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DEPARTMENT OF GEOLOGICAL ENGINEERING

ARTIFICIAL RECHARGE SIMULATION BASED ON ANISOTROPY EVALUATION FROM INTERWELL CONNECTIVITY

MASTER OF SCIENCE THESIS

ENGİN GÜNAY

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Graduate School of Natural and Applied Sciences

THESIS CONFIRMATION

The thesis, prepared by **ENGİN GÜNAY**, titled as **"ARTIFICIAL RECHARGE SIMULATION BASED ON ANISOTROPY EVALUATION FROM INTERWELL CONNECTIVITY"** has been accepted unanimously/majority by the jury listed below that fulfils the necessary conditions for master degree of Department of Geological Engineering at 21/09/2016.

THESIS DEFENCE JURY

Prof. Dr. Moumtaz RAZACK **(Head of Jury)** Signature:
Department of Geosciences,
University of Poitiers, Poitiers, France

Asst. Prof. Dr. Bedri KURTULUŞ **(Supervisor)** Signature:
Department of Geological Engineering,
Mugla Sitki Kocman University, Muğla

Asst. Prof. Dr. Mathieu LE COZ **(Co-Supervisor)** Signature:
Department of Geosciences,
University of Poitiers, Poitiers, France

Asst. Prof. Dr. Özgür AVŞAR **(Member)** Signature:
Department of Geological Engineering,
Mugla Sitki Kocman University, Muğla

Asst. Prof. Dr. Gilles POREL **(Member)** Signature:
Department of Geosciences,
University of Poitiers, Poitiers, France

Asst. Prof. Dr. Jacques BODIN **(Member)** Signature:
Department of Geosciences,
University of Poitiers, Poitiers, France

Asst. Prof. Dr. Aude NAVEAU **(Member)** Signature:
Department of Geosciences,
University of Poitiers, Poitiers, France

Date of Defence: 21/09/2016

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DEPARTMENT CONFIRMATION

Asst. Prof. Dr. Bedri KURTULUŞ — Signature:

Head of Department of Geological Engineering,
Mugla Sitki Kocman University, Muğla

Asst. Prof. Dr. Bedri KURTULUŞ — Signature:

Supervisor, Department of Geological Engineering,
Mugla Sitki Kocman University, Muğla

Date of Defence: 21/09/2016

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Engin GÜNAY

24/05/2017

ÖZET

YAPAY BESLENİM SİMULASYONU İÇİN KUYULAR ARASI BAĞLANTISALLIKTAN ELDE EDİLEN ANİSOTROPİ DEĞERLENDİRMESİ

Engin GÜNAY

Yüksek Lisans Tezi

Fen Bilimleri Enstitüsü

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Danışman: Yrd. Doç. Dr. Bedri KURTULUŞ

İkinci (Ortak) Danışman: Yrd. Doç. Dr. Mathieu LE COZ

Eylül 2016, 89 pages

Bu tez, Birleşik Arap Emirliklerinde yer alan Liwa akiferinin yapay beslenme simulasyonu için iki farklı heterojen araştırmasını ortaya koyar. Yapay beslenme çalışmasının bir parçası olacak olan modelleme için heterojenlik araştırması gereklidir. Çalışma bölgesinde gerçekleştirilen kapsamlı pompa testlerinden elde edilen kısa dönem ve uzun dönem datasetleri karakterize edilmiştir. Kuyular arasındaki bağlılık çalışması kısa dönem pompa testlerinden elde edilen düşüm verileri ile yapılmıştır. Bununla ilgili olarak, heterojen anisotropik ortamı detaylı incelemek için kuyular arası bağlılık ölçübirimine dayanan interpolasyon yöntemi geliştirilip kullanılmıştır. Dolayısıyla, yerel bağlılık ölçübiriminin uzaysal analizi ile anisotropi elde edilmiştir. Geliştirilen yöntemin hassaslıkları analizlerdeki sınırlamalar çalışılarak anlaşılmıştır Muhtemel yüksek bağlılık gösterebilecek uzaysal gruplanmalar, litolojik özellik olan tanecik boyutunun araştırılması ile çalışılmıştır. Öte yandan, uzun dönem düşüm verilerinin yönelimi büyük ölçekte heterojenlik göstergesi olarak araştırılmıştır. Geniş çaplı kuyu varlığının etkisi, ortamın hidrolik özelliklerinin değişimi açısından incelenmiştir. Bu tip heterojenlik, uzun dönem düşüm verilerinin alışılmamış artış gösteren geç zaman türevinin analitik analizler sonucu ile açıklanmıştır. Büyük ölçekte olan heterojenliğin sınırları belirlenmiştir. Elde edilen iki tip heterojenlik bulguları yapay beslenim durumunda test edilmiştir.

Anahtar Kelimeler: Bağlantısallık, Heterojenlik, Anisotropi, Yapay Beslenim

ABSTRACT

ARTIFICIAL RECHARGE SIMULATION BASED ON ANISOTROPY EVALUATION FROM INTERWELL CONNECTIVITY

Engin GÜNAY

Master of Science (M.Sc.)

Graduate School of Natural and Applied Sciences

Department of Geological Engineering

Supervisor: Assist. Prof. Dr. Bedri KURTULUŞ

Co-supervisor: Prof. Dr. Mathieu LE COZ

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This study combines two different heterogeneity approach to the artificial recharge area in Liwa aquifer located in the United Arab Emirates. For the purpose of modelling that will be the part of the artificial recharge, heterogeneity study is essential. After extensive pumping tests carried out in the study area, datasets of short term and long term drawdown are characterized. Connectivity between the wells are studied with the help of short term drawdown dataset. A methodology is developed and utilized to evaluate the heterogeneous anisotropic media in detail based on the connectivity metrics proposed. Hence, the spatial analysis of local connectivity metrics is obtained as anisotropy. Constraints of the analysis are studied to understand the sensitivities of the developed methodology. Grain size as lithological properties is used to survey possible spatial grouping that may result in high connectivity. On the other hand, long term drawdown data trend is studied as large scale heterogeneity indicator. Effect of extensive wellbore presence is investigated in terms of the change in hydraulic property of the medium. For the long term dataset, analytical analysis for this type of heterogeneity is applied to the uncommon increasing trend of the late time derivative in drawdown curves. Boundaries of this large scale heterogeneity are determined. Findings of this two different approach to the dataset are tested on a simple artificial recharge case.

Keywords: Connectivity, Heterogeneity, Anisotropy, Artificial Recharge

RÉSUMÉ

ESTIMATION DE L'ANISOTROPIE À PARTIR DE LA CONNECTIVITÉ INTER-PUITS POUR LA SIMULATION DE LA RECHARGE ARTIFICIELLE

Engin GÜNAY

Thèse du Master

Faculté des Sciences Fondamentales et Appliquées

Superviseur: Assist. Prof. Dr. Bedri KURTULUŞ

Co-superviseur: Assist. Prof. Dr. Mathieu LE COZ

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Cette étude combine deux approches de caractérisation des hétérogénéités dans le cadre du projet de recharge artificielle de Liwa aux Emirats Arabes Unis. En effet, les hétérogénéités du milieu géologique sont cruciales afin de modéliser les effets de cette recharge. Les très nombreux pompages d'essai réalisés dans la zone d'étude ont permis de produire un jeu de données très large de rabattement à court et long termes. Une méthode est développée et appliquée pour évaluer l'anisotropie du milieu à partir d'un indicateur de connectivité. Une analyse de sensibilité est réalisée afin de déterminer les paramètres optimaux et les informations lithologiques sont utilisées pour déterminer l'origine des anisotropies mises en évidence. Par ailleurs, les tendances concernant le rabattement à long terme sont étudiées pour mettre en évidence des hétérogénéités à une échelle plus large. En particulier l'augmentation de la pente du rabattement au cours du temps est interprétée comme étant liée à des variations latérales des propriétés hydrauliques du milieu. Les distances associées à ces transitions sont déterminées. Les résultats de ces deux approches sont intégrés à un modèle numérique simulant la recharge artificielle.

Mots Clés: Connectivité, Hétérogénéité, Anisotropie, Recharge Artificielle

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1. INTRODUCTION

1.1 Importance of Heterogeneity in Modelling

In hydrogeology, groundwater modelling carries a vital importance in terms of visualization and estimation of the unseen but predictable processes. Not only visualization but also determination of the properties and their reliability can be tested regarding the hydrogeological and geostatistical analyses. Natural and artificial processes (system balance, transportation, pumping and etc.) have been simulated on those tools to observe the effect on the system. Importance of mapping the heterogeneity comes at this point. Due to modelling process is realized for mimicking the complexity of nature, heterogeneity parameters should supply efficient and adequate information to the model. The heterogeneity issue in the groundwater modelling is caused from the spatial variations of the hydrodynamic parameters. Therefore heterogeneity mapping of these hydrodynamic parameters such as hydraulic conductivity/transmissivity is critical issue. However limited amount of input data for heterogeneity investigation is a problem.

Heterogeneity mapping concerns the determination of the hydraulic properties at first. Correspondingly, the hydraulic property of an aquifer is defined as the material characteristics and it reflects the local property where the pumping test belongs. Due to random spatial variations in the characteristics of geologic units, convergence of the measured properties to the reality might be questionable. Modelling of the media have been conceptualized by estimating the fact that the value obtained from pumping test is the property of larger area than it actually is. However, after determination of the hydraulic properties from pumping test, another problem shows up as insufficiency of input data amount.

Abovementioned restraints require prediction of properties for unknown/unsampled locations (interpolation). Averaging of these locally measured values is necessary for prediction. Several methods of interpolation (inverse distance, triangulation, spline and etc.) can be used according to the purpose. To obtain better results regarding spatiality and variability of the known values, geostatistics is a key factor to be used. As argued by de Marsily et al. (2005), heterogeneity was started to be considered as a variable which might have structural distribution that could be effected from geological processes. Variogram (covariance) was introduced to define this kind of structural distribution. They summarized that, subsequently, three methods were proceeded to deal the continuous process description of heterogeneity. Krigging to be a representative method for assigning optimal value to the model from measured local value regarding the differences between other measured values, Pilot Point method as inverse calibration to deal the spatial distribution and lastly Monte-Carlo Simulations of model to make inference about the uncertainty of flow and transport in relation to spatial heterogeneity.

Mostly, methods used for mapping was developed in respect to the lack of input amount. Additional data might facilitate the study of heterogeneity in hydraulic properties with respect to characterization features, such as roughness and connectivity (Heße et al., 2015). Instead of inferring data from existed one, great amount of data might be possible to use in that purpose if possible. In that case, different approach for heterogeneity mapping could be practiced. In this thesis, short term and long term of great drawdown data amount were used for studying connectivity and investigating wellbore effect, respectively.

1.2 Use of Connectivity Metrics for Spatial Heterogeneity

Local heterogeneities could be located in a way that is not possible to be determined with traditional methods but likely to be tracked (as oscillations and uncommon trend) from the drawdown data.

Local heterogeneity effect on pumping data would be included to the modelling process if the inquiries considered as the reaction of the observation well to pumping well. Respectable amount of drawdown data from short term pumping test can be assessed indirectly as connectivity. This might give the possibility to determine connectivity metrics for integration into heterogeneity mapping. Particularly, connectivity relation between wells will be examined. Spatial heterogeneity brings the upscaling problem of the point measurements in the media in terms of representation (Wheater et al., 2010), yet numerous punctual measurements can be used to study systematical analysis of spatial heterogeneity regarding connectivity.

In their commentary, Michaelides and Chappell (2009) pointed out the lack of a simple, useful and applicable methodological framework for quantifying connectivity, although the concept is widely accepted as qualitatively important.

In this work, because the connectivity between observation well and pumping well is studied, it is possible to recall this connectivity as interwell connectivity. As simple description, connectivity is the measurement of how well two locations connected to each other. Additionally, connectivity metrics can be defined as the parameters based on the statistics of conductivity, transport and flow which refer to the hydrological response (Knudby & Carrera, 2005). In spite of difficulties (lack of data, agreed method of measure), several connectivity indicated metrics have been defined and attempted for delineation.

Renard & Allard (2011) have published a general review of the connectivity metrics. According to them, concept of connectivity metrics can be classified as four main groups. First, static one is described as the connection depend on the properties of the medium. Rather than being a physical property, dynamic connectivity metrics were defined as the relation to the physical processes. This second type of metrics are more diverse type since they include dynamic processes (flow or transport).

The data used for this concept can compromise to this kind of metrics inference due to flow effect between pairs of wells. Last two types of classification are the global and localized types of metrics. Localized types are the ones with the punctual information.

It is also indicated that the characterization of an aquifer is needed to gather information from all types of metrics defined.

With respect to setting up a relation between the drawdown measurements and the connection of observation and pumping well, Meier et al. (1998) obtained a result from the analysis of Jacob's method which provide worthwhile information about hydraulic connection parameters. It was possible when analytical study is done regarding the drawdown analyses under radially convergent flow toward a pumping well in heterogeneous aquifer. It is implied that observation well responding faster and more, are better connected to pumping well than the others.

Another research from Knudby and Carrera (2006) is about the indication of connectivity performed from the apparent hydraulic diffusivity (D_a). This indication is found after complex statistical analyses were done about the series of different connectivity degrees. Study showed that D_a covers the effects of both flow and transport connectivity. Whilst transport connectivity includes the width of the connection of discontinuous bodies, flow connectivity (connected features effect on the flux increase) focuses more on the continuity of the fast paths. This upholds the process-dependent type (dynamic metrics) description. Radial flow considered as an important process for deducing connectivity. Estimated storativity provide information about connectivity of pumping and observation well when analytical study is carried out regarding the Jacob's method in radially convergent flow to a single point in heterogeneous media (Sanchez-Vila et al., 1999). Trinchero et al. (2008) also used the Cooper-Jacob estimation of storage coefficient. Referring to a flow point to point connectivity between points, S_{est} is based on the hydraulic response in pumping test. They also included the transport process and used estimated porosity (φ_{est}) from breakthrough curve.

Although punctual information nearby pumping well S_{est} did not give any information about the transport point to point connectivity φ_{est}, they managed to delineate the areas that have good connection to pumping well as capture zone. Difficulties are widely present while integrating the connectivity metrics into heterogeneity mapping. Open-

ended definitions of these types of metrics, lack of descriptive analyses quantitatively and hypothetical relations of connectivity to heterogeneity are some of them.

Renard & Allard (2011) emphasize that dynamic connectivity metrics can be characterized with organized data gathered from different scales as reflection of physical local property and can be compared with large scale tests (long-term pumping test) for quantification. Furthermore, since the geological or geophysical analyses provide clue about degree of connectivity as facies proportions, body geometry, channels and lenses, they should be integrated into this attempt of heterogeneity study based on connectivity quantification.

Throughout the study of connectivity metrics in this thesis, it is proposed that Cooper & Jacob (1946) solution can be carried out for the adjustment of radius as connectivity unit. Drawdown measurements for each pumping test and regarding information (distance between pumping well and observation well, drawdown measurement for specific time and hydraulic properties) were treated in that manner. Subsequently, radii obtained from the homogeneously assumed medium in Cooper & Jacob assumption were processed to observe heterogeneity in terms of response between pumping well and observation well pairs.

The real geometries of the media were adjusted to visualize the hydraulic response in the area based on pair response. This process was referred as "*Anamorphosing*" procedure in the methodology chapter. Numerous pairs, their indication of fast paths were used as input to create a delineation. Simulation of rearranging the pairs of wells in terms of having reliable results was included as well.

Creating multiple simulation cases for different time and drawdown values, number of pairs and number of simulations was necessary to observe their effect on the result. Hence, sensitivity analysis part of the study was realized to investigate the change in the results of these cases. In terms of handling such amount of data and their arrangement efficiently, a Linux shell script containing operations of GRASS 6.4.4 was developed and utilized.

1.3 Wellbore Effect on Medium

Investigation of heterogeneity from unconventional methods includes drawdown data trend analyses. Expected trend after late time segment in long term drawdown data is decreasing derivative. Observable increase of derivative in late time of long term drawdown can be studied in that manner. Analysis with classical methods (Cooper-Jacob, Neuman etc.) might show inconsistence in case of this issue. The effect might be caused from disk formation as two zone aquifer system which may be treated as another type of heterogeneity. In their study, Desbarats & Bachu (1994) examined the properties of spatial variability showing conductivities. Although part of their work consisted of the geostatistical methods for the purpose of horizontal heterogeneity scale investigation, it also showed the opportinity to do study on the conductivities from well scale to the basin scale. This more large scale heterogeneity presence could be developed by the effect of numerous wellbores in a bounded area.

