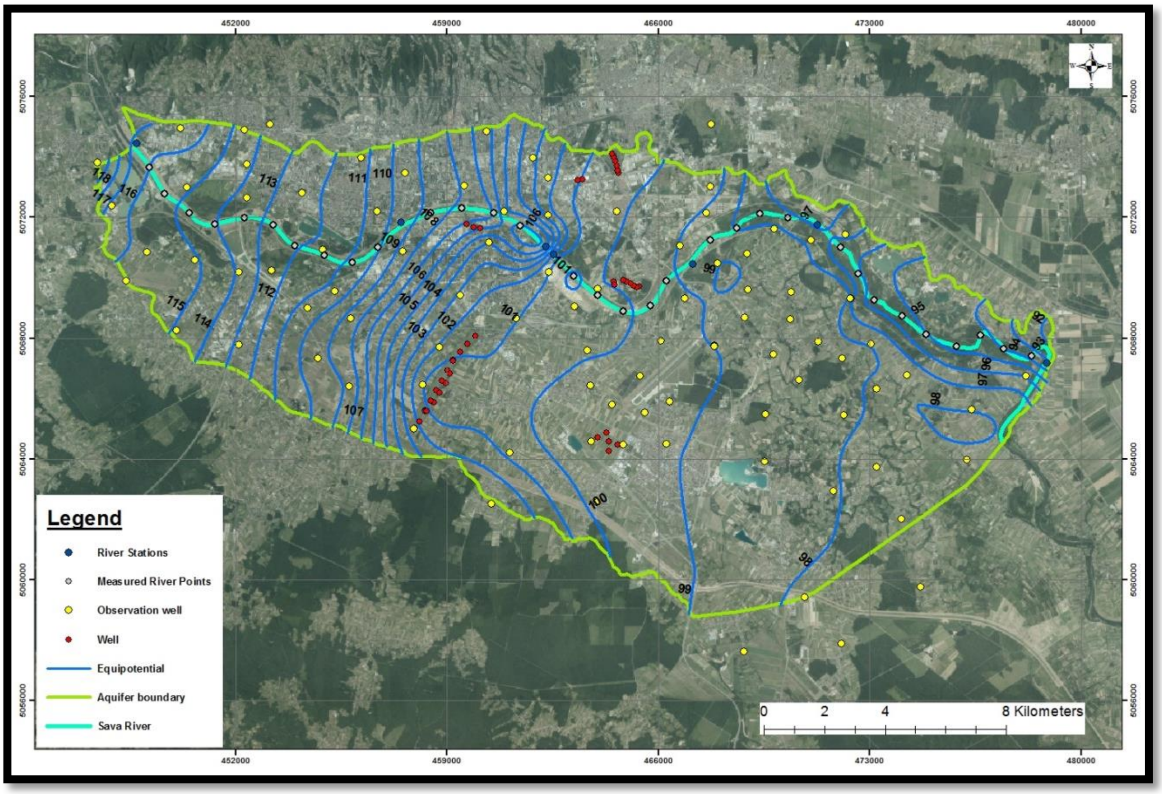


Figure 4.17: Spline, Low Water Levels, Weight = 0.1

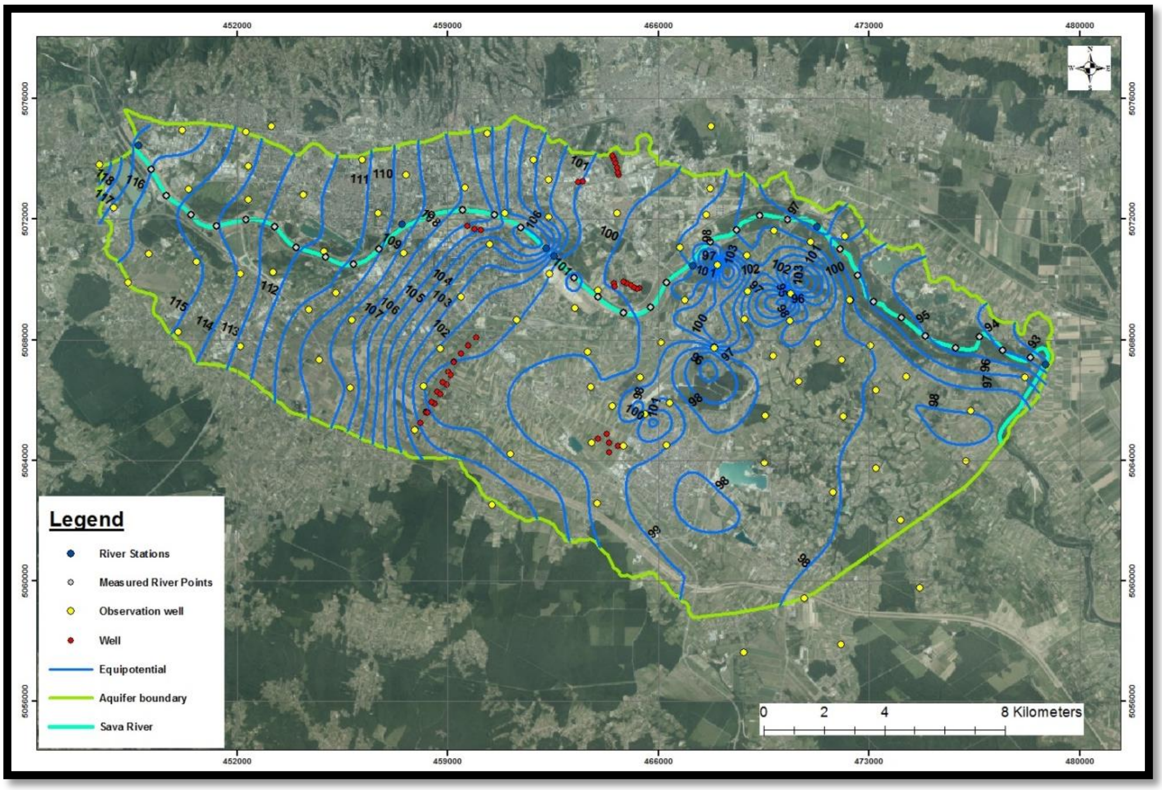


Figure 4.18: Spline, Low Water Levels, Weight = 1

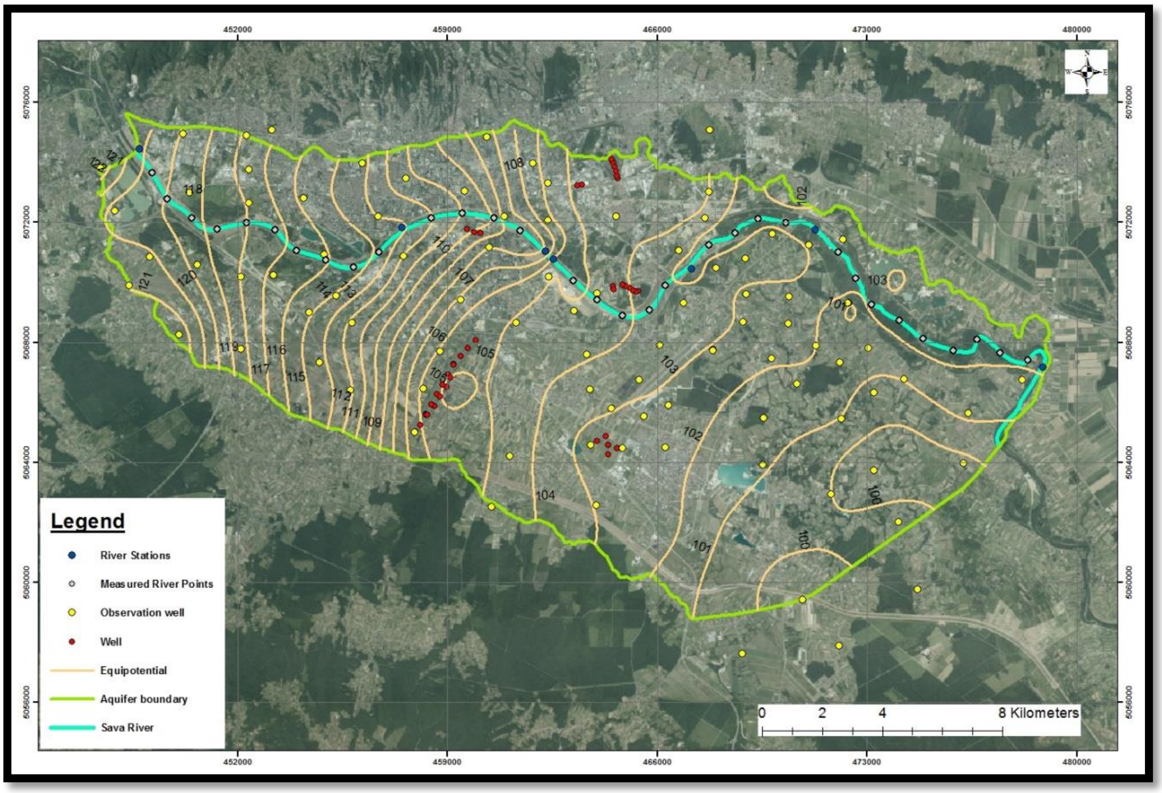


Figure 4.19: Spline, High Water Levels, Weight = 0.1

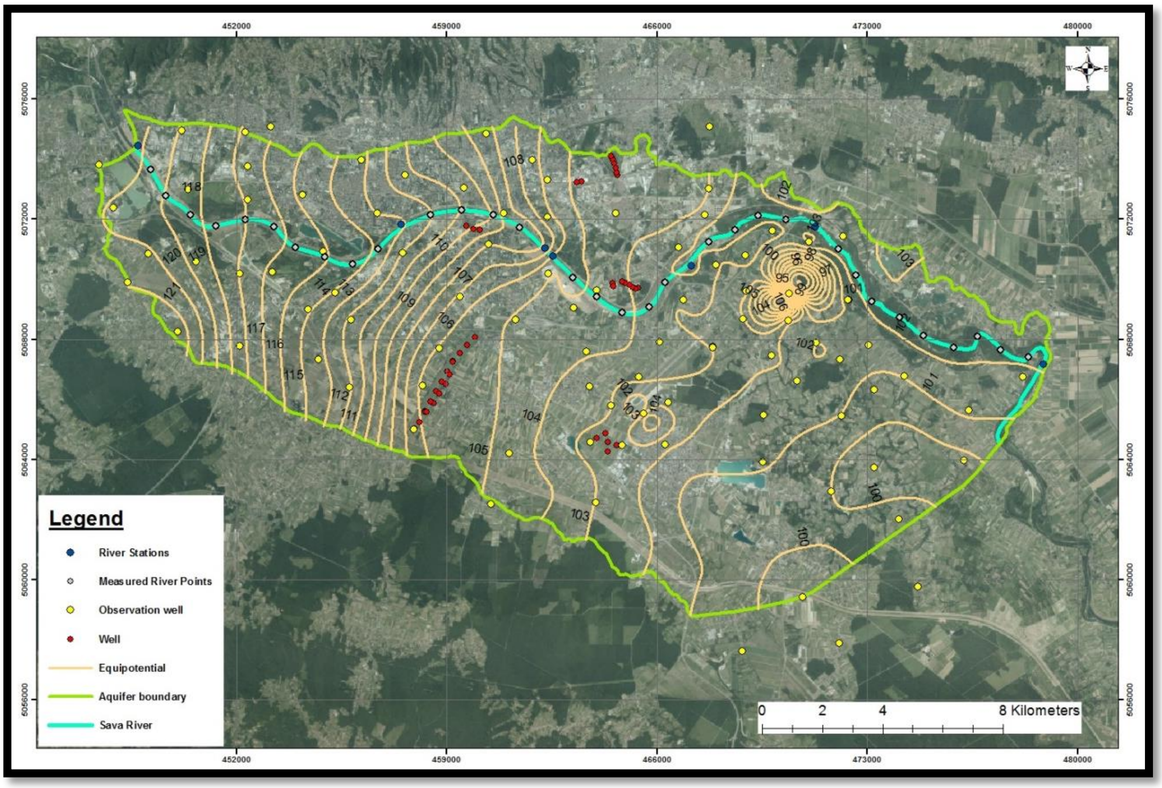


Figure 4.20: Spline, High Water Levels, Weight = 1

In this case, as was explicated previously, using Spline with Tension method, when the weight is increased, the smooth of the surface is decreased. Thus, the Weight = 0.1, that the software uses default, gives a better interpolation. In general, using those parameters, Spline interpolates of a coherent way the levels of this aquifer, resulting a smooth water surface and displaying the influences of Sava River, the river dam and the well fields.

Considering those results, the monthly interpolation was done using Spline with Tension method and the Weight = 0.1 (FIGs. 4.21, 4.22):

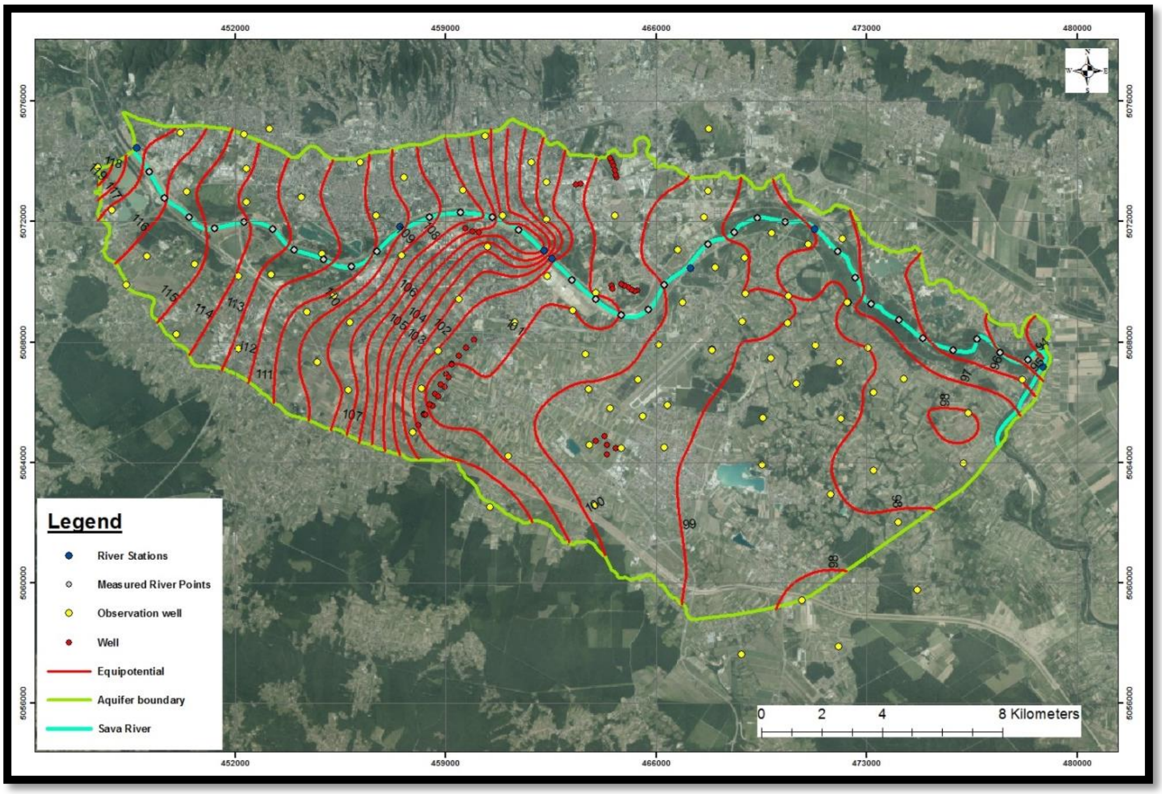


Figure 4.21: Spline, Low Water Levels, Monthly

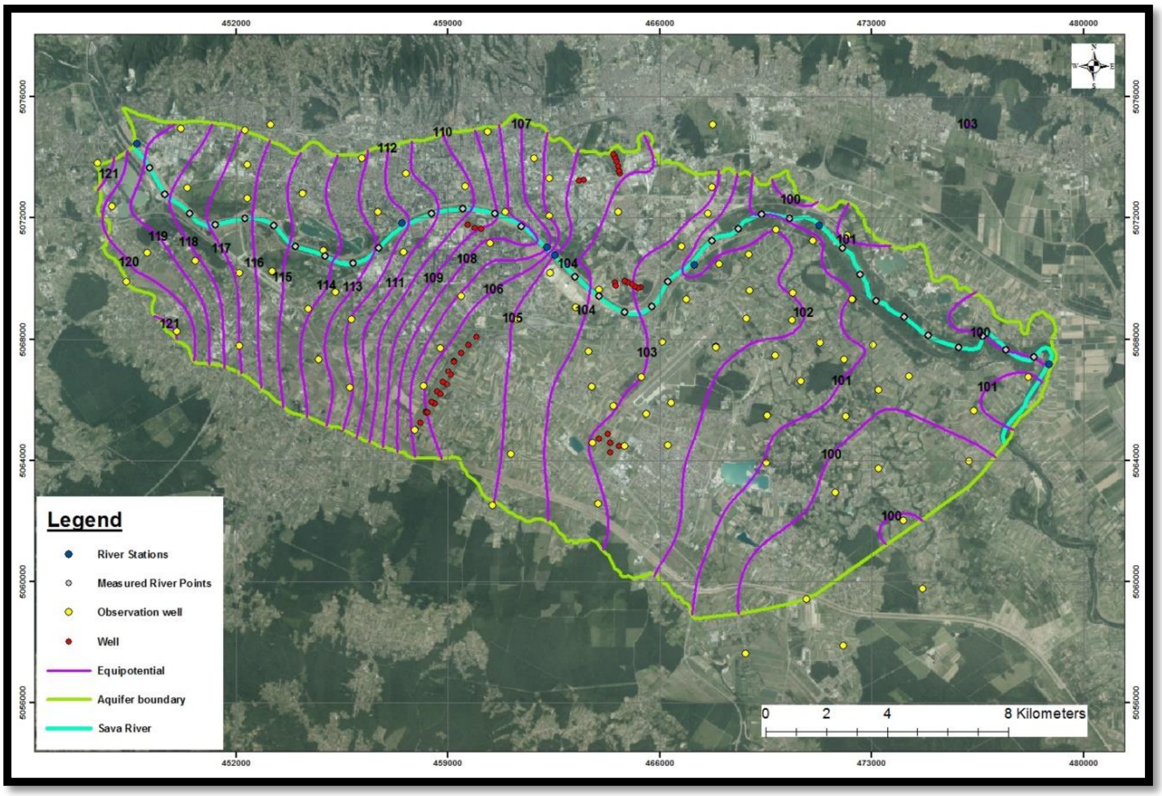


Figure 4.22: Spline, High Water Levels, Monthly

Interpolating monthly, Spline gives good results in the form of the equipotential lines because most of them are regular as it was expected. However some local areas still appear. Thus Spline could be a good reference but not the best method.

4.2.3 Kriging

The Kriging method uses statistical models that provide predicted surfaces and also measure the certainty or accuracy of the predictions. Kriging needs two tasks to make a prediction: to know the dependency rules and to make the prediction. These two tasks are done through two-steps process: estimating spatial autocorrelation through variograms and covariance function, which depend on the model of autocorrelation to predict the unknown values. The options and parameters that it has to decide are the next (FIG. 4.23).

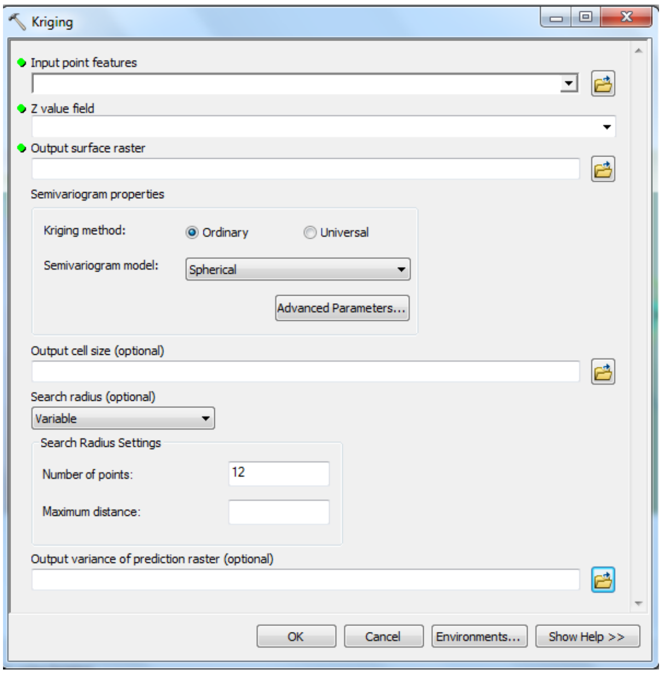


Figure 4.23: Kriging Options

The first step is also to choose the raster file that it is going to be interpolated, that means choose the file of low or high waters. After that it musts select the value of the ground water level as Z value field. Then it is time to change the default parameters established:

- **Kriging method**: it could be used Ordinary or Universal Kriging. Ordinary Kriging is the most used and it assumes the constant mean is unknown. It is a good way to solve the problem unless there is some scientific reason to reject the assumption. The Universal Kriging is based in a predominant trend in the data and it can be modeled by a deterministic function or polynomial. It just may be used when the trend in the data is known and it is possible give a scientific justification to describe it.

After doing the interpolation with both methods, Ordinary Kriging has been chosen because it gave more coherent results.

- **Semivariogram model**: for Ordinary Kriging there are five kinds of semivariogram model: spherical, circular, exponential, Gaussian and linear. The five of them have been used to do the interpolation and all of them give almost the same results. Thus, the semivariogram used was the spherical because it is the default one.
- **Search radius**: it can be Variable or Fixed. For all the methods it has been used the Variable due to the sampled points are situated randomly so that the points have not got the same number of sampled points closer to them (FIGs. 4.24, 4.25).