One possible effect of the wellbores to the medium can be a conduit effect on the medium. Wells with around 20 meter screen might behave as a conduit. In fact, screen associates the zones of different head and transmissivity for vertical flow conductance even in unconfined aquifers of relatively homogeneous sand and gravel formations (Church & Granato, 1996). This might show bias in the measurements. Significant wellbore flow that occurs in long screened monitoring wells (Reilly et al., 1989) and presence of large amount of wells can show an indirect change in the medium property considering the configuration of drilling.

During the modelling process of groundwater system, intraborehole flow shows important improvement on the model calibration when considered explicitly (Ma et al., 2010). Although several of these studies were completed considering solute transport, artificial recharge case will have the effect as well.

The influence on the physical properties can be considered as another type of effect caused by abounding presence of wellbores. The indirectly effect on the pumping data can be discussed as both drilling influence and wellbore skin influence on the flow process. As described by Kruseman and de Ridder (1994), well loses caused by skin

effect can be related to disturbed material during drilling, mud effect as plugging, gravel pack and screen. In the literature, even for two well system (one observation and one pumping well), it is noted that this skin effect might show up as an error in the results when the pumping location is considered without a radius. However, in the reality wells have their radii and influences should be considered. For systems having numerous wells this subject should be taken into account.

Variation in the medium properties due to this kind of wellbore activity may cause two-zone aquifer systems. A composite model including the well bore storage and finite thickness skin effect (few millimeters to several meters) was derived for two-zone aquifer system (Novakowski, 1989). A term "patchy aquifer" is used for the analysis of constant-rate pumping test for the well located at the center of a disc with anomalous hydraulic properties (Barker & Herbert, 1982). This patchy aquifer with cylindrical inhomogeneity can be considered as a composite aquifer system and its effect on system can be classified as positive or negative patch zone regarding the lower or higher permeability than the original properties of formation, respectively (Chiu et al., 2007).

The study of Butler (1988) is based on the flow behavior investigation for media with a circular disk having different properties inside and outside. Applications of this analysis was indicated as for geologic structures and well skin case presence. According to him, drawdown data has two component as those dependent or independent to near-well properties.

Wells (discontinuities) located inside the cone of depression are said to have effects on the flow behavior by different material diffusivity around discontinuity. In addition, analyses of the observation well data should be done after some time period when the inertial mechanism effects have disappeared as much as possible on the interval. This is because presence and dependence of observation wells effects on pumping well complicates the analysis due to the difficulty in representation of its head loses (Butler & Zhan, 2004). Present data trends were interpreted regarding this possible effect of developing high number of wells. They were examined by using Butler (1988) principles. The long term drawdown data trend (increasing derivative through late

time) that indicates such kind of effect were analyzed in AQTESOLV v4.5 and used to obtain the hydraulic properties and radius of possible disk formation. Therefore, two different properties, inside and outside the disk formation of heterogeneity, were obtained.

2. STUDY AREA AND DATA DESCRIPTION

2.1 Physiography

Study area is located in the northern part of the Liwa Crescent in United Arab Emirates (Figure 2.1). Data were obtained from the Strategic Water Storage / Recovery project located in this area. It lies in the UTM grid zone 39 N and covered by the north latitudes of 23°28’ - 23°32’ and east longitudes of 53°55’ - 53°59’.

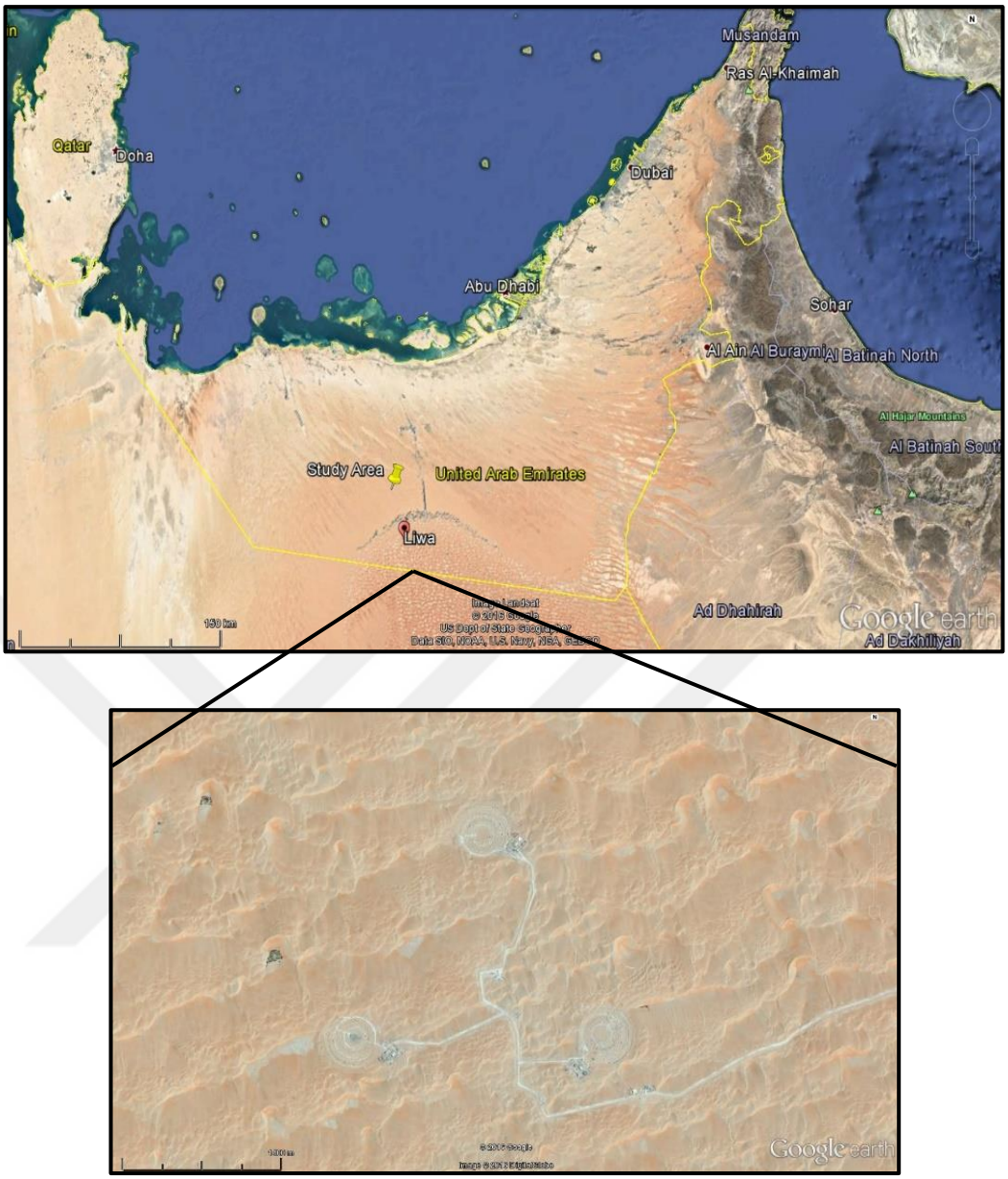


Figure 2.1. Google Earth image of the study area (Google Earth, 2014)

Geographical zone classified as tropical desert and high temperature and less rainfall are the properties of the study area. It is densely covered by sand dunes and locally with sabkhas.

Several meteorological stations are observable controlled by National Center of Meteorology & Seismology (MCMS) in the country. The closest two stations are called as Madinat Zayed and Mezaira which are located 19 km Northwest and 25 South-southwest to the project area, respectively. Highest mean of monthly total

rainfall observed in Mezaira is 3.7 mm at January and in Madinat Zayet, it is 7.6 mm at April (Figure 2.2). Data were obtained to understand the area regarding geographically and to realize the aridity level of the environment.

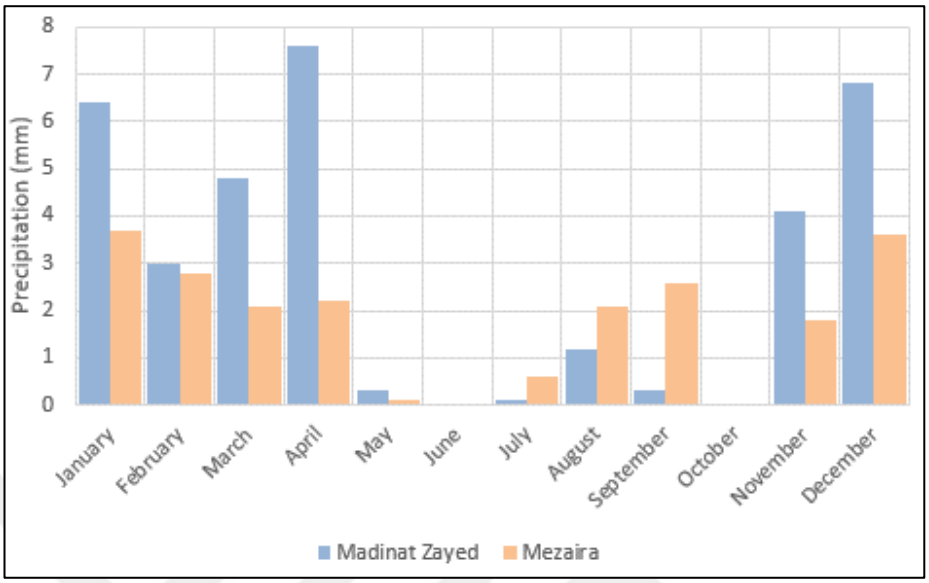


Figure 2.2. Mean of Monthly Total Rainfall (mm) in between 2003-2015 for station Madinat Zayed (170 m elevation) and 2004-2015 for station Mezaira (204 m elevation) (data obtained from NCMS)

It can be foreseen that evaporation is extremely high in UAE. Through the western coast rate of 7.5-8 mm/day was observed. 9-9.5 mm/day in the east due to higher wind speeds. In the east, where desert foreland and gravel plains located, 10-11 mm/day of evaporation was measured. In the southwestern desert regions, where Liwa is located, evaporation reaches to 12 mm/day which are the highest rates in the country (Alsharhan, Rizk, Nairn, Bakhit, & Alhajari, 2001).

Additionally, UAE can be said to be divided mainly into two parts as elevation. Sandy desert zone and mountainous zone. Sandy desert zone covers the 90% of the country and extending from North-West to East, where mountainous region has the N-S extend. Mountain region located eastern part of the country, sandy desert zone gradually rises as sand dune elevation from the sea level up to 250 m in Liwa area (Environment Agency Abu Dhabi, 2008).

2.2 Geology

Majority of UAE structural province in the Arabian Peninsula is located in the Rub Al-Khali basin (Figure 2.3). Structural development of UAE depends on the effects of the plunge of Rub Al-Khali basin and Central Arabian Arch through the Arabian Gulf. Sedimentation and increment of the thickness of the formations is observed towards this direction with indication of increasing rate of subsidence (Irani, 2001).

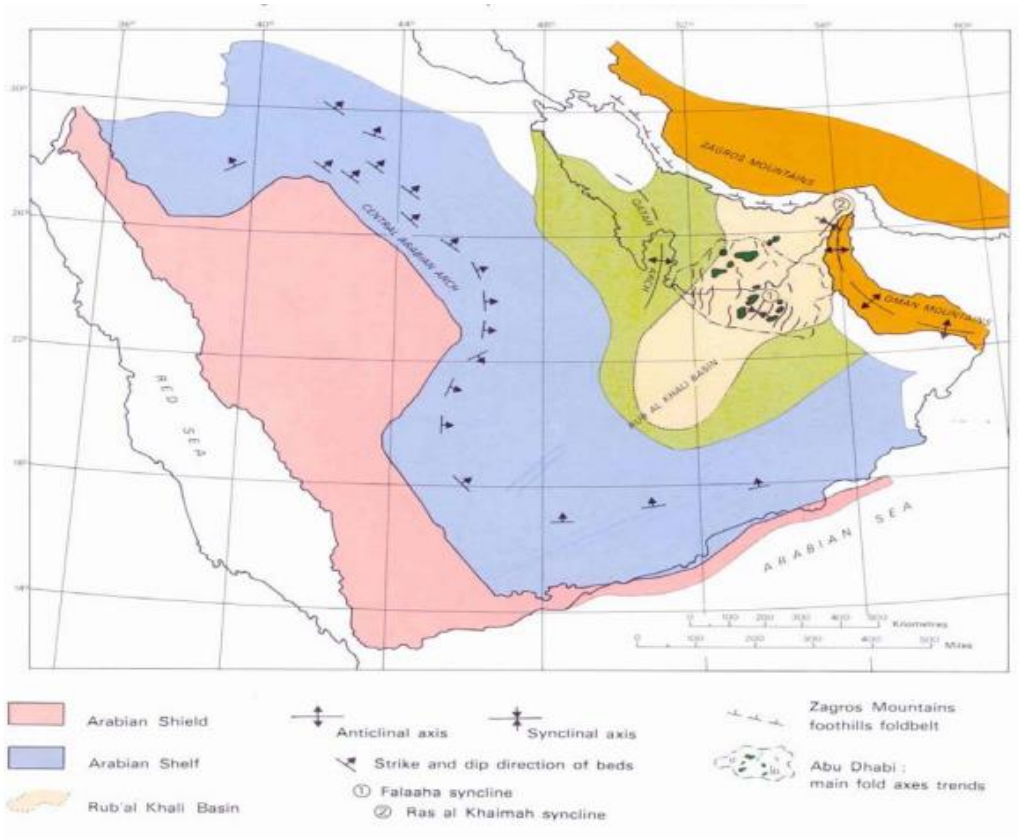


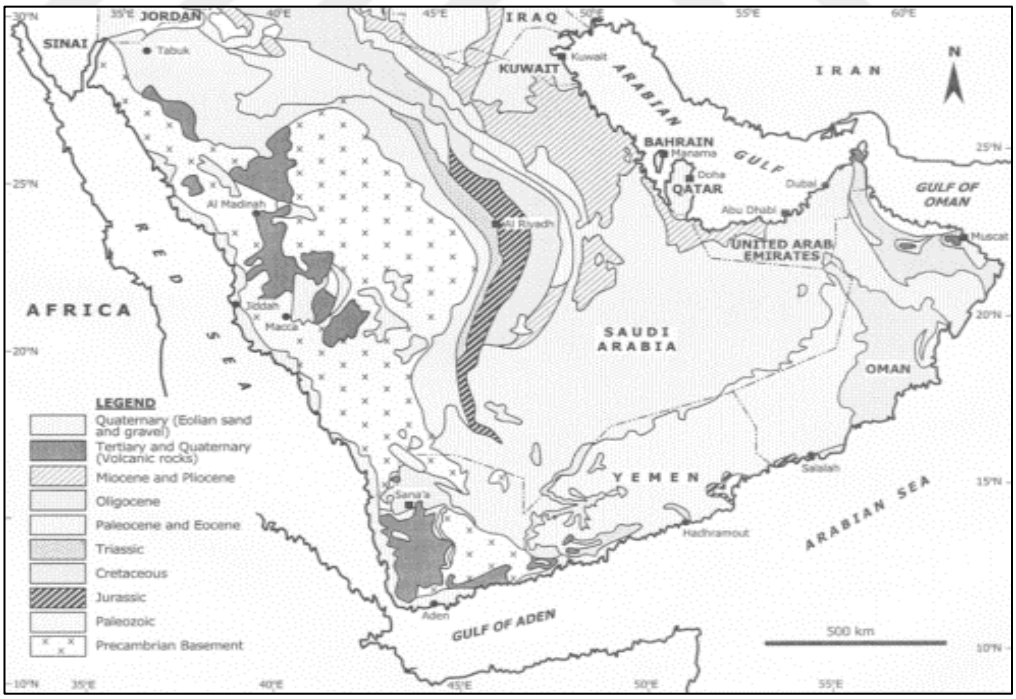
Figure 2.3. Location of Rub al Khali basin in the structural provinces of Arabian Peninsula (Irani, 2001)

Regionally, for the southern part of the UAE, eolian sand coverage is observable (quaternary deposits) and its limits lasts the southeast of the Saudi Arabia. However in the northwest of the UAE, Miocene and Pliocene units (Figure 2.4.a) are observable which might be classified as the inland and coastal sabkha deposits.