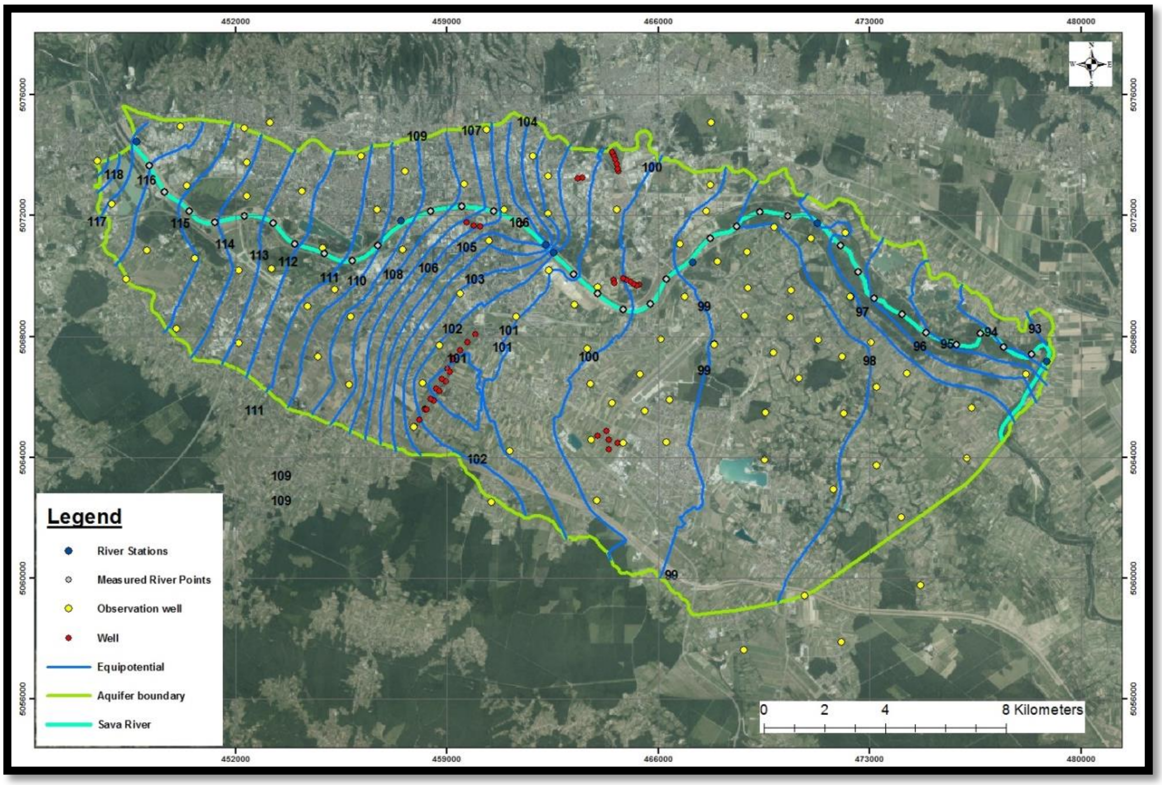


Figure 4.24: Kriging, Low Water Levels

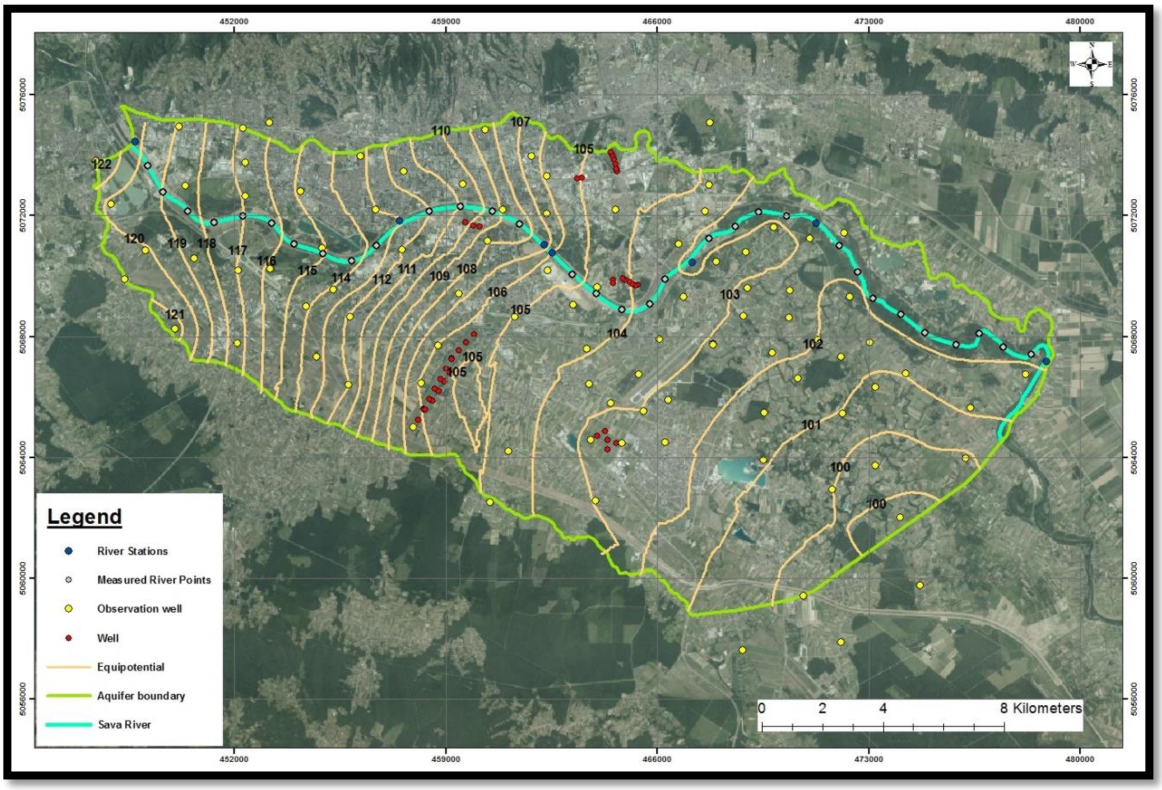


Figure 4.25: Kriging, High Water Levels

Using the Ordinary Kringing Method, as has happened with Spline Method, it has been obtained maps that could adapt to the reality of the aquifer without those local points. The only problem could be the irregularity of the headlines but they could be corrected when these are drawn manually. Thus it does not affect to understand the dynamic of the aquifer.

As it was done before, either Kriging was used to do the monthly interpolation following the characteristics describe before. These are the results (FIGs. 4.26, 4.27).

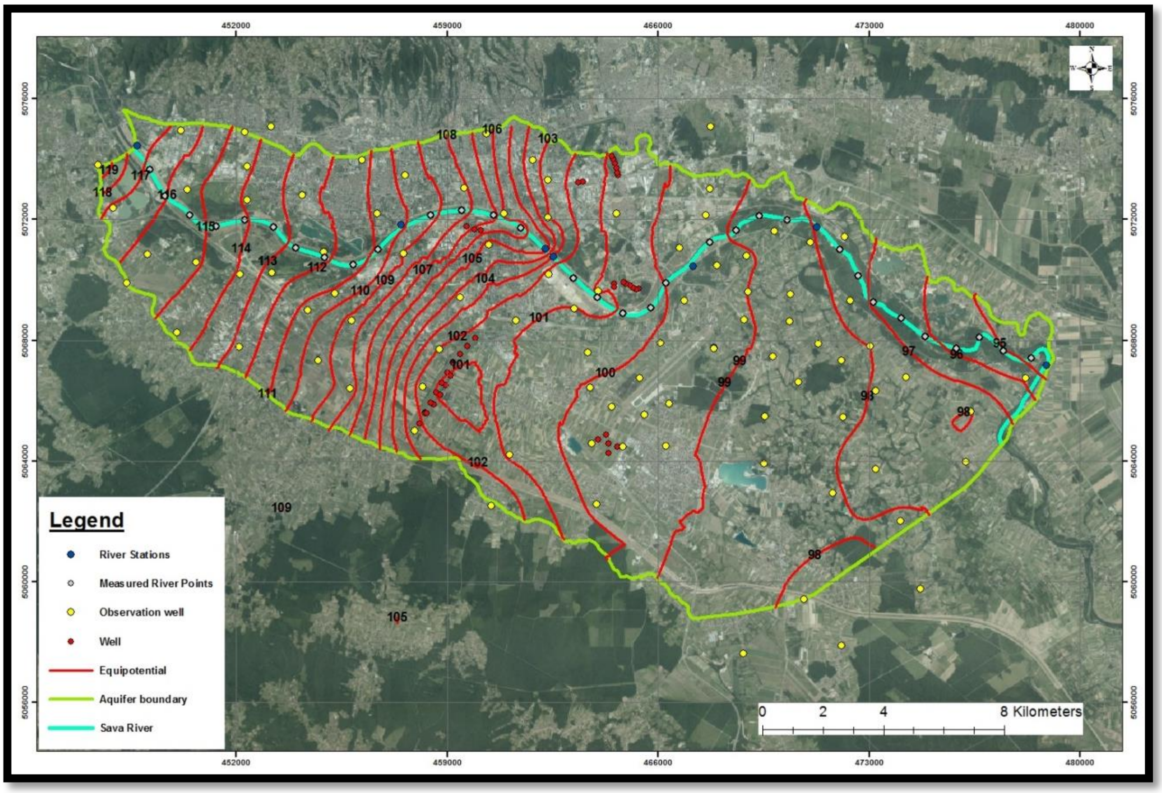


Figure 4.26: Kriging, Low Water Levels, Monthly

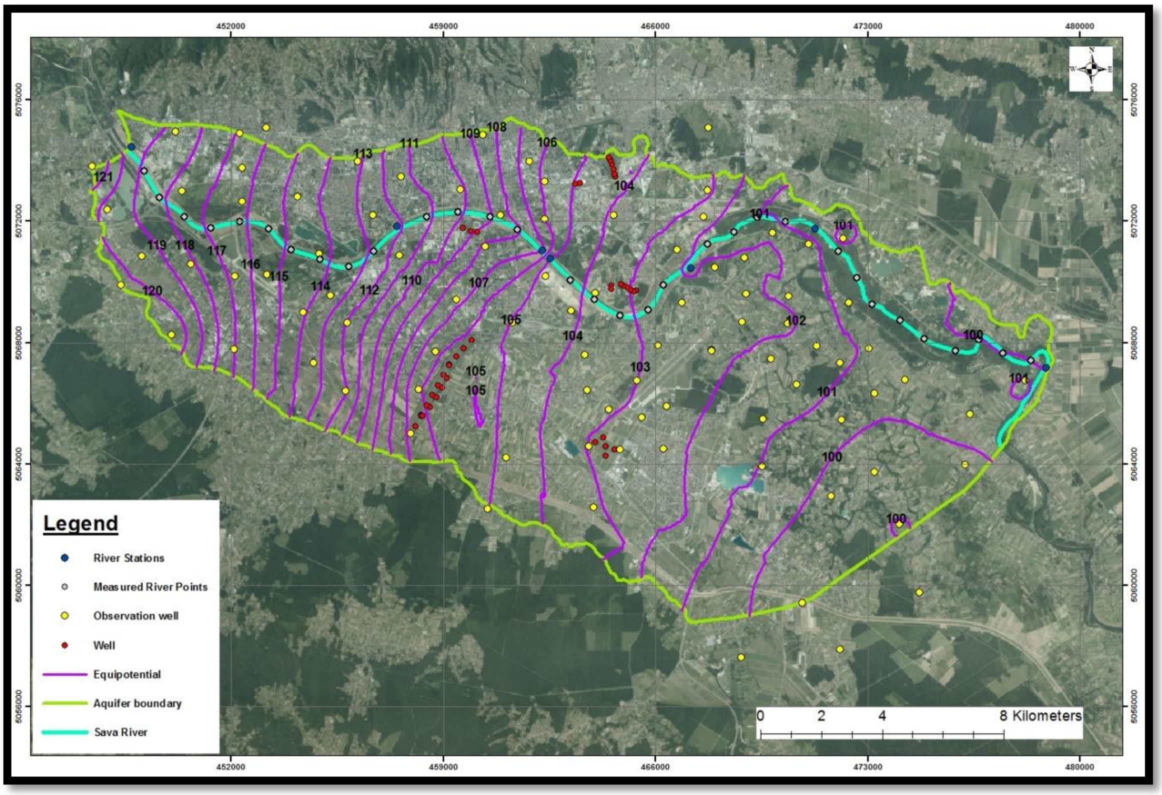


Figure 4.27: Kriging, High Water Levels, Monthly

The monthly equipotential lines created by Kriging have the same characteristics than the daily headlines, they are irregular but they have a correct form to explain the movement of the flow aquifer.

4.2.4 Natural Neighbor

The Natural Neighbour method represents the simplest element in a given space like a triangle in 2 dimensions and a polyhedron in 3 dimensions. This method can be used to work with topographic, bathymetric, geophysical and soil data. To estimate unknown values of a location, this method uses the sampled points situated around of this (FIG. 4.28).

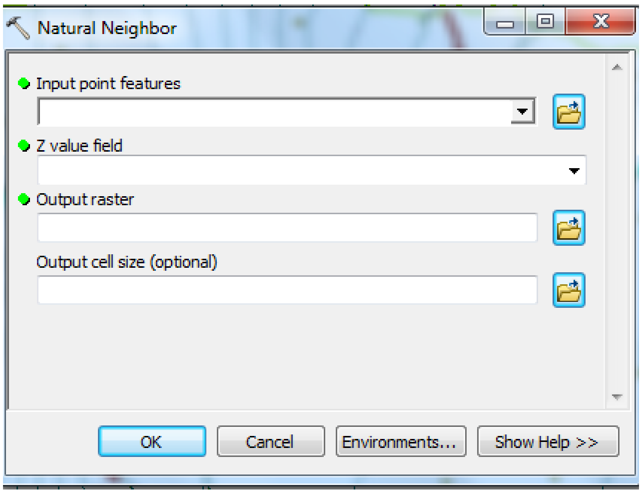


Figure 4.28: Natural Neighbor Options

As the figure above shows, this method has not got any parameter or option to choose, so it is the easiest to use (FIGs, 4.29, 4.30).