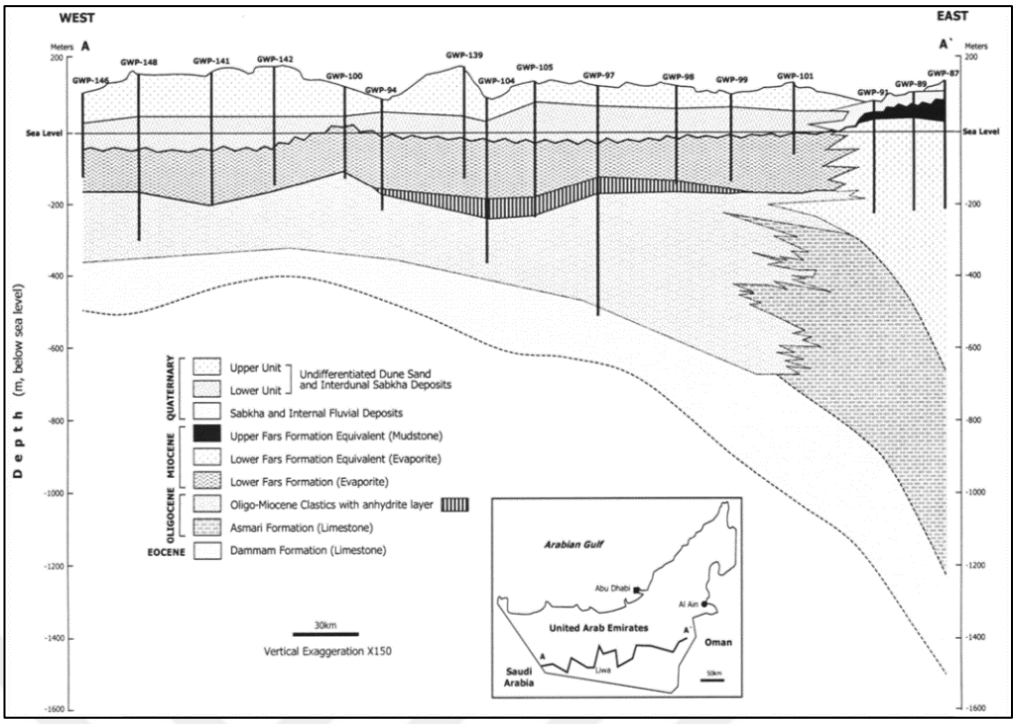
As relation to the scope of the project and for local investigation of southern part of the UAE, it is observed that the sand dunes as unconsolidated materials are widely present. Liwa region is covered by eolian sands and partly by sabkha deposits.

Interest area of the study have the medium to very fine sand lithology. Interdunal sabkha deposits are present between dunes and mainly located throughout the Liwa Crescent area, and contains thin sand and silt deposits. The thickness of this unit is highly variable (between 50 and 150m). Concerning units that were verified from the well log data shows that 3 main lithological presence (Figure 2.4.b);

At top, medium to very fine, loose to very dense sand unit is present. This unit is the continuum of the sand dunes (thickness is approximately 90 m). Saturated thickness of this unit is approximately 45 m and it contains the water table. Secondly and following this unit, calcareous sandstone with intercalations of siltstone, mudstone, evaporates and thin sand lenses are present. Average thickness of sandstone is estimated to be 35 m. At last, carbonates (calcarenite, limestone, dolomite and gypsum) are present.



a)



b)

Figure 2.4. Simplified geological map of the Arabian Peninsula (a) and stratigraphic cross section of UAE (b) including Liwa area (modified from Alsharhan et al., 2001)

2.3 Hydrogeology

The topographic condition of the study area have an effect on the precipitation. Tectonic rifting in the Red Sea basin and its surrounding topography restrains land runoff to local drainage basins neighboring to the sea. Equivalently, Oman and Yemen Mountains restrict drainage to sea as well. Thus water isotopes study from runoff, shows that precipitation occurs not regionally but locally (Wood, 2011).

Since the climate and topography does not allow efficient precipitation, natural discharge to the study area is questionable. Most of the falajes (used for the water transportation from where the precipitation occurs) were located in the easternmost part of the UAE and are presently dry. These were accepted as the means for

developing the groundwater together with the shallow hand dug wells or wadi rainfall harvesting structures (Environment Agency Abu Dhabi, 2008).

In mountain side, sand and gravel aquifers are common and the other parts of the region sand dune aquifers are most common type (Figure 2.5). In the west part of the country, Quaternary aquifer is underlain by the Lower Fars Formation which is the aquitard of the western region (Environment Agency Abu Dhabi, 2008). Coastal sabkha located in westernmost part of the country is the main discharge area of the regional flow system caused from the Oman Mountains. Because precipitation is low through the mountainous area and relatively high distance from this location to the project area, recharge of the system is doubtful. For Liwa aquifer, it is suggested with Carbon-14 dating that the last recharge was between 5000 and 9000 years BP and it is confirmed with the continuous water level measurements that it is not currently receiving recharge (Wood, 2011).

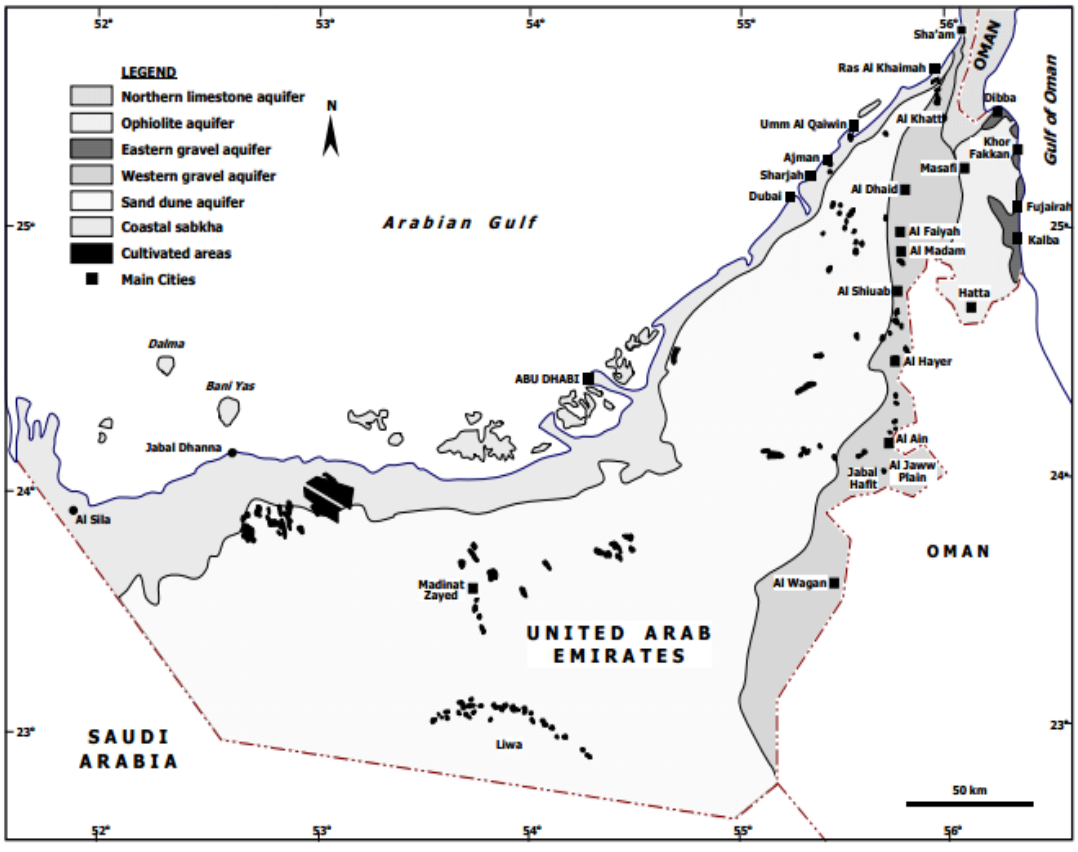


Figure 2.5. The main aquifers in the UAE (Rizk & Alsharhan, 2003)

Low recharge of the area might cause not local groundwater flow but regional. In the case of regional flow, from the system as through the both Oman and Yemen mountains.

Regarding the surface conditions, depth to groundwater has relatively high elevation in the study area. This can be considered as favorable aquifer property in terms of storing significant amount of water. It is observed that through the southern part of the Liwa, depth to groundwater is substantially decrease and because of the existed sabkha deposits in this region, salt amount is expected to be relatively high.

Map that shows hydraulic head in the region indicates that hydraulic gradient is from the eastern mountains and to the Arabian and Oman gulfs. Local gradient for study area is encountered in north, south of the area due to the water table mounding. It is also through the western Abu Dhabi coastal sabkhas close the Arabian Gulf (Figure 2.6) from the study area.

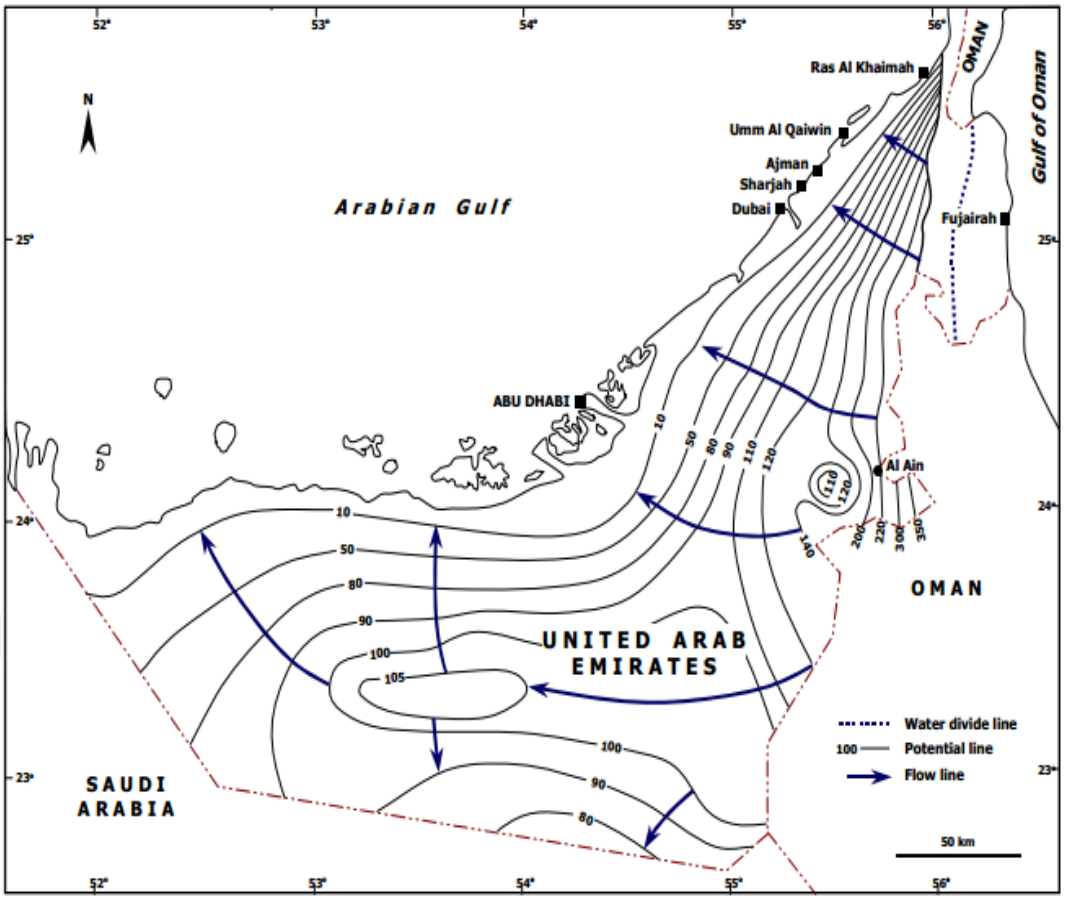


Figure 2.6. Hydraulic head map (m), asl, for the sand and gravel aquifer in 1995, UAE (modified from USGS – Groundwater Research Project, 1996; Rizk & Alsharhan, 2003)

2.4 Data

As a part of the Strategic Water Storage / Recovery Liwa project carried out in the study area, extensive pumping tests were realized. Project focuses to increase the amount of water supply to the city of Abu Dhabi in case of emergency. Water production was estimated to be 0.8 Mio m^3/day and by desalinated sea water, water storage capacity was approximately 2 Mio m^3 including surface tanks and pipelines for the city. After the project 26 Mio m^3 volume of desalinated sea water (desalination in two desalination plant close to the sea and pumping to the 3 recharge basins in the study area) was planned to be recharged to the aquifer through 27 months (Menche, 2010). During the years of 2010-2015, approximately 300 short-term and 15 long-

term tests, from different pumping wells (914 mm borehole diameter and approximately 28 m of screen), brought about numerous drawdown data. However 278 of them were used in this study. Data used belongs to the constant-rate pumping test results. Some of the short term test drawdown data approximately lasted to 800 minutes and for some of them it was around 600 minutes, accordingly, data until 600 minutes were used for the development of the methodology (Figure 2.7). This limit was 3600 minutes for the long term tests.

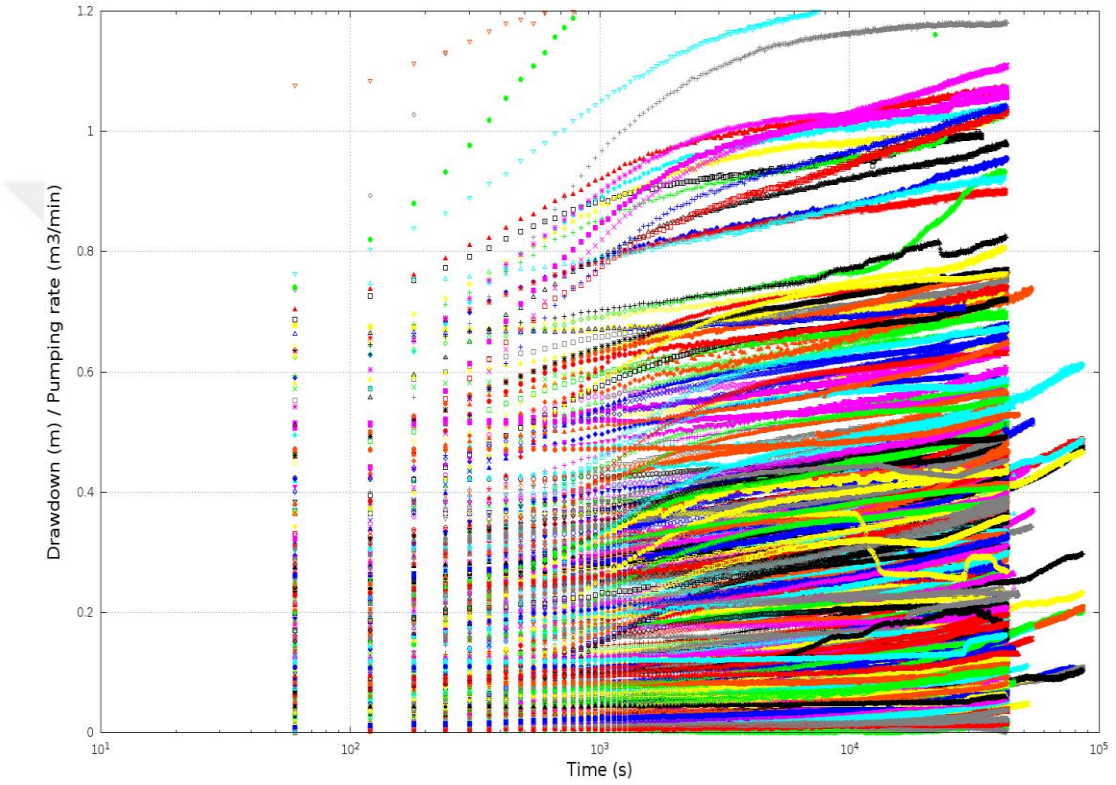


Figure 2.7. Short term data of Scheme C used for the analyses

Each test was carried out from different wells and distribution of the wells were 3 circular schemes in the area with 2 kilometers between them (Figure 2.8). Drawdown data quantities as pairs for the schemes A, B and C are 394, 383 and 302, respectively. Placement of wells are circular with increasing circle radius through the outside of the scheme. Yet, one outer circle of well distribution is as half circle, so approximately 60m of distance difference is present with shortest and longest radius of the schemes. Short term test has mostly 4 observation wells arranged in one direction from the

pumping well. Therefore, with all of those 300 wells, network of pair measurements well lineaments can be created.

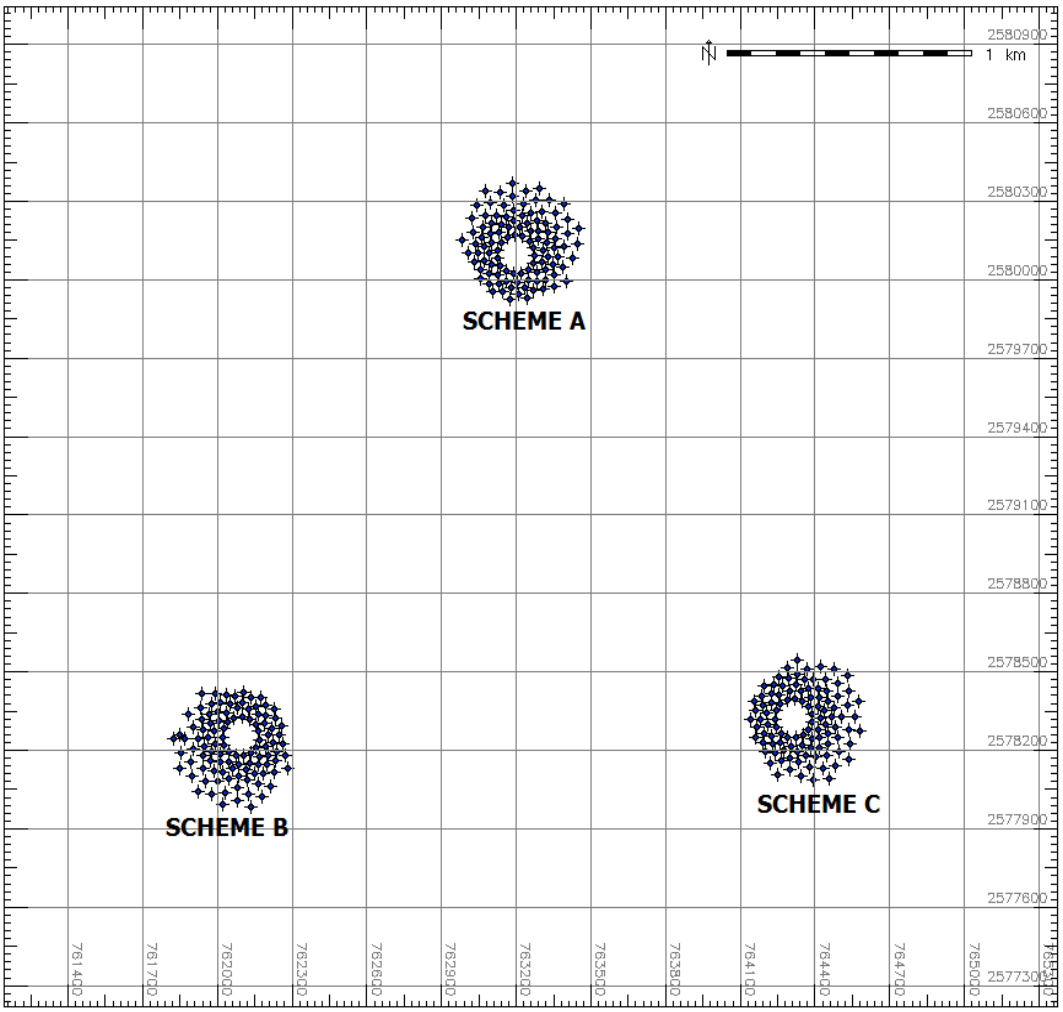


Figure 2.8. Location of the schemes and wells used for the methodology

3. METHODOLOGY FOR CONNECTIVITY INTEGRATION

Purpose behind developing this methodology is to have detailed and local analysis of the aquifer modelling procedure as better understanding the heterogeneity. Due to the flow and transport influenced by the structure of an aquifer, connectivity that can be inferred from the flow. It should be well investigated and involved in the procedure of modelling as the connectivity of the spatial points. This will be done by the methodology work that will integrate the connectivity to the process.

Connectivity metrics will be defined between well pairs as first step in the methodology. According to the defined metrics, connectivity of the local area (differently in schemes) was planned to be delineated as heterogeneity. Methodology consists of two main subjects which are measuring the connectivity and representing the connectivity. Finally, in sensitivity analysis section, factors that might have effect in application of the method will be discussed.

3.1 Measuring the Connectivity

Considering the measurement for new type of connectivity metrics, radius between wells was a key factor in this study. Connectivity type studied in this methodology is the concept of connection of the punctual locations. Pair of points was fundamental to reflect the connectivity effect as heterogeneity to the schemes. Location of numerous pairs and their drawdown data was taken as connectivity indicator. For each drawdown data in each pumping test, both geometrical and theoretical radius values was calculated according to the based on time steps of drawdown. This theoretical radius was assumed as a determinant of point to point connectivity.

3.1.1 Determination of point to point connectivity

Point to point connectivity concept was estimated through Cooper-Jacob (1946) solution for pumping tests. First, geometrical radius was obtained from the real distance between the pair coordinates. Then homogeneous equivalent radius (theoretical radius) was calculated when the medium is considered as homogeneous and isotropic (Cooper & Jacob, 1946). This theoretical radius calculation were performed by mean transmissivity, storage coefficient in a certain time with certain drawdown from each test. These factors may show differences in calculation in order to be determinative. So different values of theoretical radii can be obtained in different time steps in a drawdown curve. Therefore simulations will be done through the sensitivity analysis of the method regarding these factors. Calculation of theoretical radius is as follows;

$$r_t = 10^{\left(0.5 \log\left(\frac{2.25 * T * t}{S}\right) - \left(\frac{s * T}{0.366 * Q}\right)\right)} \quad \textbf{(3.1)}$$

Where;

T: Transmissivity (m^2/sec)

S: Storage Coefficient

s: Drawdown (m)

t: Time (sec)

Q: Flowrate (m^3/sec)

Meaning of the theoretical radius can be interpreted when the ideal homogeneous media of Cooper Jacob assumption is considered. Estimated mean of hydraulic properties were used in this assumption. In that case, if the theoretical radius (OW2) is lower than real radius (OW1), response of the media to flow is lower. In other words, lower response means having the same drawdown in same time with a distance more close (Figure 3.1) to the pumping well. This low response is caused from the relative weak connection of observation well to pumping well.

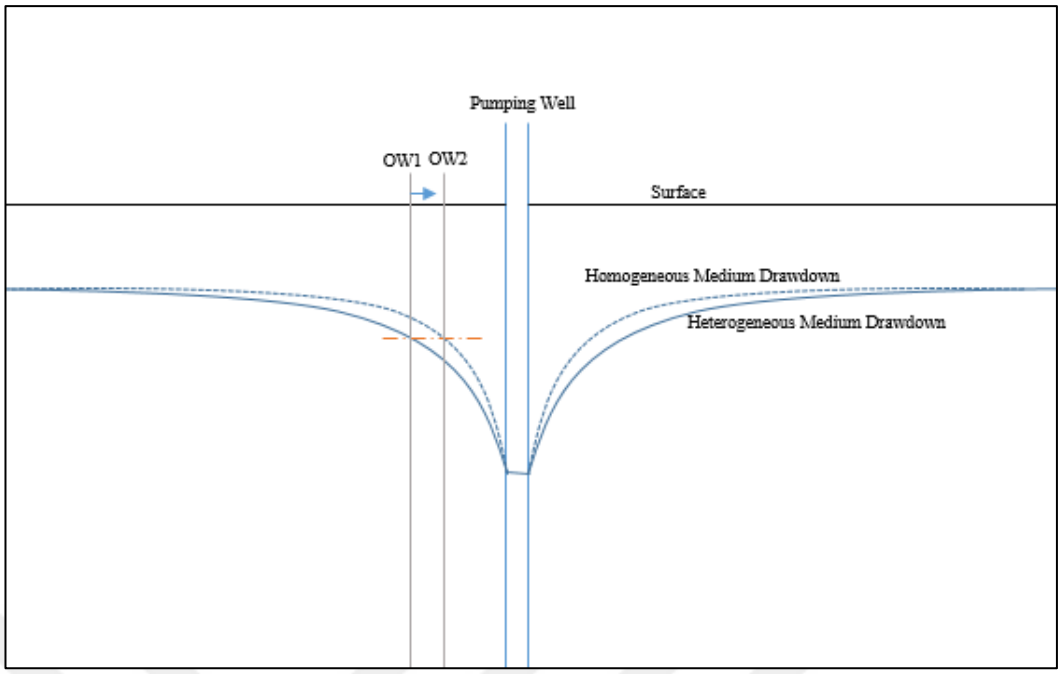


Figure 3.1. Comparison of theoretical and true radius.

For higher theoretical radius than true one, response will be the otherwise and connectivity will be higher. Ratio (R) of theoretical radius (r_t) to true radius (r) will have the same meaning for the values larger than 1, giving the result of faster response. This also can be supported by different approach. Two wells resulting with different drawdown but with same true radius to pumping well tend to represent the medium property in terms of connection. Through the better connection of pumping well and observation well path, higher drawdown would be observed. Considering this, an ideal drawdown is expected in homogeneous assumption which can be used to compare the connection (Figure 3.2). Based on their local hydraulic properties r_t will be higher in the well with more drawdown. In terms of response regarding the medium property, the well with higher drawdown (OW2 in Figure 3.1) has the higher transmissivity ($T_{ow2}>T_{mean}$) and lower storage coefficient ($S_{ow2}<S_{mean}$) than the homogeneous environment with mean values.

To obtain the same drawdown in media with mean properties, higher theoretical radius than the true one is necessary based on Cooper Jacob solution. This can be accepted as the transformation of the heterogeneous medium location of well into homogeneous and isotropic medium.

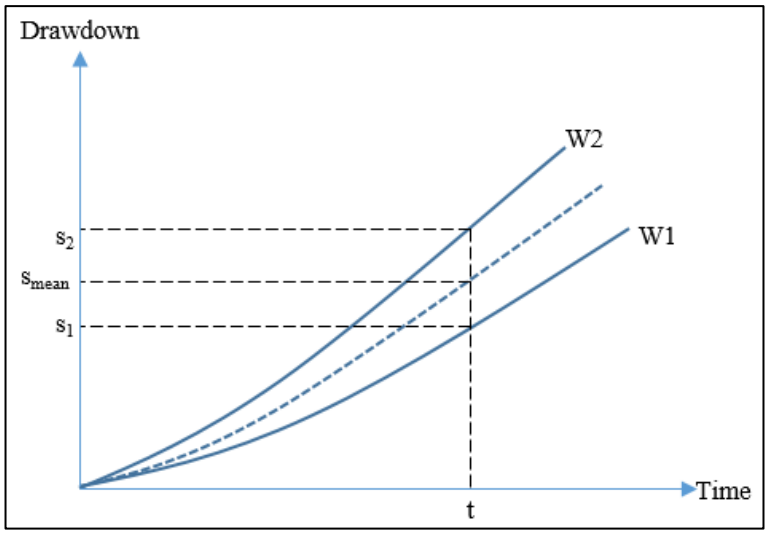


Figure 3.2. Comparison of drawdowns of wells having same radius (dotted drawdown refers to ideal and homogeneous drawdown)

All the ratios calculated should have the mean of 1 for each scheme, due to the assumption of homogeneous and isotropic environment. In fact, individual ratios determines the connectivity metrics and mean ratio of all pairs indicate the homogeneous property of the medium. During the calculation of ratio (R), mean hydraulic properties were used (Table 3.1) based on the previous pumping test analysis (Kurtulus & Avsar, 2016). However slight changes in the properties were necessary to obtain the mean ratio of 1.

Table 3.1. Hydraulic properties used in calculation of ratio R

	Transmissivity (m2/sec)			**Storativity**		
Scheme	A	B	C	A	B	C
t=100	0.011	0.004	0.009	0.008	0.007	0.004
t=300	0.011	0.004	0.010	0.018	0.020	0.009
t=600	0.012	0.005	0.011	0.028	0.037	0.015

3.2 Representing the Connectivity: Anamorphosing

For the use of connectivity in the groundwater modelling, anamorphosing technique can be utilized. Representation of the connectivity will be obtained after the

anamorphosing analysis and the resulting map might be called as a heterogeneity map of hydraulic connection. Anamorphosis is a cartographic processes used to calculate the travel time information from the chosen center (source of the map). According to the known points of travel time, rest of the map can be deformed so that it shows the travel time from source to the equal distances (Campenhout, 2010). For this study, the technique mentioned can be utilized as deformation and projection of the well location based on connectivity ratio (R) so that it shows the connection structure.

Criteria used here is the change of the true radius to theoretical one and proceeding with the deformation of the region based on reference point. To achieve that, new coordinates of the wells which are located according to the theoretical radius are needed. Each pair will have a new radius between them. Therefore new location of the points in homogeneous media are needed to be calculated systematically so that all the pairs of network should present a coherent deformation. After calculating the new coordinates of points in this homogeneously assumed medium, rectification of the true study area based on control points will be done. To show this connectivity effect in the real geometries of the study area, a process called inversion is necessary followed by sensitivity analysis of the method.

New coordinate computing, georectification of the real geometrical locations of the points and inversion of the georectification will be the parts of the anamorphosing technique.

3.2.1 New coordinate computation

Application of the connectivity effect from one well to another can be achieved by relocating the wells. These relocated wells will be used as reference point in the rectification process. To compute the new coordinate of the wells based on the theoretical radius, a layout of the data is needed.

For the layout, initially two files which are called as “WELLS” and “INTER”, respectively coded as “W” and “I” were generated. File “W” contains index of all used wells in study area, their eastings and northings as a well information file. File “I”

contains the codes of pumping well, observation well and connectivity ratio (R) that were created separately for each scheme according to the constraints mentioned in section 3.1.1. As mentioned earlier, R was calculated based on mean hydraulic properties of the medium, chosen drawdown and time with used flowrate in corresponding tests. Then a new file was created which contains randomly generated numbers which are in between 1 to 1000 with the same size of matrix "I". File is sorted in an increasing order and the indices of numbers were hold by the new variable that is accepted as the new order of indices of the file "I". These operation is needed for the random and unique organization of the file order "I" in each time it is used. This step can be referred as the import of the data.

Further, classification of the pumping and observation wells were needed for better result. "I" was reorganized and refilled according to certain criteria. Starting from the first well of the random order of "I" described above, it is rearranged according to the uniqueness of well pairs. So that calculated pairs do not have second coordinate calculation. This is because of the utilization of the wells are sometimes as pumping well and sometimes as observation well.

New coordinate of the observation well that is calculated does not get involved any second calculation by this classification. In other words, first random well used as a fixed coordinate and others were calculated based on the organization.

Organizing continues until there are no pairs of the uncalculated coordinate of the wells in the scheme. Briefly this organization supply the uniqueness of the pairs. The benefit of the organization of the data can be understood at this point where the observation well (OW1) with new theoretical radius (OW2) might be the pumping well of the next test. Therefore new coordinate for that pumping well would be fixed for further calculation. Otherwise, individual calculation of the coordinates would give independent results from other wells and therefore from the media. Simulation is necessary here due to the random selection of the first well in the data. Any other consideration of the first well would give different results. Considering the data, a simple diagram is necessary to understand the applied method (Figure 3.3).

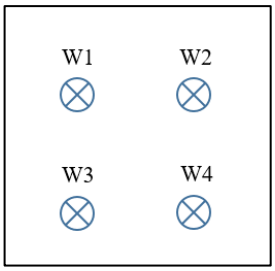


Figure 3.3. Simple demonstration of scheme for organization method

Starting with random first well W1 (as both pumping and observation well), new coordinate of first observation well (W2) is calculated. For each calculated well, priority takes place and it is used as a fixed point for the calculation of corresponding pair. In addition, if the first well is W2 (Simulation 2), according to this method, last calculation of the new coordinate of W2 would be different than the other organizations (Table 3.2). Therefore because there is not only one true new coordinate of the wells, simulation of different possibilities is necessary.