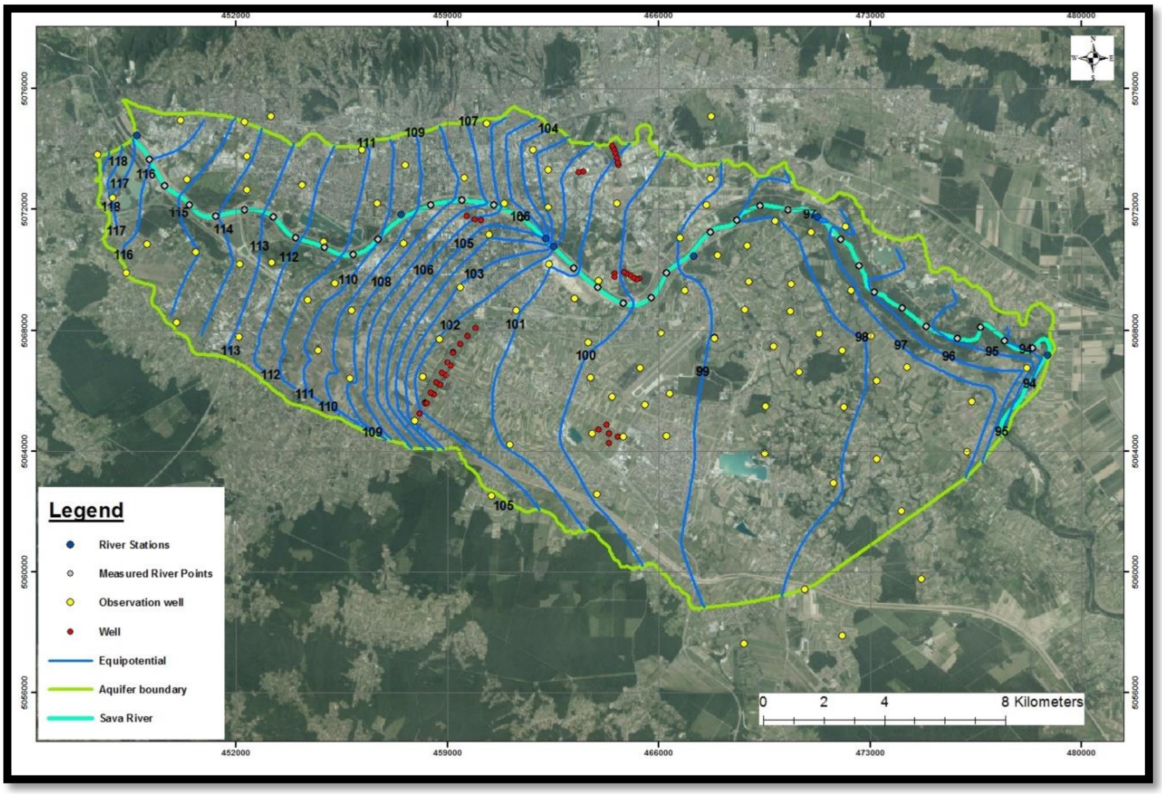


Figure 4.29: Natural Neighbor, Low Water Levels

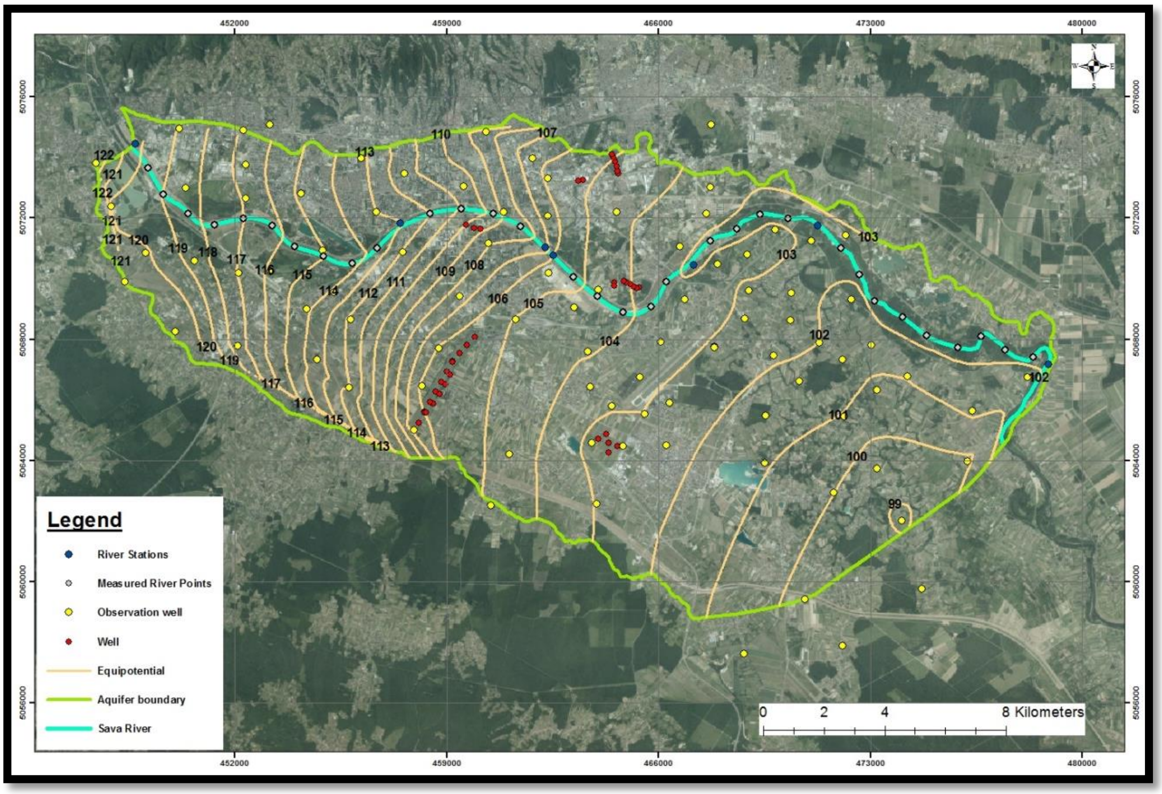


Figure 4.30: Natural Neighbor, High Water Levels

The Natural Neighbor Method offers very good results for both levels. Not choosing any option or estimate any parameter to interpolate and give good surface of interpolation, without local points drawn and with regular equipotential lines. It supposes that this method could be the best one to be used.

Finally, Natural Neighbor was also used by the monthly average. In this method is not necessary modify parameters. Then the results are these (FIGs 4.31, 4.32).

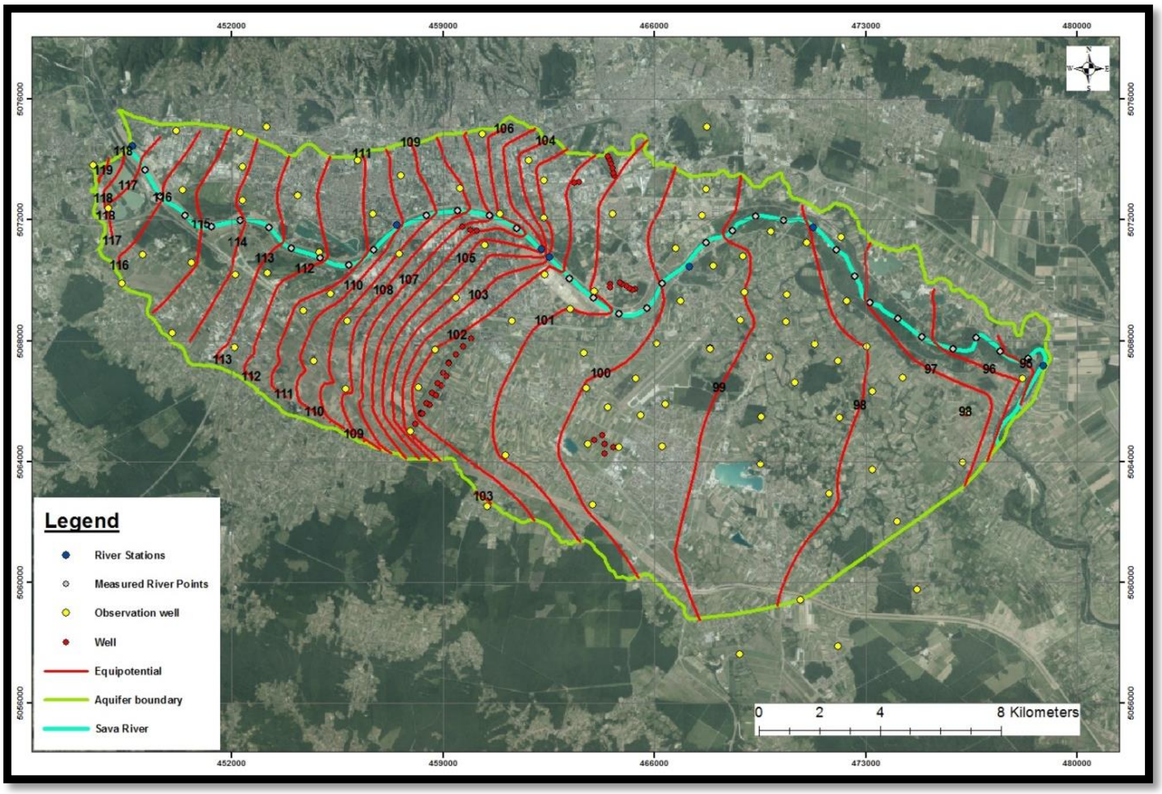


Figure 4.31: Natural Neighbor, Low Water Levels, Monthly

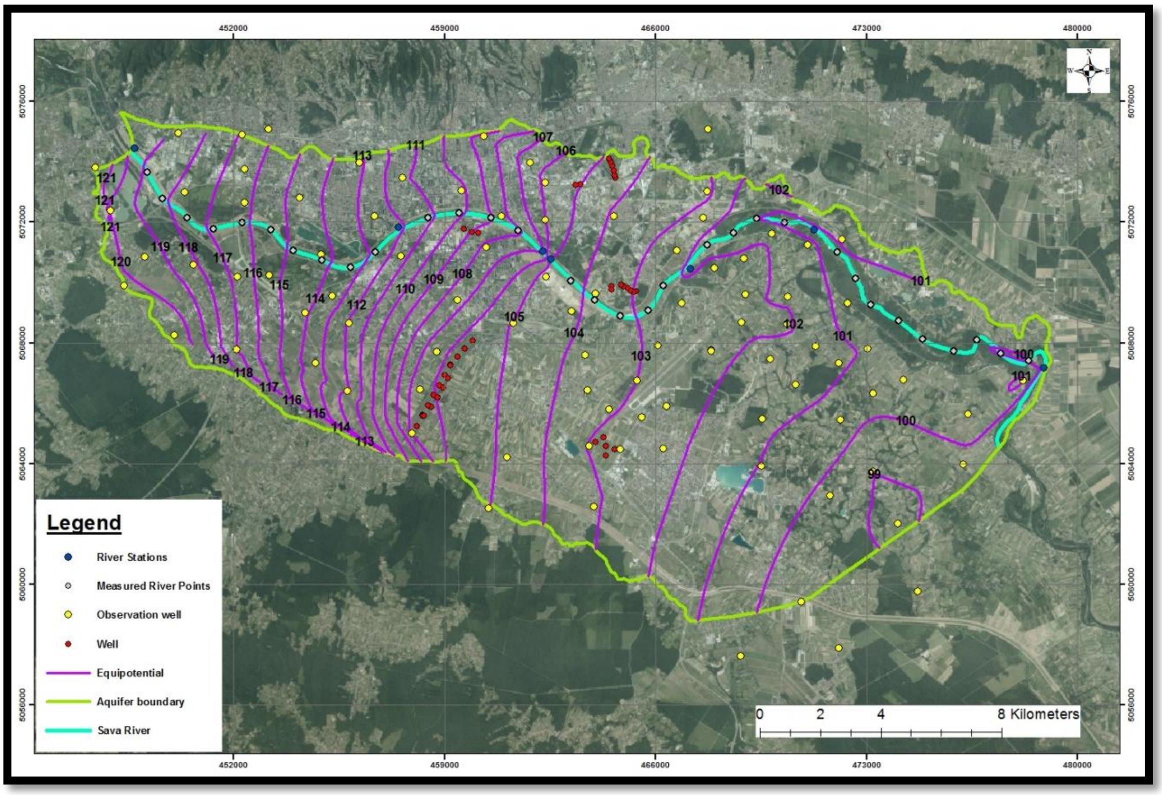


Figure 4.32: Natural Neighbor, High Water Levels, Monthly

Good results were gotten with Natural Neighbor with the monthly data as it happened with the daily data. The equipotential lines fit almost perfectly with the theoretical movement of the aquifer. They show the influence of the Sava River, river dam and the well fields.

4.2.5 Final Equipotential Maps

After study how each method interpolates the data and draws its equipotential map, it is time to draw the final equipotential map for low and high water level daily and monthly. For that the previous maps were placed in the same map and then the final maps were drawn manually following this pattern.

- Daily Low Water Level (FIG. 4.33) (ENCLOSURE 1):

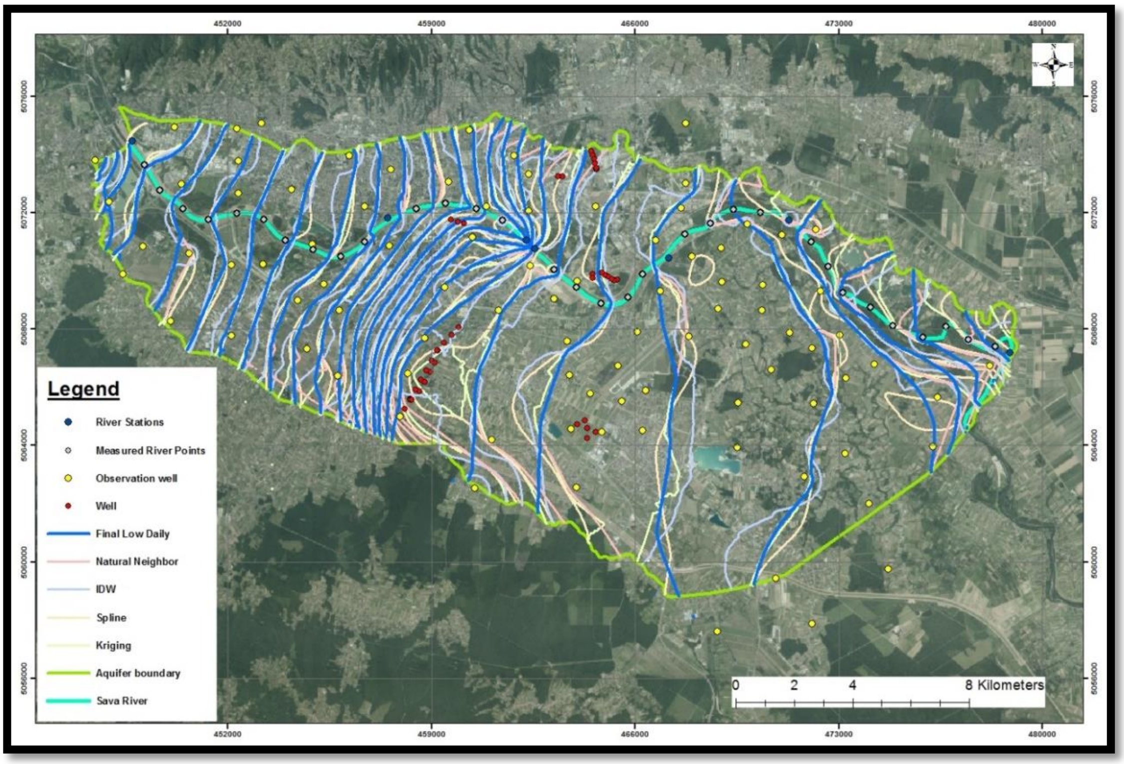


Figure 4.33: Process of Making the Final Daily Low Equipotential Map

- Daily high water level (FIG. 4.34) (ENCLOSURE 2):

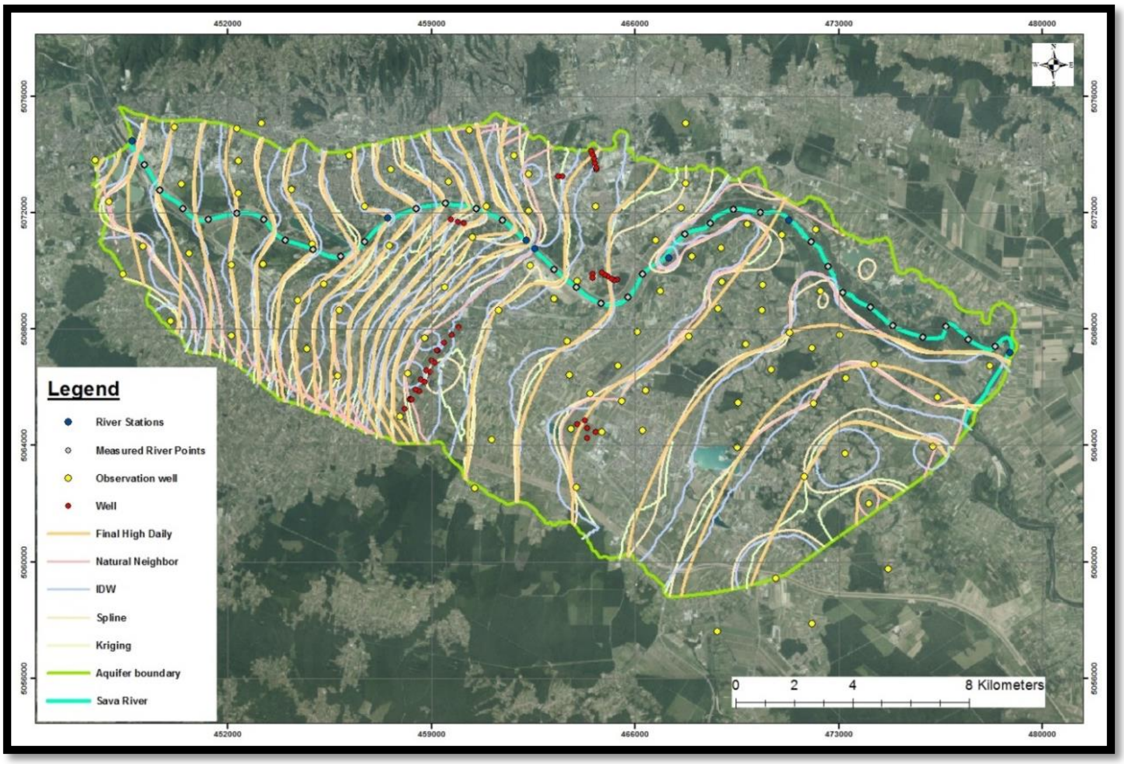


Figure 4.34: Process of Making the Final Daily High Equipotential Map

- Monthly low water level (FIG. 4.35) (ENCLOSURE 3):

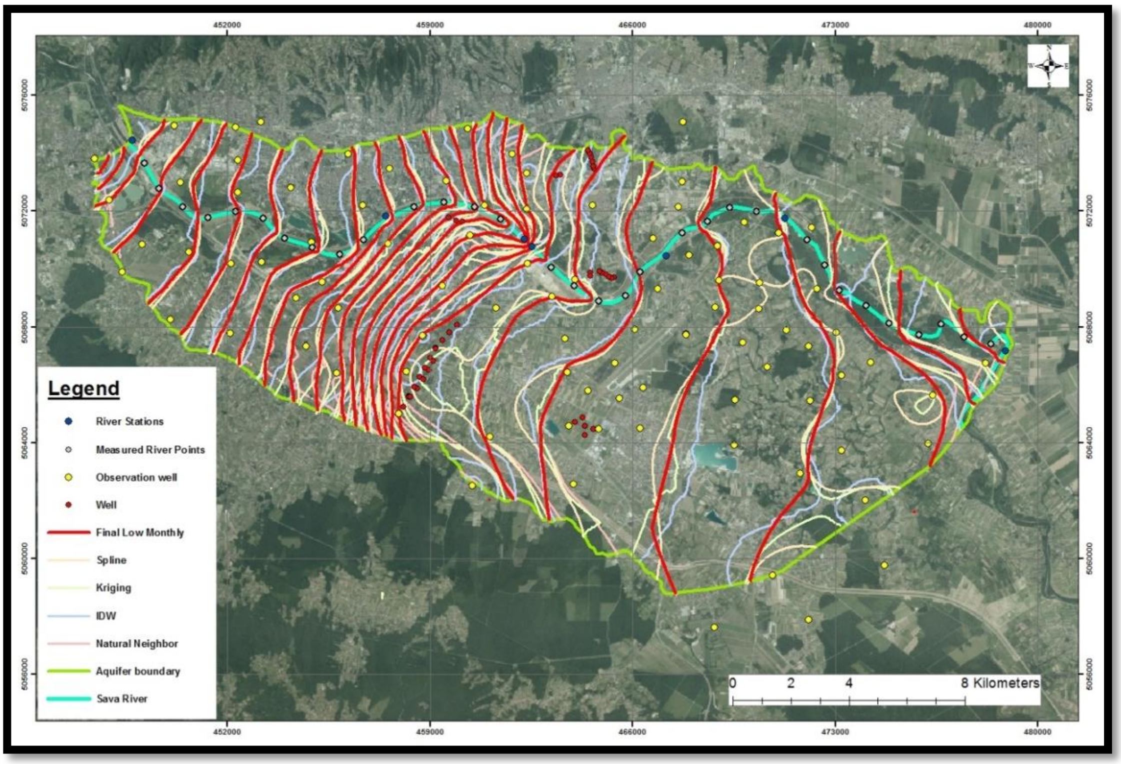


Figure 4.35: Process of Making the Final Monthly Low Equipotential Map

- Monthly high water level (FIG. 4.36) (ENCLOSURE 4):

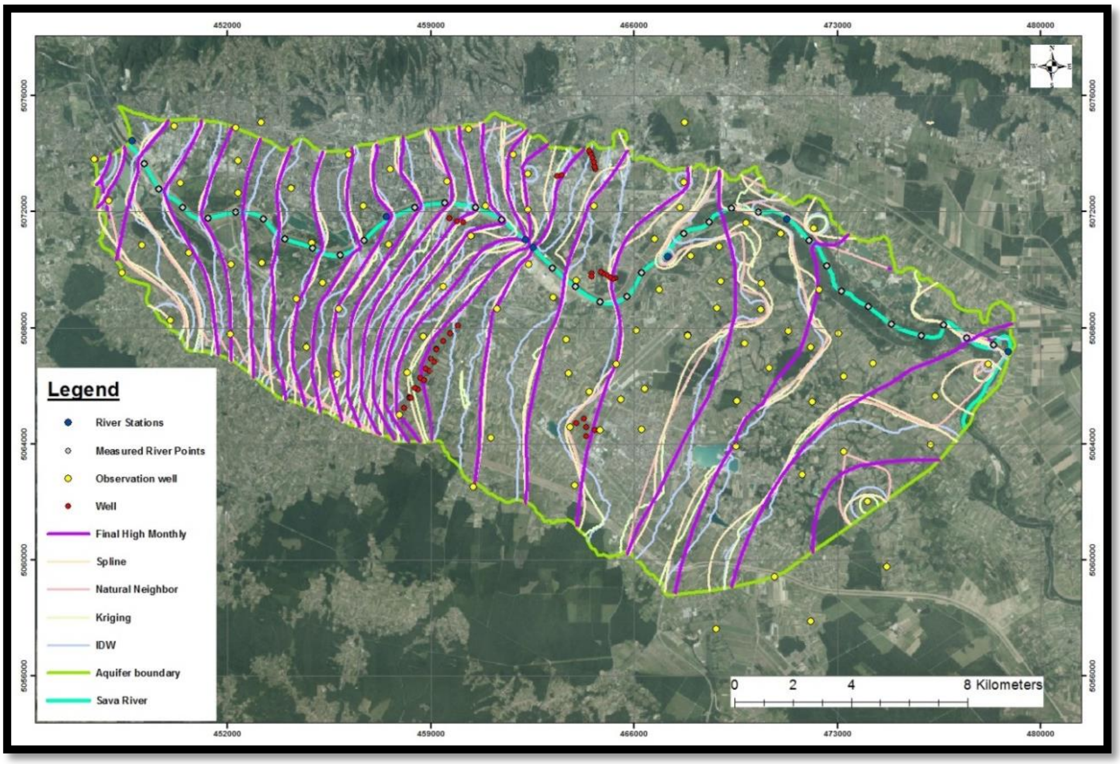


Figure 4.36: Process of Making the Final Monthly High Equipotential Map

All the studied situations show two different sides in the aquifer. The western side has closer and more regular equipotential lines, quite similar in the four scenarios with the four interpolation methods. And the eastern side that has more separation between the equipotential lines and completely different depending of the kind of interpolation method and the studied scenario.