Table 3.2. Simple demonstration of organization of the data and simulation

Simulation 1			**Simulation 2**		
PW	**OW**	**Ratio(r_t/r)**	**PW**	**OW**	**Ratio(r_t/r)**
W1	W2	a	W2	W3	c
W2	W1	b	W2	W1	b
W2	W3	c	W1	W2	a
W3	W4	d	W3	W4	d

New coordinate calculation were done by applying the Al-Kashi theorem as known as the law of cosine. Network of pairs (Figure 3.4) is used and their location was reconstructed depending on the random order discussed above.

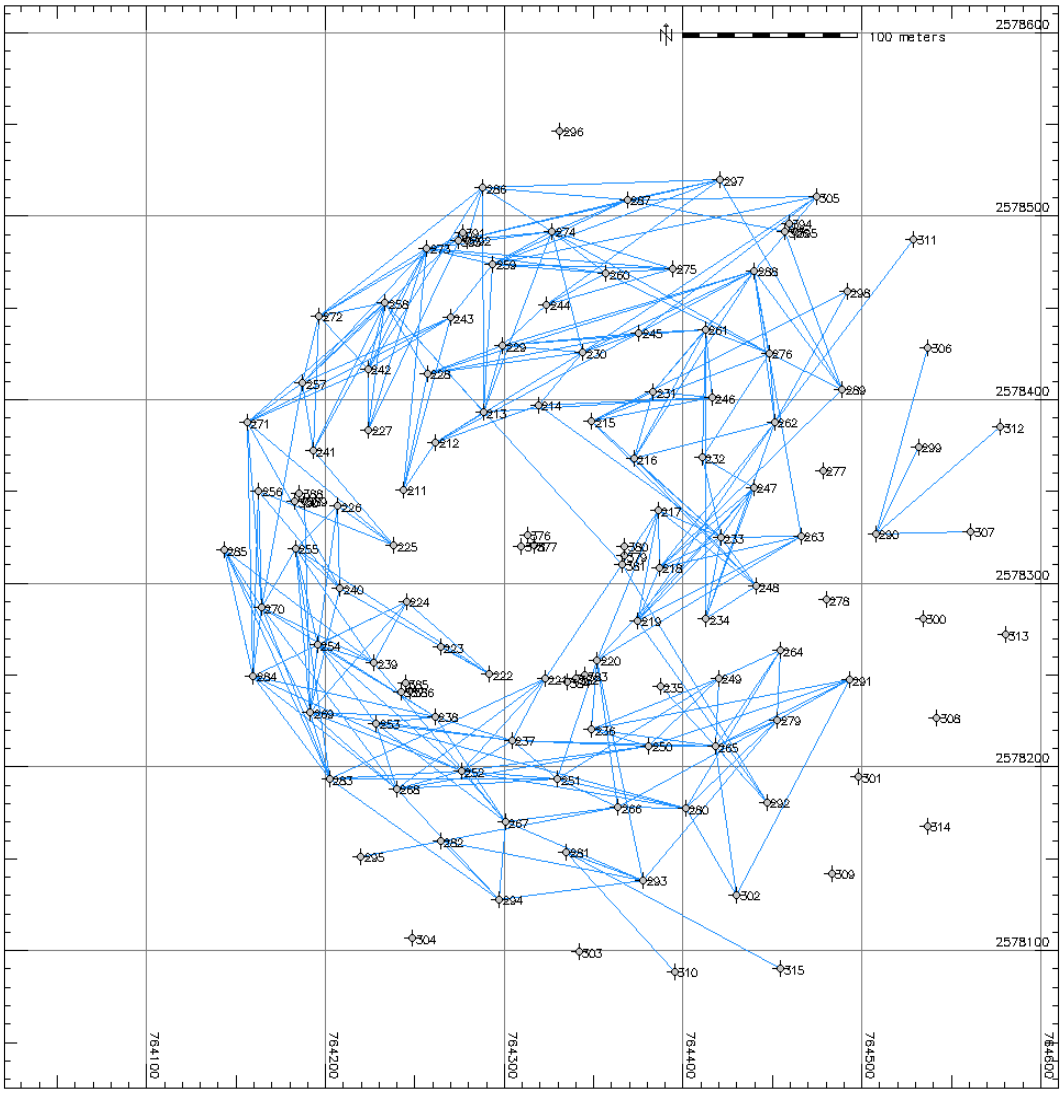


Figure 3.4. All the pairs and true radii for the scheme C at 600 minutes

In this coordinate calculation an imaginary point has been used to supply new information to Al-Kashi theorem. This point is located in very high distance through the north from the point of the pumping well. An angle is created between two lines of pumping well to imaginary point and to observation well (Figure 3.5).

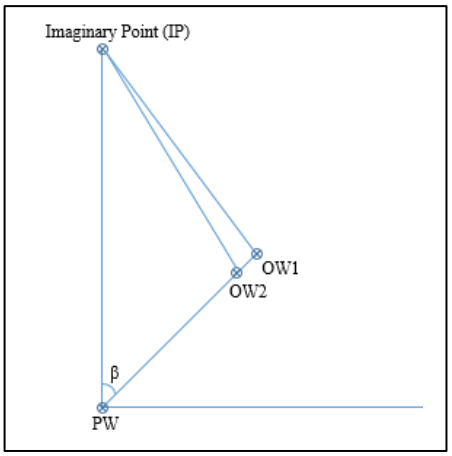


Figure 3.5. Components of the calculation

Multiplying the ratio R (say OW2/OW1) with distance between the pumping well and the observation point gives the new distance |PW-OW2|. To determine the amount of coordinate change of observation well from the pumping well, law of cosines (see below) were used first to obtain the angle β.

$$\beta = \text{acos}((|PW - OW1|^2 + |PW - IP|^2 - |IP - OW1|^2)/(2 * |PW - OW1|^2 + |PW - IP|^2) \quad (3.2)$$

Using angle β and ratio R, new coordinate could be determined based on changes in the vertical and horizontal axis.

3.2.2 Georectification

To have successful plot regarding the connectivity, several GIS steps is needed and this was achieved by bash script. For each of three schemes in the project area the script will be executed and three different connectivity simulation scenarios will be obtained. Initially, each cell was created according to the defined resolution in the script and has been coded in terms of location index.

Using these codes of the cells and their locations, transformation of the old locations of wells to new locations was completed. Rectification was done through this transformation based on the GC points (Ground Control points).

Rectification depends on the calculation of the ground control points (new coordinates of the wells) to create transformation matrix with its specified order. Order can be first, second or third polynomial order. Then the coordinates will be transformed. Hence it will have different coordinate system, it is necessary to invert it again to original coordinate system but preserving the obtained connectivity features. This process will be discussed as "inversion". Scale change by this transformation process in the connection of two points (pair of wells) is significant. It supplies information about the connectivity.

For each scheme, origin which is the center of the scheme was attributed as point vector. Domain was created along the specified extend which is covering the all wells accounted for the calculation. According to the domain size of the area, buffering pattern (isochrones) has been created from the center according to the defined resolution. Isochrones (perfect circles at first) represent the homogeneity of the ideal medium as same hydraulic response to the center from equal distances. Cell locations were transformed to homogeneous medium, and nearest-neighbor interpolation used for continuity of the data (Figure 3.6).

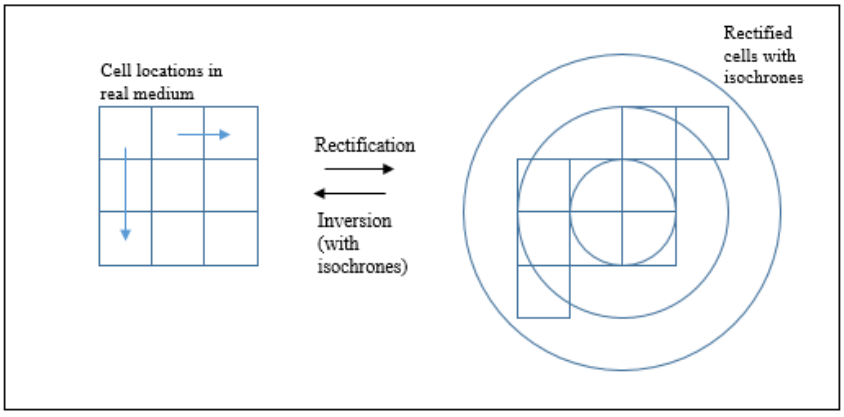


Figure 3.6. Illustration of cell locations in heterogeneous (left) and homogeneous (right) medium after rectification

Transformation order of the rectification has been used firstly as 2 dimensional. It is because the connectivity metrics described for this methodology refers to a two-dimensional property. In the z-axis, it is assumed that change of this r_t has not been affected. However this z-axis affect was investigated indirectly by analyzing the drawdown in different time steps, which will be clarified in the "sensitivity analyses" section.

1^{st} order transformation for the rectification was used for the developed methodology. It refers to the linear transformation with coefficients adjusted by least squares regression. Stretched (translation and scaling) and rotated image will present 1^{st} order transformation of the heterogeneous environment into homogeneously assumed one. Connectivity measures will indicate the heterogeneity by this georectification process. In addition to the transformations, 2^{nd} and 3^{rd} order polynomial transformation might be used and these would be done by modified Gaussian elimination method (Enslin, 2011). After trials of the 2^{nd} and 3^{rd} order of transformation, unexpected results has been observed. After the rectification process, coded cells can be told to be located at the new positions in medium which has homogeneous and isotropic property.

Right image in Figure 3.7 represents the geometry of the area (buffering zone with distortion) after rectification. Black circles are the contours of isochrones that are buffered at both real and homogeneous media. They are used to compare rectification. For this example simulation, scheme C drawdown data at the time step 600 minutes were used.

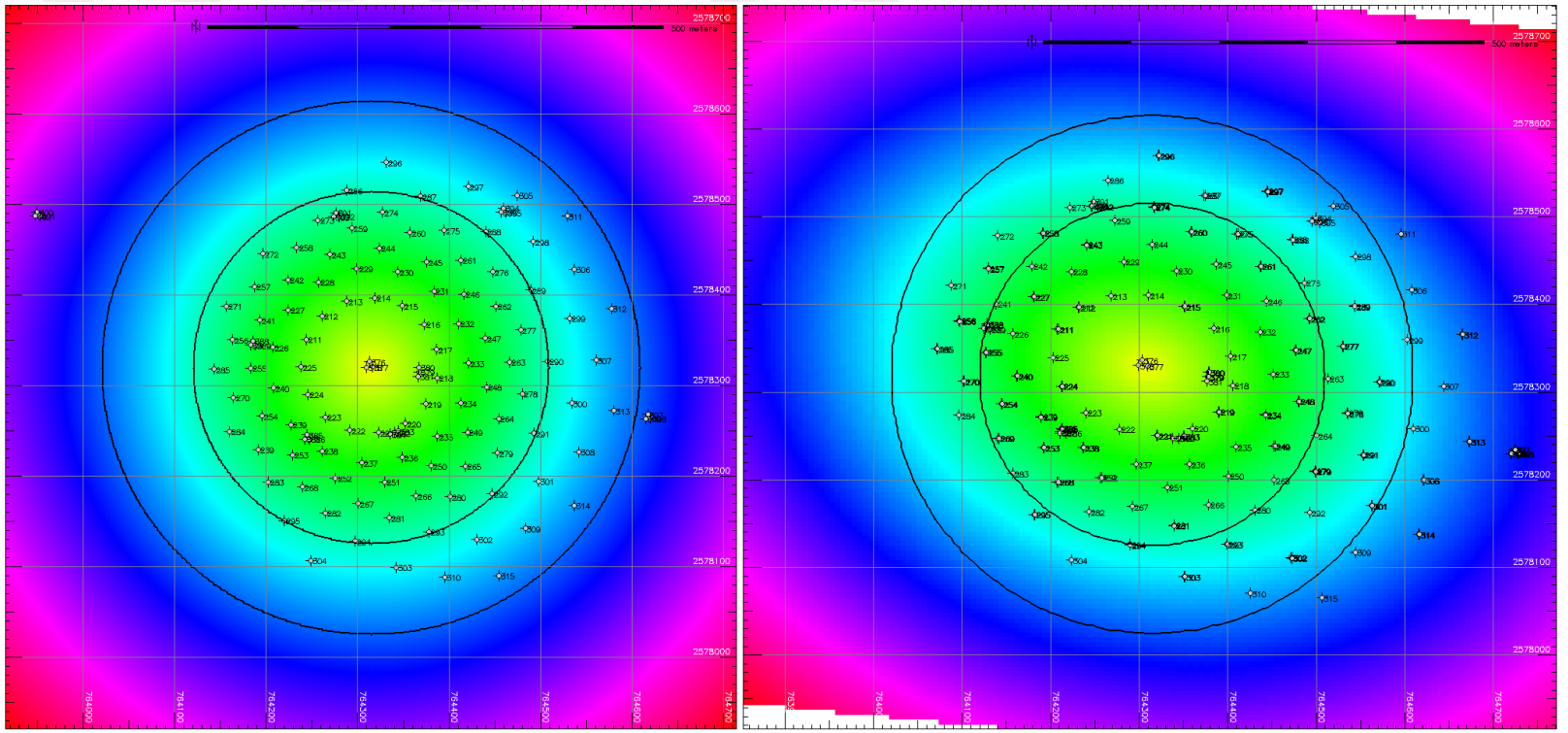


Figure 3.7. Real geometry and location of the wells are presented with perfect isochrones buffering (left) and location of each cell are rectified according to the new coordinates of the wells (right)

3.2.3 Inversion process

Rectification shows the location of the buffering cells in the homogeneously assumed medium. However we need to observe the connectivity effect in the location of the real medium. Therefore this rectification effect should be transformed back to the original location. After inversion process it is expected to have the heterogeneous and anisotropic medium delineation. Each cells of buffer zone (isochrones) has an elevation value increasing radially according to radius and cells have corresponding index coding (cells were coded regarding their rows and columns number). During rectification, this index codes were rectified as well. Therefore rectified raster map containing index codes can be used to trace the cell location change. When a different perfect circle buffering is done in the homogeneous media (rectified location), all the cell values and corresponding index coding (rectified codes of cells) has an equivalence in the real location (Figure 3.8). By keeping the codes of the cells (rectified) that have the elevation value of the perfect isochrones (homogeneous medium), rectification reflection can be observed in real geometry as heterogeneity map based on connectivity.

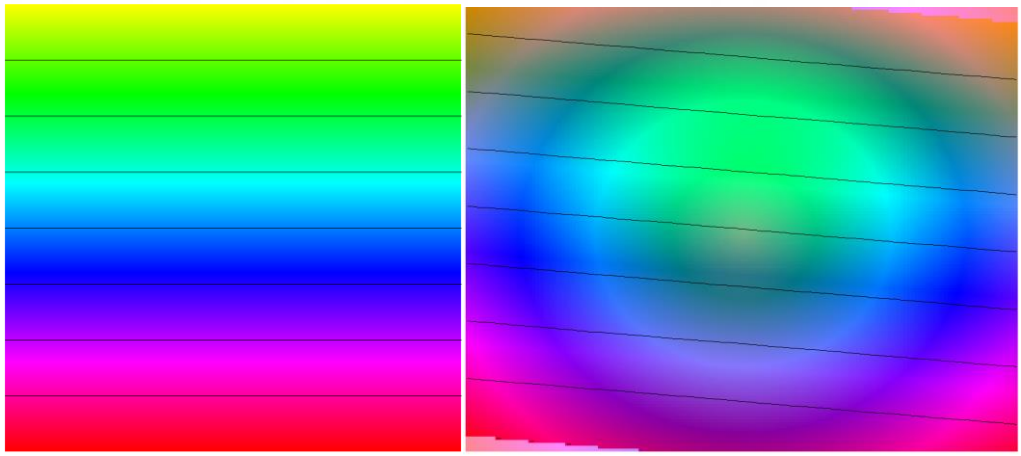


Figure 3.8. Raster maps that contain index code values (left). Rectified version of this map and buffering zone (right)

Distribution of the wells in perfectly homogenous medium was accepted as the same hydraulic response is present between the pairs with similar properties. This means from the center of the scheme, drawdown is perfectly symmetrical. In other words, connection from center to equal radius are the same.