This is because of, mainly, the thickness of the aquifer. The eastern side has higher thickness than the western side, generating more irregularities in the observation wells (FIG. 2.10). Moreover, this eastern side of the aquifer is highly influenced by the well fields and, in the northern side of Sava River, by the city of Zagreb, where the underground buildings and the waterproofing of the soil modify the aquifer flow.

5. ANALYSIS OF RESULTS AND DISCUSSION

5.1 DAILY INTERPOLATION VS. MONHTLY INTERPOLATION

The Zagreb aquifer is a very dynamic system due to the high of hydraulic conductivity which varies between 3000 m/day and 1000 m/day. That makes a very big influence among the Sava River and the aquifer producing differences in the direction flow depending of the level of water.

This fact gains big importance, for example, when a research is focused in the movement of a pollution leak in the aquifer. The water level data used in this moment would involve changes in the position of the plume due to the high hydraulic conductivity.

Below, the differences between daily and monthly equipotential lines are showed for low and high water level (FIGs. 5.1, 5.2):

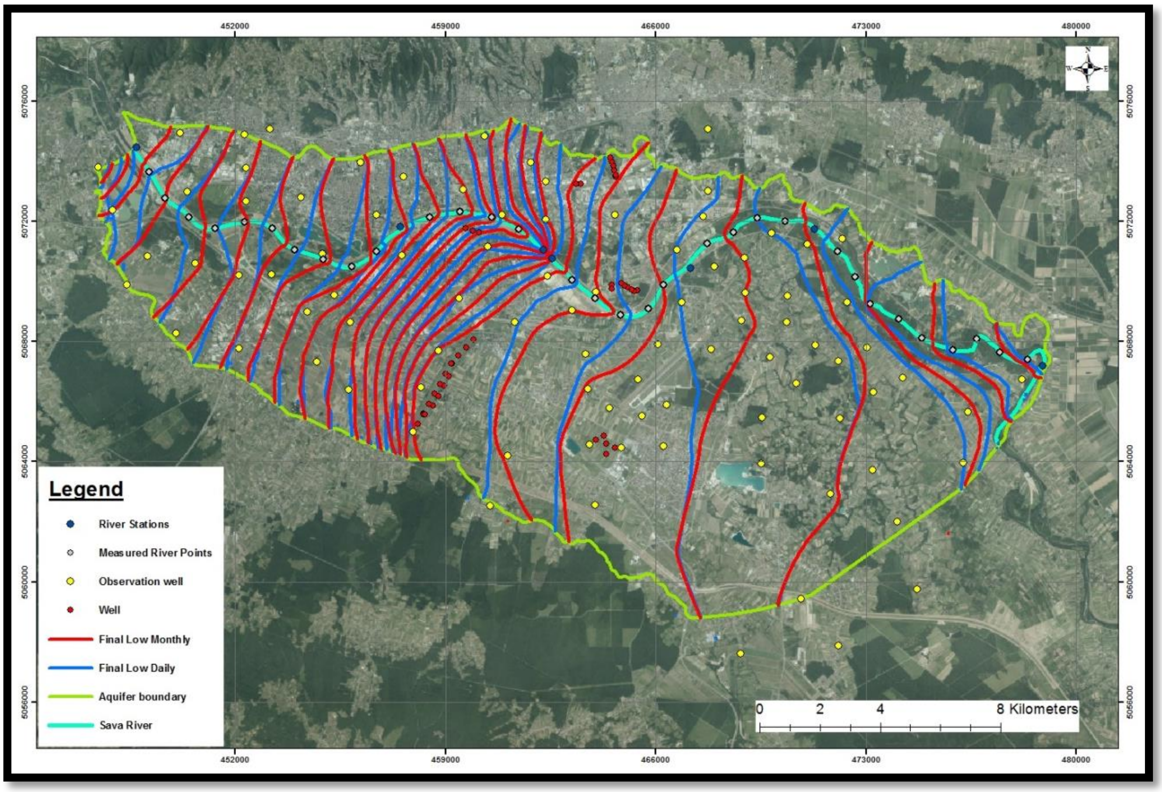


Figure 5.1: Daily and Monthly Low Water Level

This map shows the different equipotential lines of daily and monthly high water level. In the western side are more similar than in the eastern side. In general the direction of the flow seems to be the same, except in some areas of the east side of the aquifer, especially at the north of Sava River, where the daily equipotential lines drive the flow to the boundary of the aquifer and the monthly ones to the Sava River.

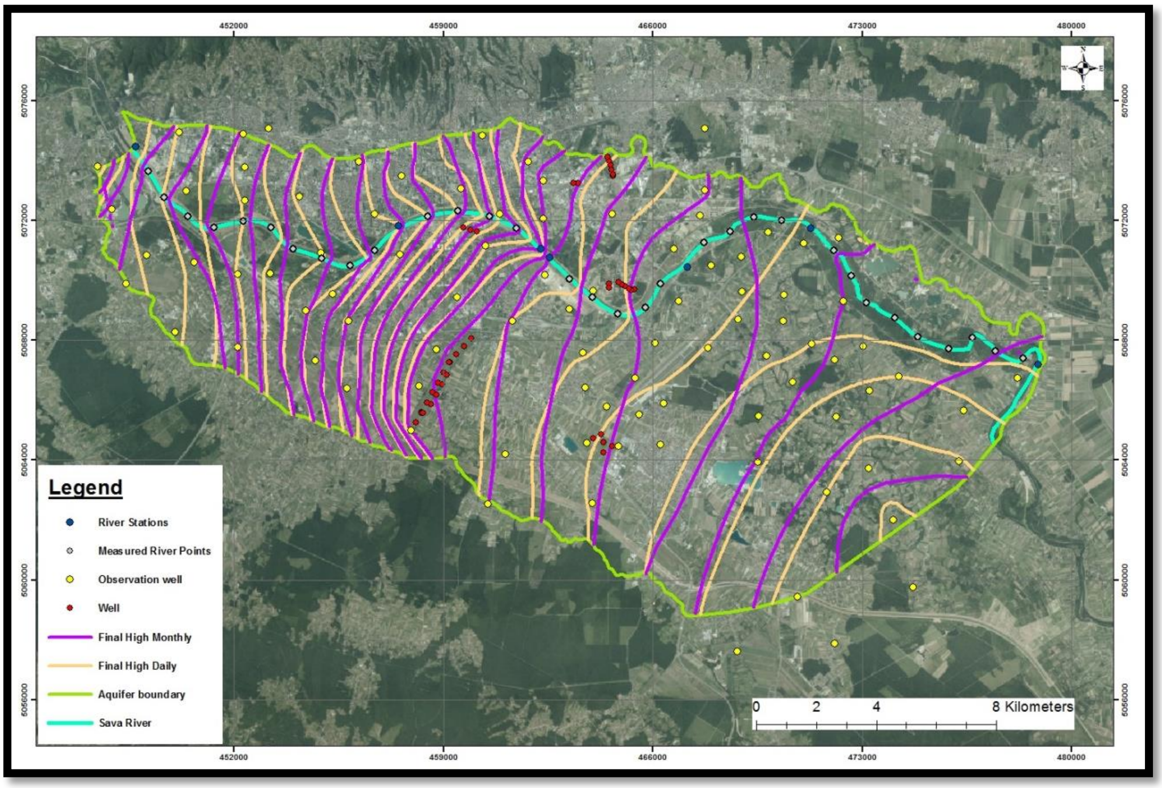


Figure 5.2: Daily and Monthly High Water Level

In this case, the map shows the equipotential lines of daily and monthly high water level. As the previous map, the western side presents more similar results than the eastern side. But the differences in the eastern side are bigger, in some areas crossing themselves almost perpendicularly. That means great changes in the flow movement, driving the water in one case from the aquifer to the river and in the other from the aquifer to the boundaries.

5.2 LOW WATER LEVEL VS. HIGH WATER LEVEL

Looking at the results of the interpolation, it can be detected clearly big differences between how the system works with low and high water levels. The movement and direction of the flow, the location of the inflows and outflows change depending of that.

The next figures show the differences among low and high water levels with daily and monthly data (FIGs. 5.3, 5.4).

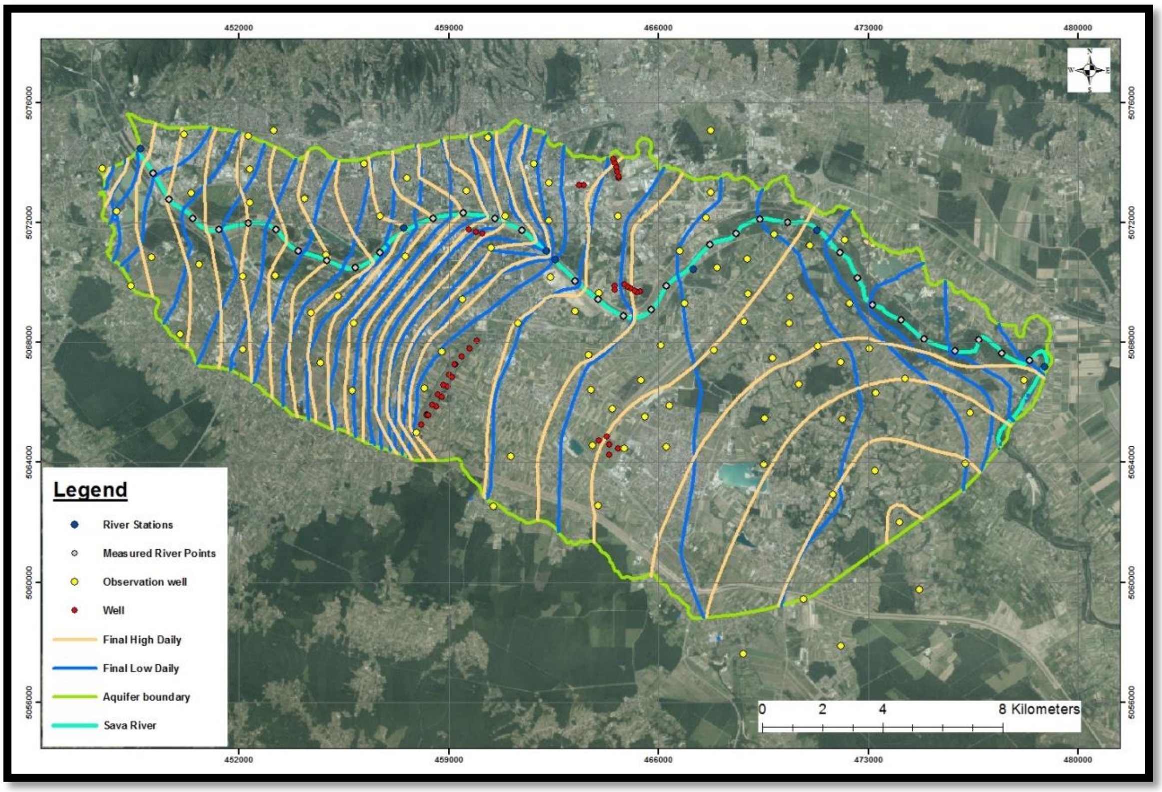


Figure 5.3: Daily Low and High Water Level

This figure shows big differences between the both scenarios which is normal because they are the highest and lowest water level in 15 years. Thus, while the flow movement, during the low one, goes from northwest to east-northeast, the movement during the high water level day goes from west to southeast.