In real location, it was observed that an anomaly (Figure 3.9) was created by using point to point connectivity metrics. An elliptical anomaly is observed in this way and a black vector was assigned to the elevation value of 100 to visually observe the anomaly.

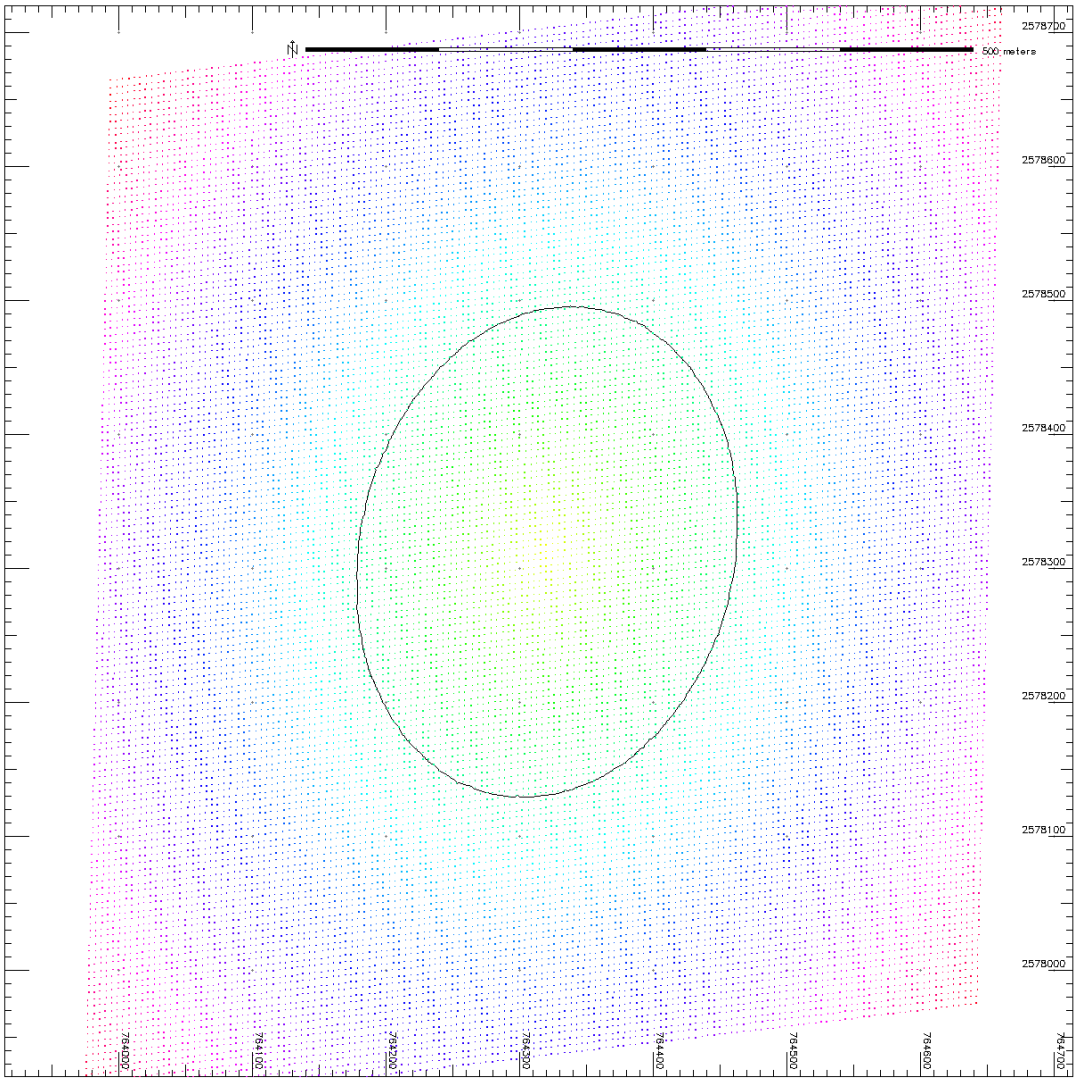


Figure 3.9. Raster map of transferred code locations and corresponding buffer zone values after inversion

The presentation of the anomaly refers to the result of one simulation of Anamorphosing. According to the simulation number, numerous different results can be obtained.

For each simulation, location of each well will differ according to the first random well chosen as described in section 3.2.1. After simulations of same scenario, ellipses were combined and added to each other as one raster value from their center to observe the probability of the medium anomaly (Figure 3.10) regarding the number of simulation.

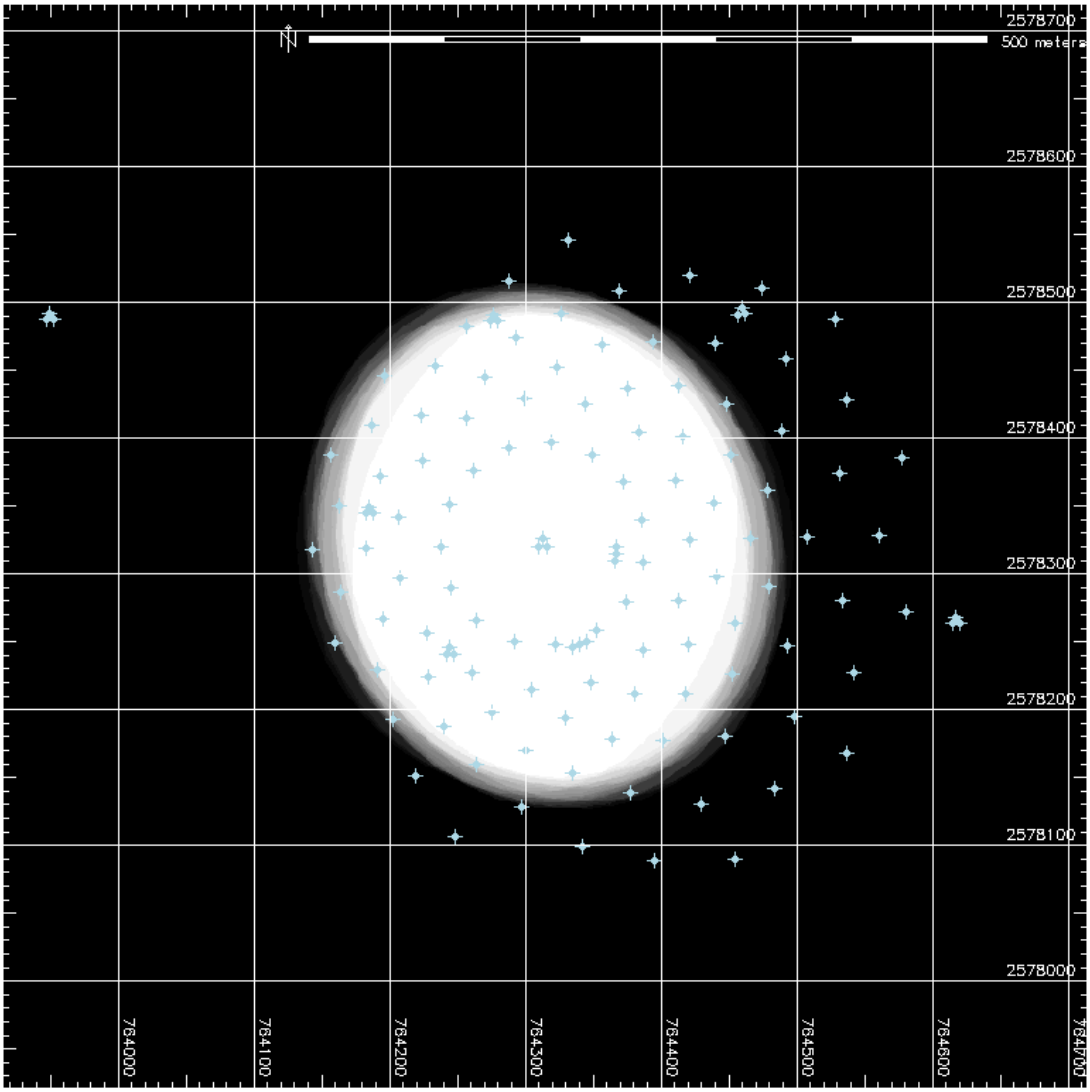


Figure 3.10. Anomaly probability of scheme C after 25 simulation based on drawdown data at 600 minutes of 290 pairs

Elliptic representation of medium property based on connectivity can refer to the anisotropy. Figure 3.10 shows the direction and extent of the fast path in scheme scale based on local connectivity indicator. For this visual representation of the elliptic anisotropy, sensitivity analysis should be realized to understand the effect of constraints.

3.3 Sensitivity Analysis

The presentation of the anomaly as one ellipse refers to the result of one simulation of "Anamorphosing" method. To understand this connectivity visualization and their constraints, sensitivity analysis were done by creating scenarios. For this part of the study, four main cases were created depending on the number of pairs (Table 3.3).

For the Case A, all the pairs obtained from data were used. Other cases were constructed by decreasing the number of pairs to observe the change in the results. According to the data, number of pairs may differ from one time step to another. Additionally, during the decrement of pair amount, randomness was the key factor and mean of ratio values was kept 1 as mentioned in section 3.1.1.

Table 3.3. Scenarios depending on the number of pairs and time steps

		Case (Number of Pairs)			
	Time Steps (minutes)	Case A	Case B	Case C	Case D
Scheme A	100	394	300	150	75
	300	394	300	150	75
	600	374	300	150	75
Scheme B	100	383	300	150	75
	300	383	300	150	75
	600	364	300	150	75
Scheme C	100	302	200	100	50
	300	302	200	100	50
	600	290	200	100	50

Another constraint is the simulation number. For each 36 scenarios presented in Table 3.3, four different simulation numbers were tested. These were decided to be 100, 75, 50 and 25 based on the trials. Therefore 144 different scenarios were ran to observe the effect of all constraints (time step, number of pairs and simulation number). For each of four simulation number scenarios, first random well chosen (see section 3.2.1) by the "Anamorphosing" method was different to supply randomness and homogeneity.

After each simulation, an ellipse that represents the anisotropy was obtained and its characteristics were analyzed. For these characteristics (Figure 3.11), ratio of shortest distance to longest distance from the center (as conjugate ratio) and angle between north and major axis direction were used.

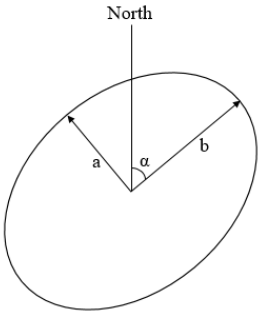


Figure 3.11. Characteristics of the ellipse

According to the results, Scheme A and B (Appendix B) show relatively homogeneous and isotropic media rather than Scheme C (Figure 3.12, 3.13). Therefore, sensitivity analysis are more distinctive in Scheme C.

For the Scheme A, ratio does not significantly change through the increasing time step, simulation number and number of pairs. Although maximum and minimum values show slight difference through constraints, ratio has narrow range. Varying direction of anisotropy can be observed for Scheme A.

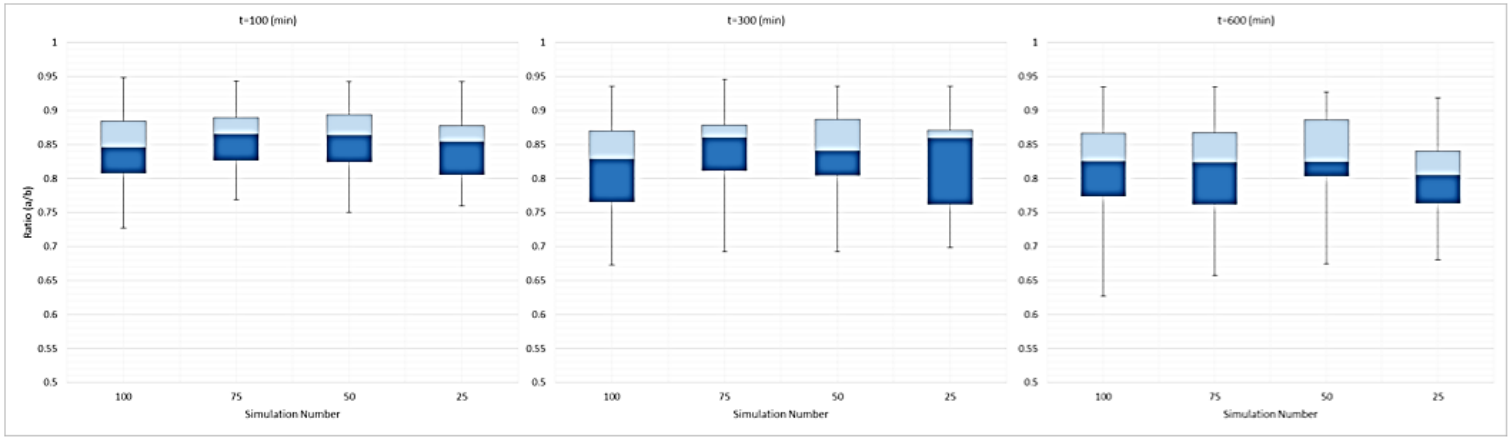
At time steps 100 and 300 minutes, median show similarity between all cases (constraint as number of pairs). However, results obtained at 600 minutes may reflect the medium property more than the results obtained at 100 and 300 minutes in terms of cone of depression volume. For cases C and D at 600 minutes, median of direction changes significantly. Therefore for this scheme, Case B at 600 minutes with 50 simulation is efficient and representative. In case of lower number of pairs, Case C at 300 minutes with 25 simulation could be optimal as well (see Appendix B for boxplots).

Ratios stabilizes at 600 minutes for all simulation scenarios in scheme B. Decrease in number of pairs for time steps 100 and 300 minutes makes them more stable and similar at 600 minutes. In terms of direction, Case A and Case B show very similar degrees for all scenarios. Decreased pair number of Case C indicates higher values while D shows more narrow range. For lower number of pairs (Case C & Case D), time step of 600 minutes is more reasonable. In that case, simulation number of 75 gave more stable results. Case D of 600 minutes with 75 simulations is optimal scenario for this scheme (see Appendix B for boxplots).

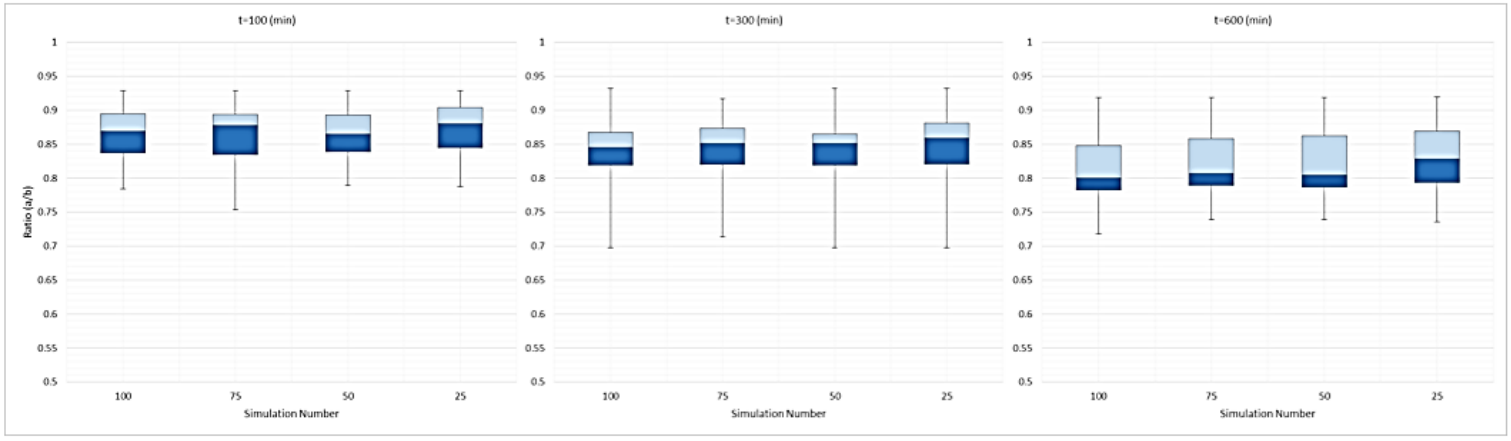
Scheme C shows relatively higher range of values for the scenarios with high number of pairs (Figure 3.12.a). It seems that, this scheme is more sensitive to number of pairs than other schemes. For the time steps 100 and 300, decreasing number of pairs makes the range narrower (Figure 3.12.c). In case D, change in ratio is more noticeable (Figure 3.12.d). Case D may be told to be representative in terms of number of pairs, if the time step considered to be at 600 minutes. Minor effect on simulation number might be observed as being more stable after 25 simulation. Directions obtained from case D (Figure 3.13.d) do not have similarity when compared with other cases. At time step 600 minutes, case C is more stable than case D. This difference was observed at the time steps 300 and 600 minutes. Case C of time step 600 with 50 simulation show optimal results.