That changes completely the dynamic of the system. Both days the Sava River fills the aquifer in the western side due to the influence of the river dam. But downstream, the movement change depending of the level in the aquifer. On the one hand, when there is low water level the flow goes from the aquifer to refill the Sava River from its right bank. On the other hand, when there is high water level, the Sava River keep filling the aquifer towards southeast to have the outflow through the boundaries of the aquifer.

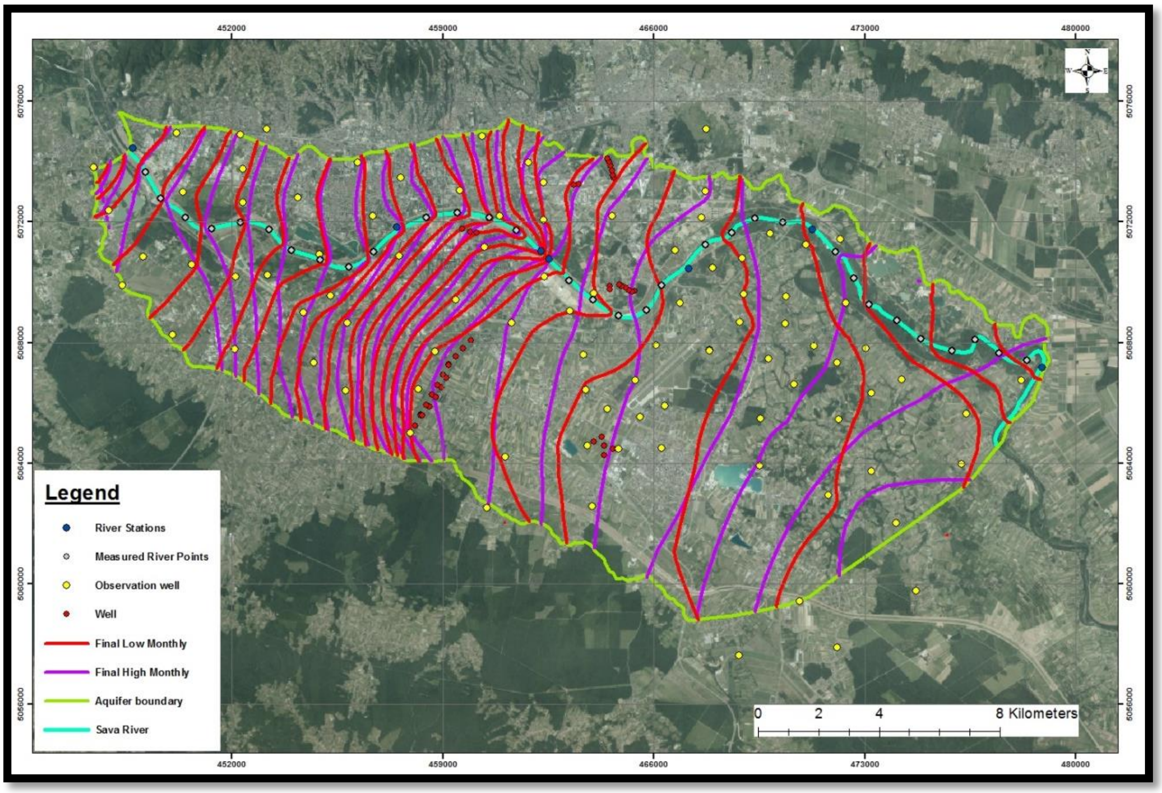


Figure 5.4: Monthly Low and High Water Level

In this case the figure shows the difference between the monthly average of the lowest and highest month in 15 years, so that there are not so big differences as in the previous one, but the behavior of the aquifer is pretty similar.

Upstream the river dam is the river which fills the aquifer because of the influence of it. And in the east side of the system, the aquifer gives water to the river during low levels and the river fills it when it is time of high water levels, as it happened in the previous figure.

5.3 COMPARISON OF RESUSLTS FOR DIFFERENT INTERPOLATION METHODS

As it has been explained before, the results obtained through the different interpolation methods have been analyzed to check their accuracy and then try to help in the selection of the most appropriated method for this system.

The methods used for this studio have been: Pearson, Spearman, Root Mean Squared Error and T-Test giving the next results:

Table 4: Accuracy of the Results for Low Daily Interpolation

	Pearson	Spearman	RMSE	P-Value (Pearson)	P-Value (Spearman)
IDW	0.9999	0.9997	0.0248	0	0
KRIGIN	0.9999	0.9996	0.0453	0	0
NN	0.9999	0.9997	0.0424	0	0
SPLINE	0.9999	0.9997	0.0385	0	0

Table 5: Accuracy of the Results for High Daily Interpolation

	Pearson	Spearman	RMSE	P-Value (Pearson)	P-Value (Spearman)
IDW	0.9997	0.9997	0.1414	0	0
KRIGIN	0.9997	0.9996	0.1421	0	0
NN	0.9997	0.9995	0.1425	0	0
SPLINE	0.9997	0.9996	0.1427	0	0

Table 6: Accuracy of the Results for Low Monthly Interpolation

	Pearson	Spearman	RMSE	P-Value (Pearson)	P-Value (Spearman)
IDW	0.9999	0.999	0.0883	0	0
KRIGIN	0.9998	0.9997	0.0942	0	0
NN	0.9998	0.9988	0.0937	0	0
SPLINE	0.9999	0.9989	0.0914	0	0

Table 7: Accuracy of the Results for High Monthly Interpolation

	Pearson	Spearman	RMSE	P-Value (Pearson)	P-Value (Spearman)
IDW	0.9997	0.9995	0.134	0	0
KRIGIN	0.9997	0.9994	0.1362	0	0
NN	0.9997	0.9982	0.1541	0	0
SPLINE	0.9997	0.9994	0.1355	0	0

Looking at the results obtained of the accuracy study, we cannot appreciate large differences between the different interpolation methods. All of them have pretty big accuracy with the initial data. The Pearson and Spearman correlation are almost 1, the Root Mean Squared Error is very low, close to 0 and the p-value of the t-Test is 0.

For example, within the equality of the results, the IDW method has obtained the largest accuracy, but, it has been seen that with this method, no coherent interpolations are gotten. And the accuracy with Natural Neighbor was the worst one, but the graphical results obtained with the interpolation were the best ones.

Thus these results do not have enough relevance to say which method makes a better interpolation as it was found in other researches like Sun et al 2009. In this study the results show differences between methods which could have appeared because the aquifer levels had more variation and, also, the extension of that aquifer is bigger and less observation wells were used.

6. CONCLUSIONS

The first conclusion that can be extracted of this paper is that the Natural Neighbor is the best interpolation method for this aquifer system. It can be affirmed after to have interpolated the Zagreb aquifer system with the different methods those have been already explained (Inverse Distance Weight, Spline, Kriging and Natural Neighbor) and after to having analyzed the results that they have provided. There are two main reasons that support this conclusion:

- Unlike the other methods, the Natural Neighbor has not got options or parameters that must be modified to make the interpolation. That can be considered a good point because the results depend of the accuracy of the sampled data and move away from the subjectivity of the people who is modeling.
- Other reason, probably more empirical, is the results that have been got with each method. While Inverse Distance Weight does not get coherent results with any option or parameter used, the other three methods do. Then if it keeps analyzing the results, Spline draws some local points that really do not exist. Kriging does not draw those local points but the equipotential lines are not regular. And finally, Natural Neighbor does not draw those local points and the equipotential lines are regular, how theoretically they have to be.

It has been able to conclude this due to the results obtained with the accuracy study not make large difference between the methods, being the four of them very accurate. This equality becomes it in irrelevant for make the decision about which method is the most appropriated to be used in the Zagreb Aquifer System.

Other conclusion is connected with the big difference in the movement of the flow of ground water in the aquifer system. First of all, in the general movement of the flow, when the water level is lower, the flow goes from northwest to east. And during periods of high water level goes from west to southeast. This change of direction modifies completely the dynamic of the system especially downstream of river dam. In this area during low water levels the aquifer discharge in Sava River and on the contrary, when there are high water levels Sava River fills the aquifer.

Finally, the last conclusion is the importance of the time step for the data. The Zagreb aquifer system has big variation of hydraulic conductivity and as it has been shown previously, there are changes in the direction of the flow depending on the data are daily or monthly. That means that, if the target of the research is to study whether varies the direction of the flow or management the available resource, it might be used the monthly average. But, if the goal is to identify the movement of a pollution leak, it would be better to use daily data.