As a result of sensitivity analysis for this methodology, number of pairs might be taken as around 100-150 depending on the scheme. Generally between 25 and 50 simulations makes the analysis stable. Therefore, it would be appropriate to take the simulation

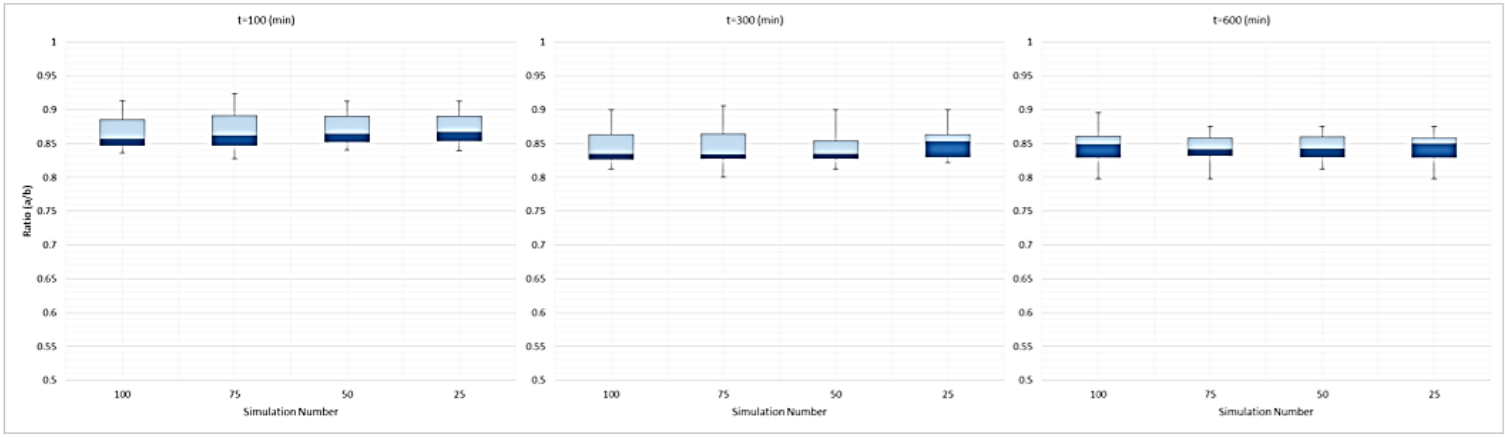
number as 50. Time step of 600 minutes can be told to be optimal, depending on the purpose of investigation. Lower time steps might be helpful to investigate the connectivity of different configuration of properties (depending on flow in aquifer), which should be studied in particular.


t=100 (min)
t=300 (min)
t=600 (min)
Ratio (a/b)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
100
75
50
25
Simulation Number

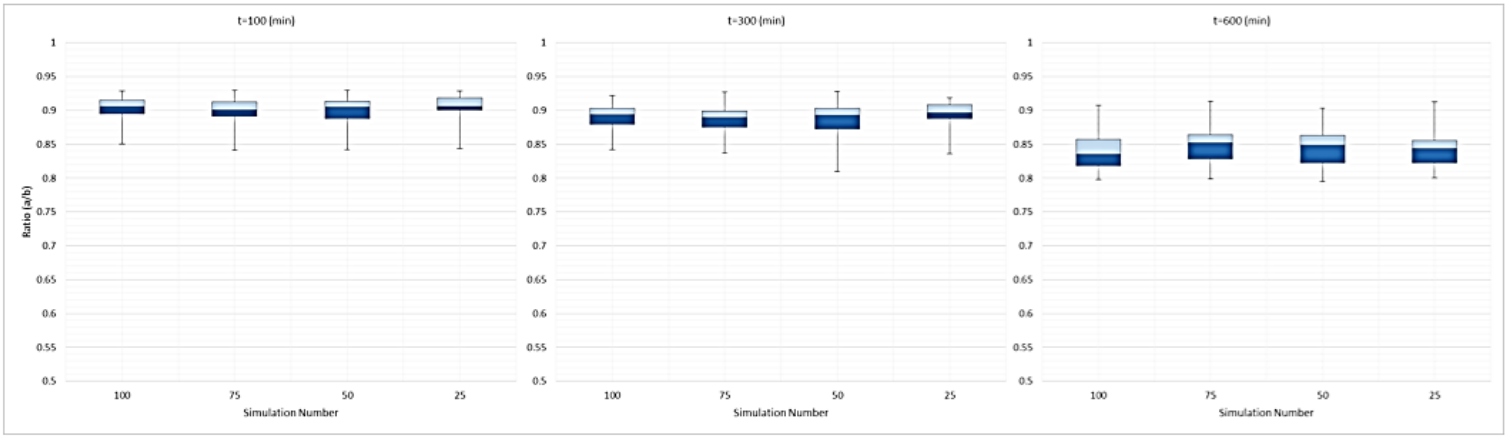
a)


t=100 (min)
t=300 (min)
t=600 (min)
Ratio (a/b)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
100
75
50
25
Simulation Number

b)

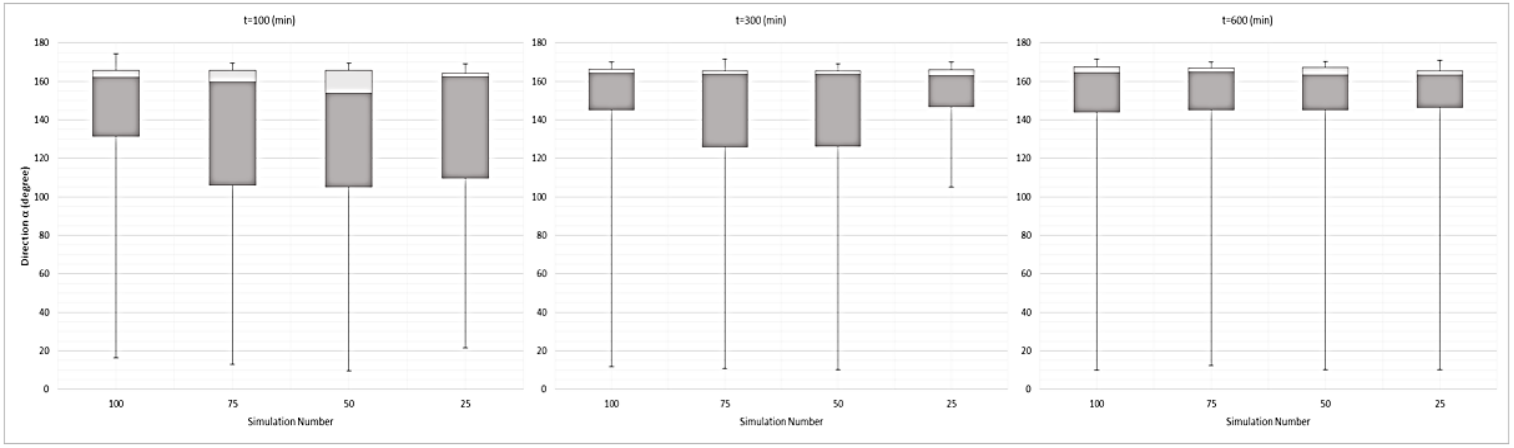

t=100 (min)
t=300 (min)
t=600 (min)
Ratio (a/b)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
100
75
50
25
Simulation Number

c)

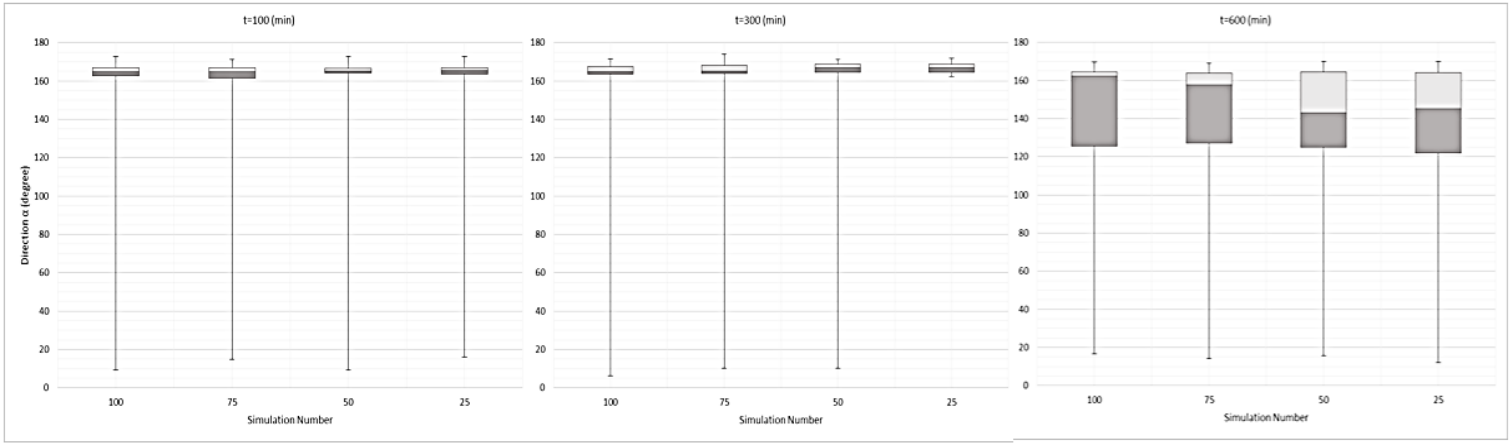


d)

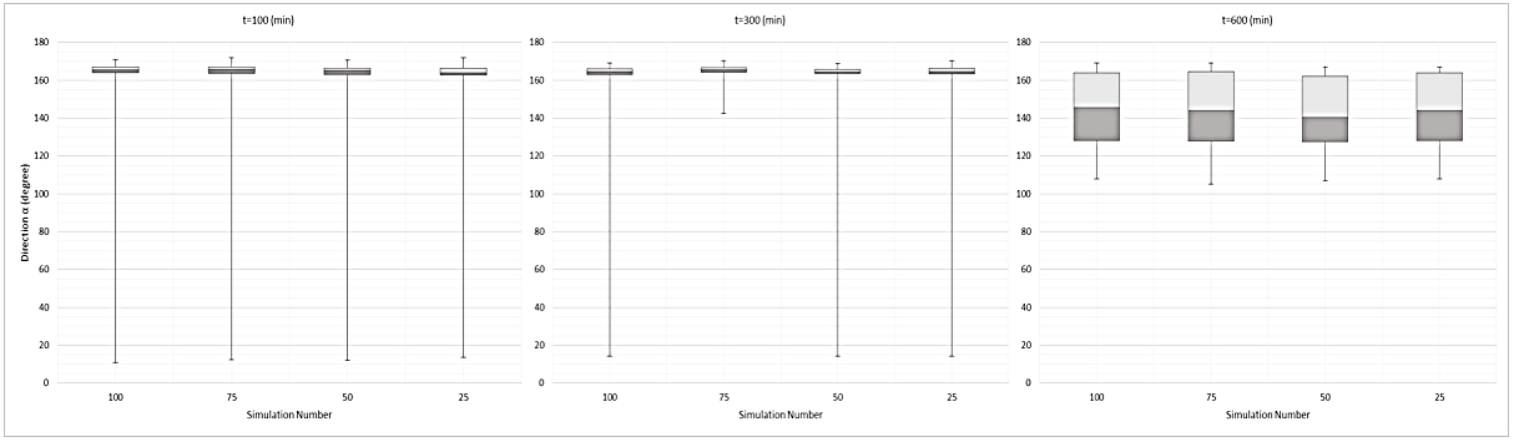
Figure 3.12. Boxplot of anisotropy ratios simulated from scheme C. Case A (a), Case B (b), Case C (c) and Case D (d) with corresponding scenarios of simulation number and time step


t=100 (min)
t=300 (min)
t=600 (min)
Direction α (degree)
0
20
40
60
80
100
120
140
160
180
100
75
50
25
Simulation Number

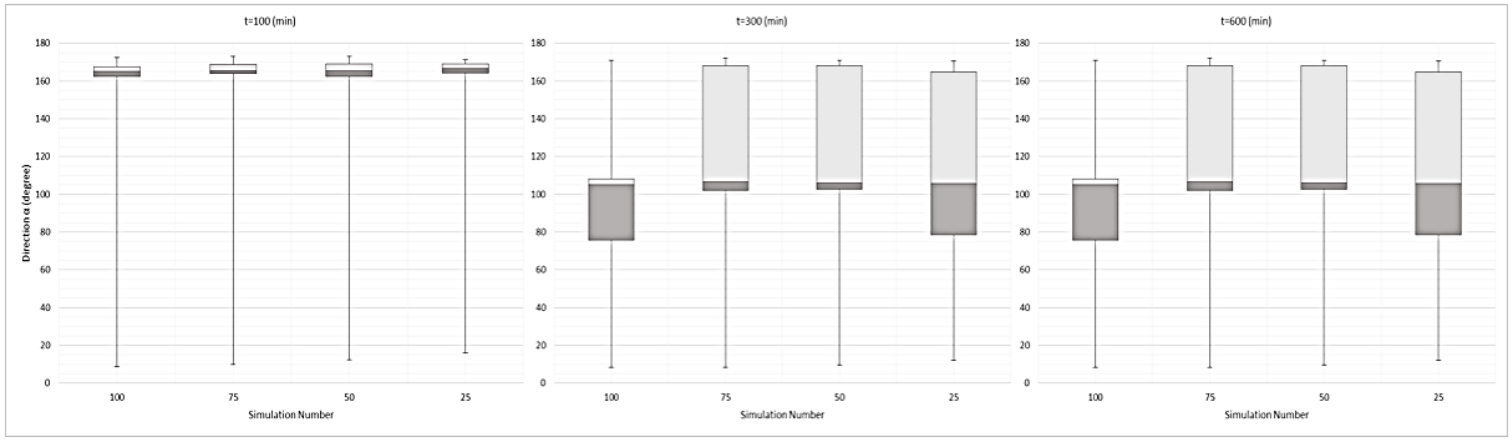
a)


t=100 (min)
t=300 (min)
t=600 (min)
Direction α (degree)
0
20
40
60
80
100
120
140
160
180
100
75
50
25
Simulation Number

b)


t=100 (min)
t=300 (min)
t=600 (min)
Direction α (degree)
0
20
40
60
80
100
120
140
160
180
100
75
50
25
Simulation Number

c)



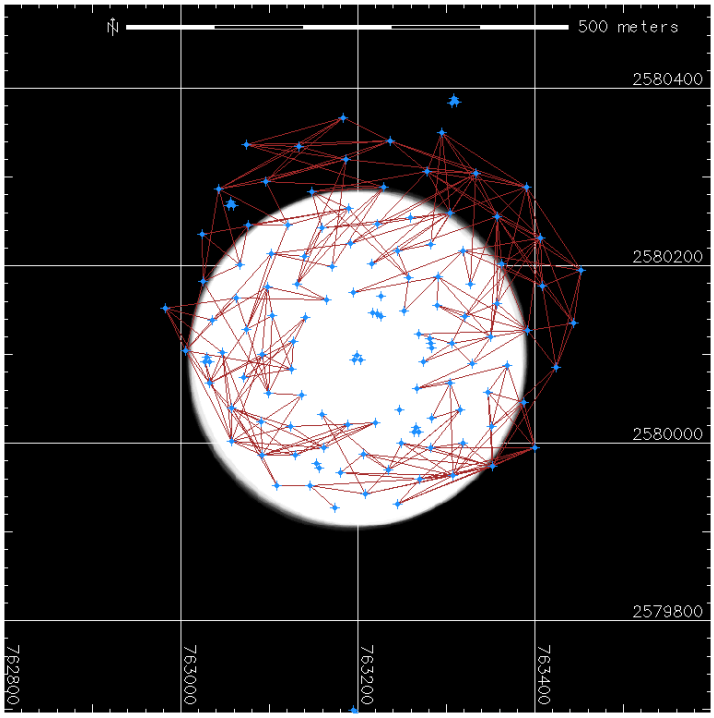
d)