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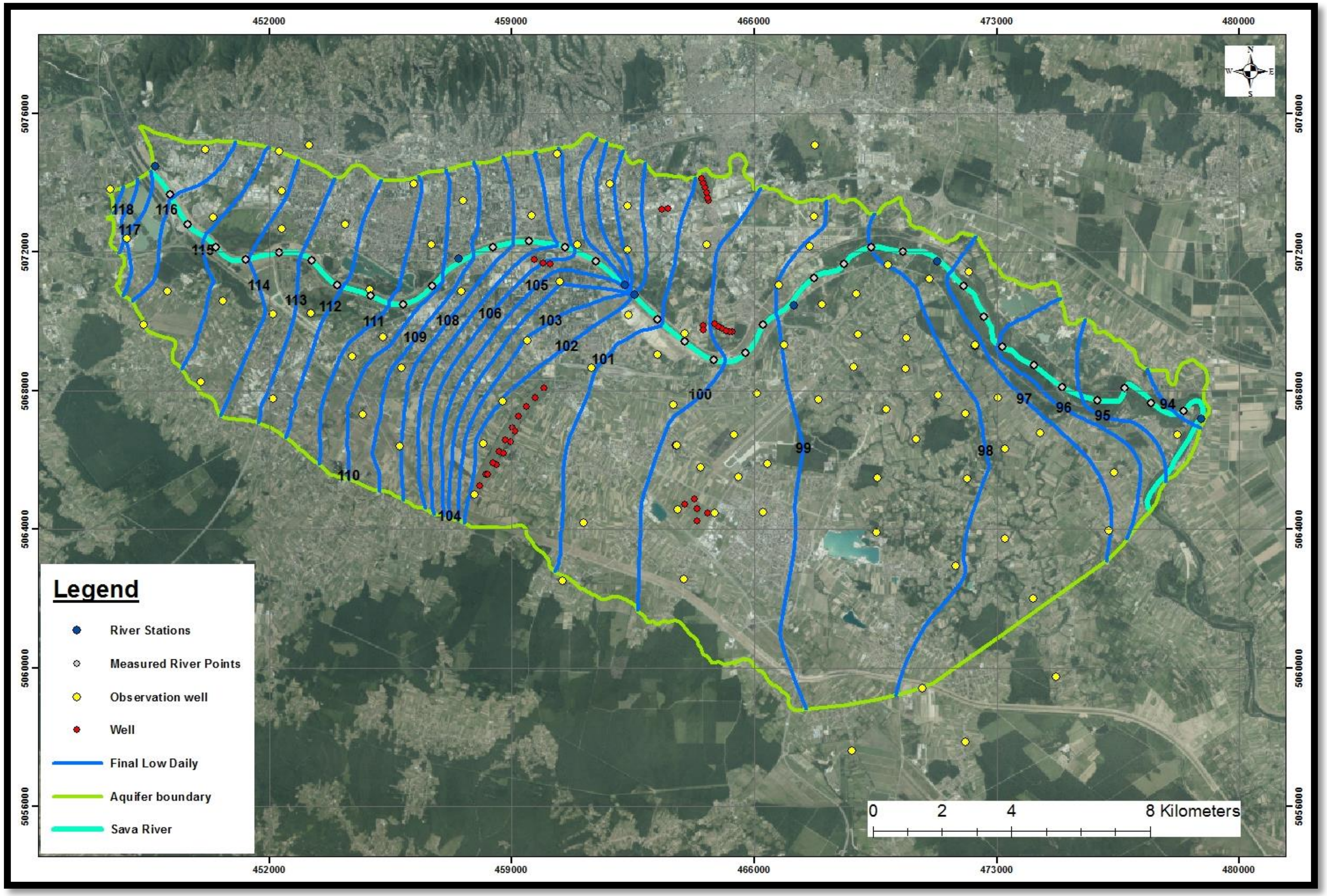
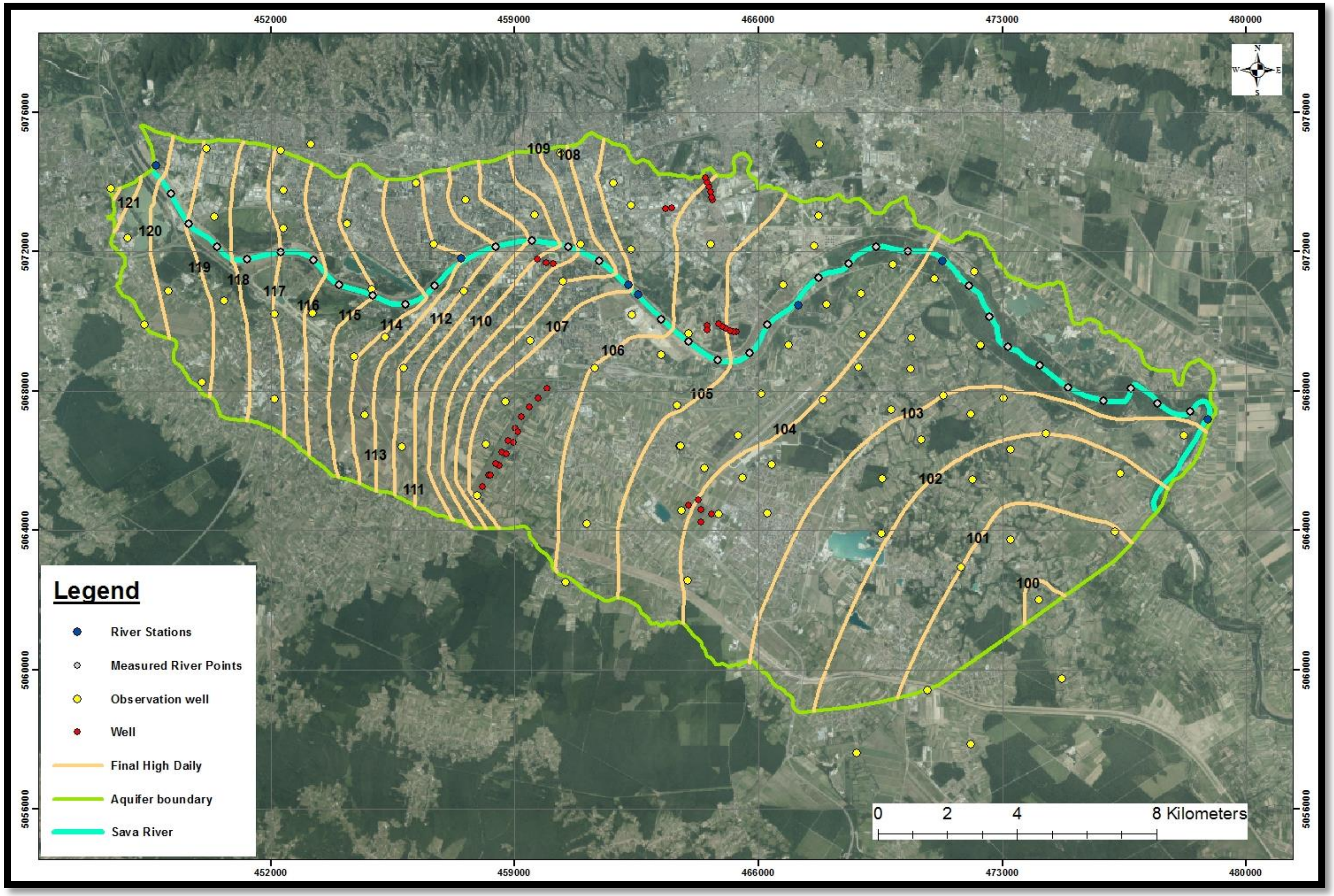
ENCLOSURE 1



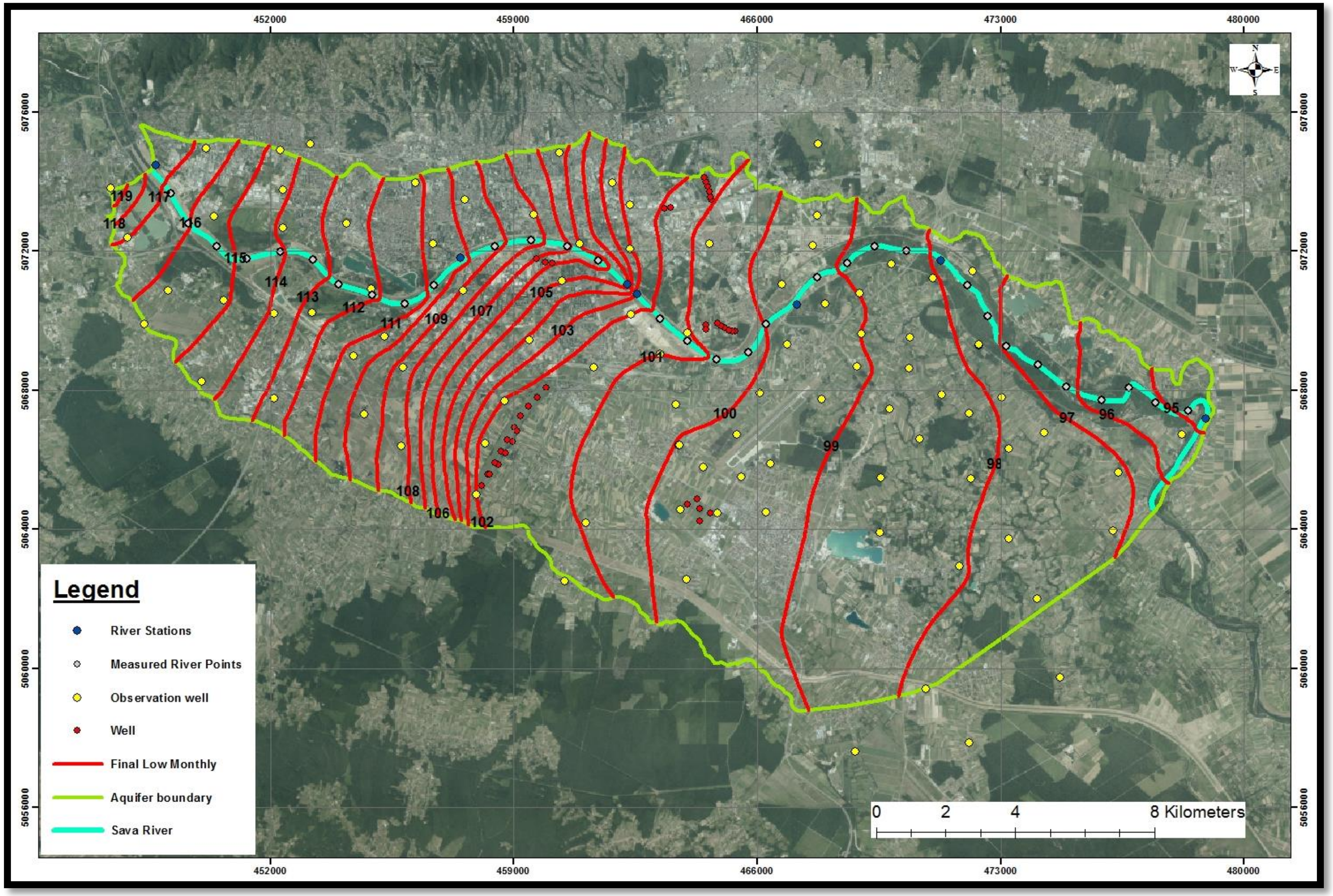
Enclosure 1: Final Daily Low Water Level

ENCLOSURE 2



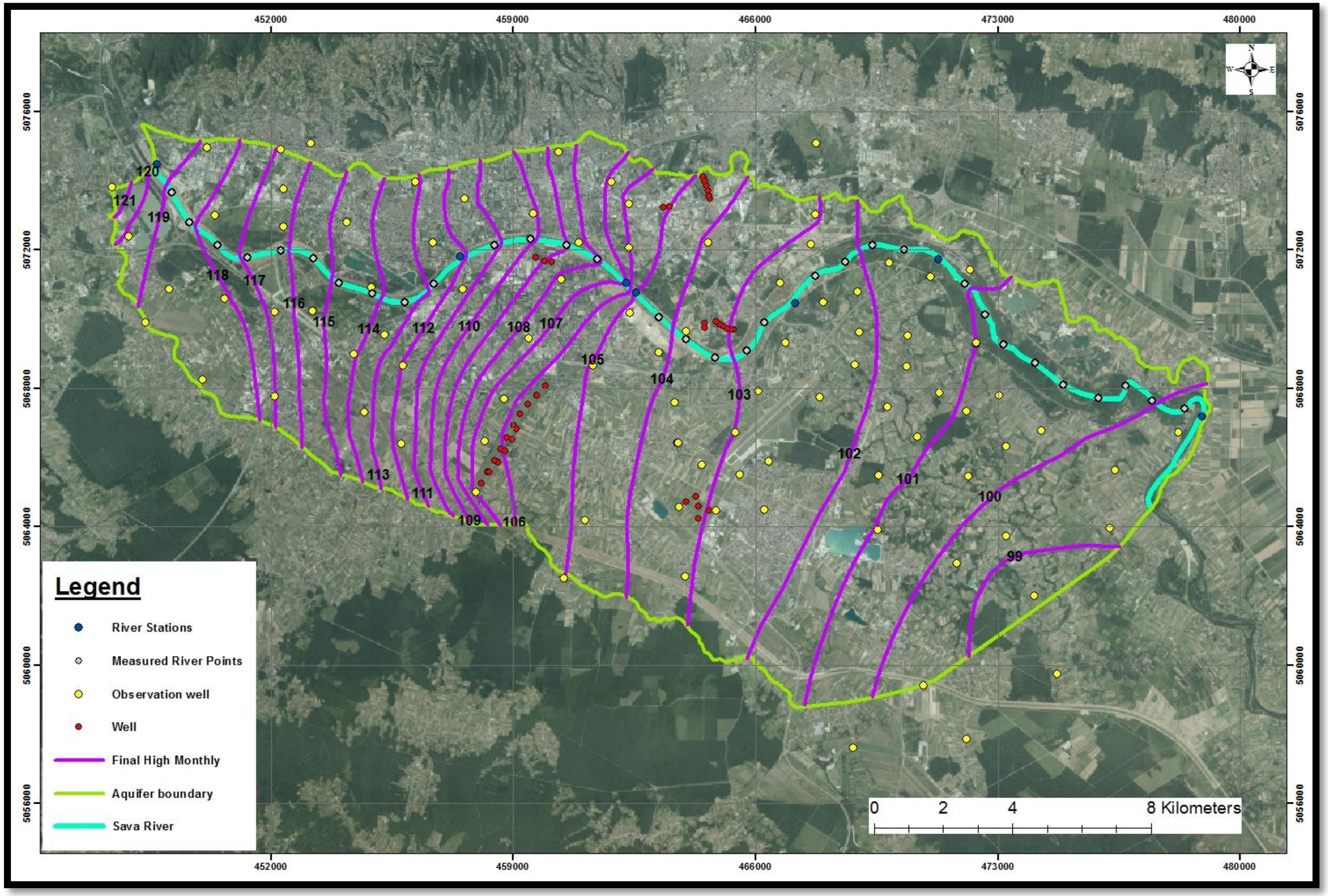
Enclosure 2: Final Daily High Water Level

ENCLOSURE 3



Enclosure 3: Final Monthly Low Water Level

ENCLOSURE 4



Enclosure 4: Final Monthly High Water Level