Figure 3.13. Boxplot of direction angles simulated from scheme C. Case A (a), Case B (b), Case C (c) and Case D (d) with corresponding scenarios of simulation number and time step

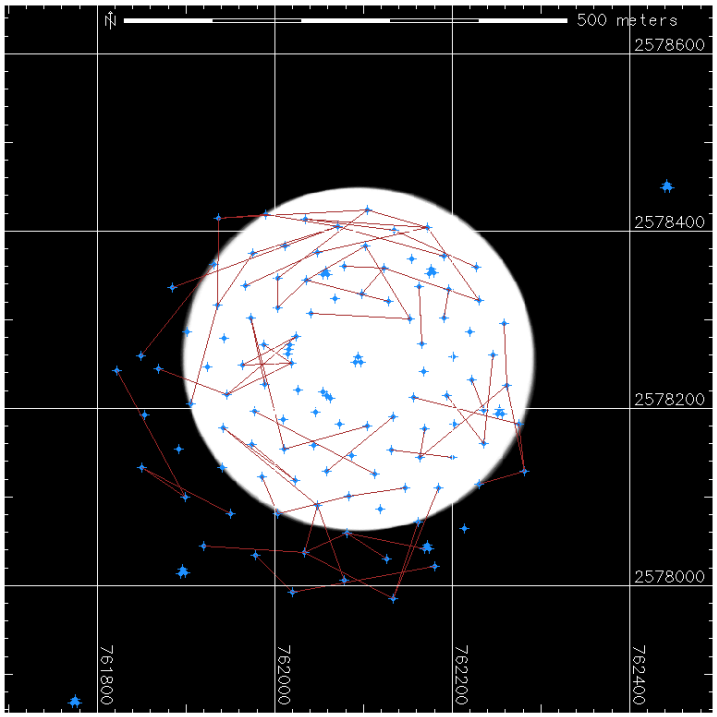
4. ANALYSIS OF PROPOSED HETEROGENEITIES

4.1 Application of the Method

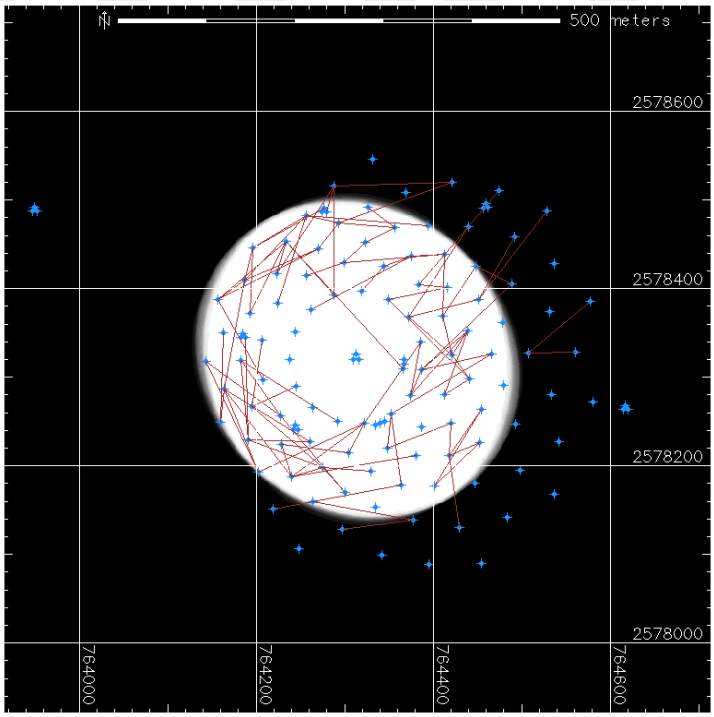
After the sensitivity analyses, representative and optimal scenarios were used to apply as medium property. According to that, time step 600 minutes of drawdown used for each schemes. Case B with 50 simulations, Case D with 75 simulations and Case C with 50 simulations were used in schemes A, B and C, respectively (Figure 4.1).



a)



b)



c)

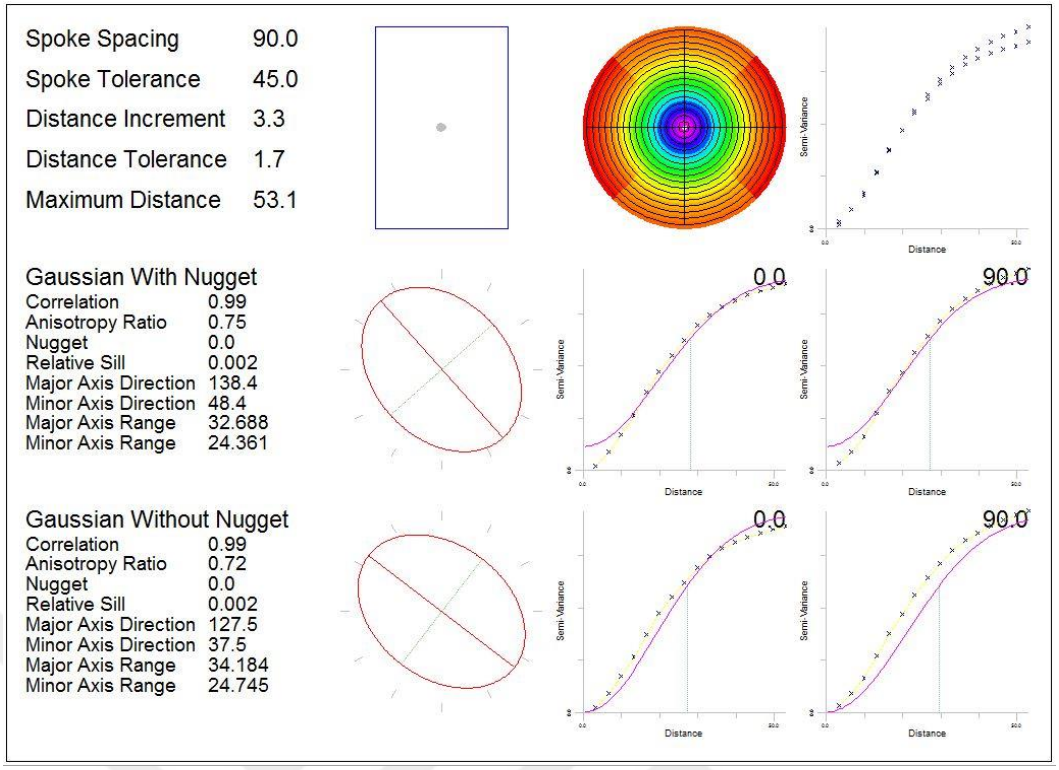
Figure 4.1. Anamorphosing results and pairs of scenarios for schemes A (a), B (b) and C (c)

To illustrate the anomaly, conjugate ratios and directions of scheme A, B and C were obtained from the corresponding scenarios. Anisotropy ratio of 0.92 with 66° for scheme A, 0.92 to 88° for scheme B and 0.84 to 141° for scheme C were the mean characteristics of the determined scenarios.

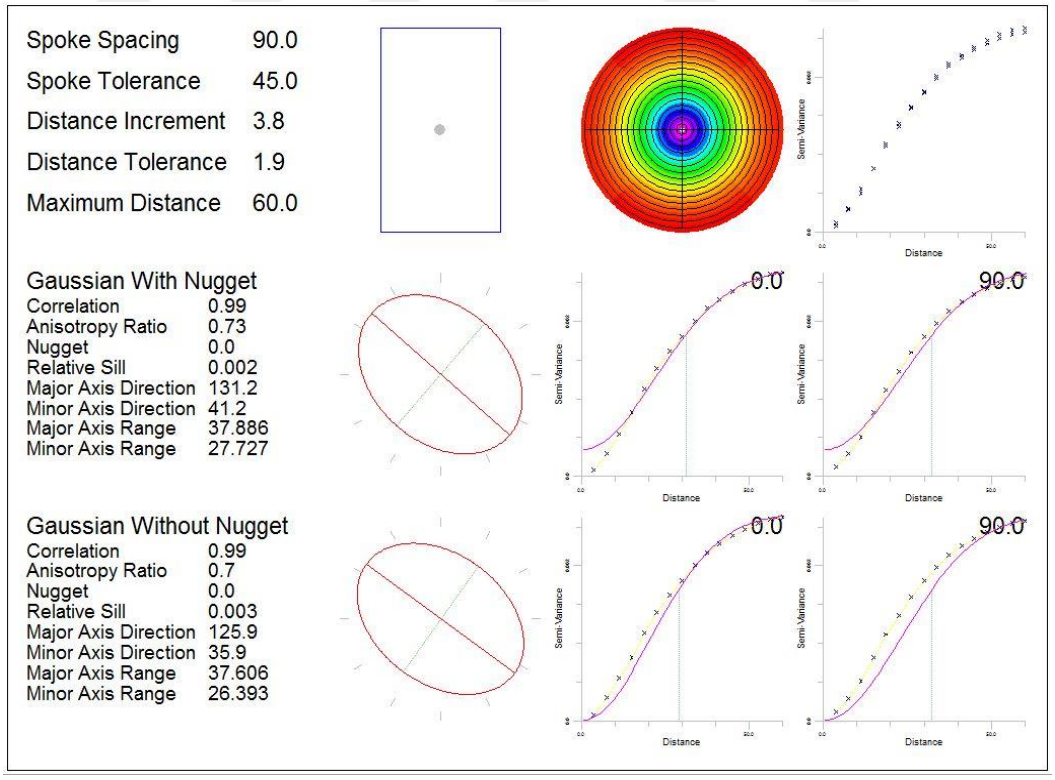
As an application of anamorphosing methodology to mapping, this section of the study contains correlation of descriptive sensitivity analysis results with local facies heterogeneity. Lithology descriptions obtained from boreholes were examined. Including several monitoring wells, 350 boreholes were used as input to logging software. Sand was the main lithology observed, however according to the particle size, four main groups were created. “Very fine”, “very fine to fine”, “fine” and “fine to medium” grain sizes were located regarding their top and base depths. Mean base depth observed was approximately 80 meter from the ground elevation. Accordingly, they were sampled based on their size grains group at each 10 meter. Using the lithological database obtained after sampling, variogram analysis was realized to see a trend in spatial orientation of grain sizes.

This might be correlated with the connectivity anisotropy results obtained from the “Anamorphosing” methodology. Best fitting methods were observed as Gaussian with nugget and Gaussian without nugget for variogram.

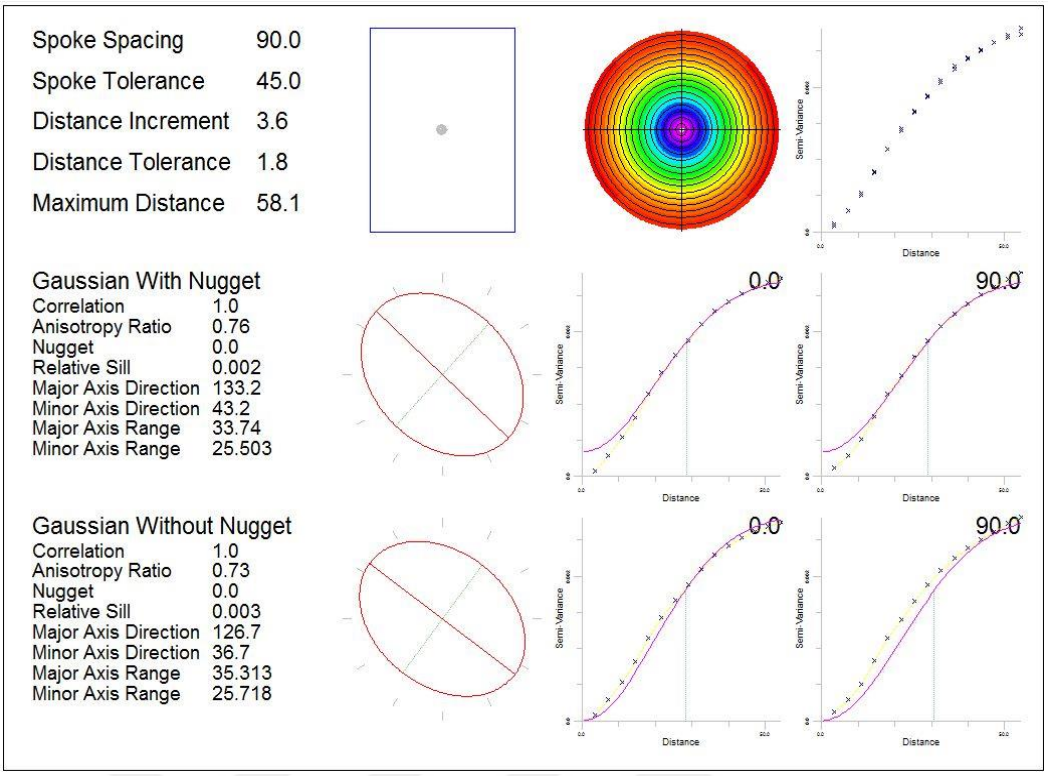
Anisotropy ratio and direction obtained from connectivity study and the results obtained from variogram analysis shows similarity only for Scheme C (Figure 4.2.c). Difference in trends were observed for Scheme A (Figure 4.2.a) and B (Figure 4.2.b) in variogram analysis, since ratios obtained from anamorphosing were close to isotropy.


Spoke Spacing 90.0
Spoke Tolerance 45.0
Distance Increment 3.3
Distance Tolerance 1.7
Maximum Distance 53.1
Gaussian With Nugget
Correlation 0.99
Anisotropy Ratio 0.75
Nugget 0.0
Relative Sill 0.002
Major Axis Direction 138.4
Minor Axis Direction 48.4
Major Axis Range 32.688
Minor Axis Range 24.361
Gaussian Without Nugget
Correlation 0.99
Anisotropy Ratio 0.72
Nugget 0.0
Relative Sill 0.002
Major Axis Direction 127.5
Minor Axis Direction 37.5
Major Axis Range 34.184
Minor Axis Range 24.745
Semi-Variance
Distance
0.0
90.0

a)


Spoke Spacing 90.0
Spoke Tolerance 45.0
Distance Increment 3.8
Distance Tolerance 1.9
Maximum Distance 60.0
Gaussian With Nugget
Correlation 0.99
Anisotropy Ratio 0.73
Nugget 0.0
Relative Sill 0.002
Major Axis Direction 131.2
Minor Axis Direction 41.2
Major Axis Range 37.886
Minor Axis Range 27.727
Gaussian Without Nugget
Correlation 0.99
Anisotropy Ratio 0.7
Nugget 0.0
Relative Sill 0.003
Major Axis Direction 125.9
Minor Axis Direction 35.9
Major Axis Range 37.606
Minor Axis Range 26.393
Semi-Variance
Distance
0.0
90.0

b)



c)

Figure 4.2. Variogram analysis of lithology features for Scheme A (a), Scheme B (b) and Scheme C (c)

4.2 Wellbore Effect

For larger scale heterogeneity investigation in the medium, wellbore effect is analyzed. Application of the Butler (1988) solution will take place in this section.

When the data trend of drawdowns for long term tests were investigated, the late time shows increasing derivative until the end. Even if the small part of the raw data was edited to discard the oscillation effect caused from the pumping start and stop, this increasing derivative was not expected.

Radius of influences for the long term tests are ranging from 200 to 300 meter and inside this region there are several wells drilled and developed. Increasing derivative might be caused from the disk effect as creating barrier zone depending on properties,

so each data were analyzed according to the Butler (1988) principles (Figure 4.3). According to that, drawdown data of each pair were fitted with a good match based on the late time data. Results can be observed in Appendix C.

Example match comparison of Butler solution (same data in Figure 4.3) with other methods can be observed in Appendix D.

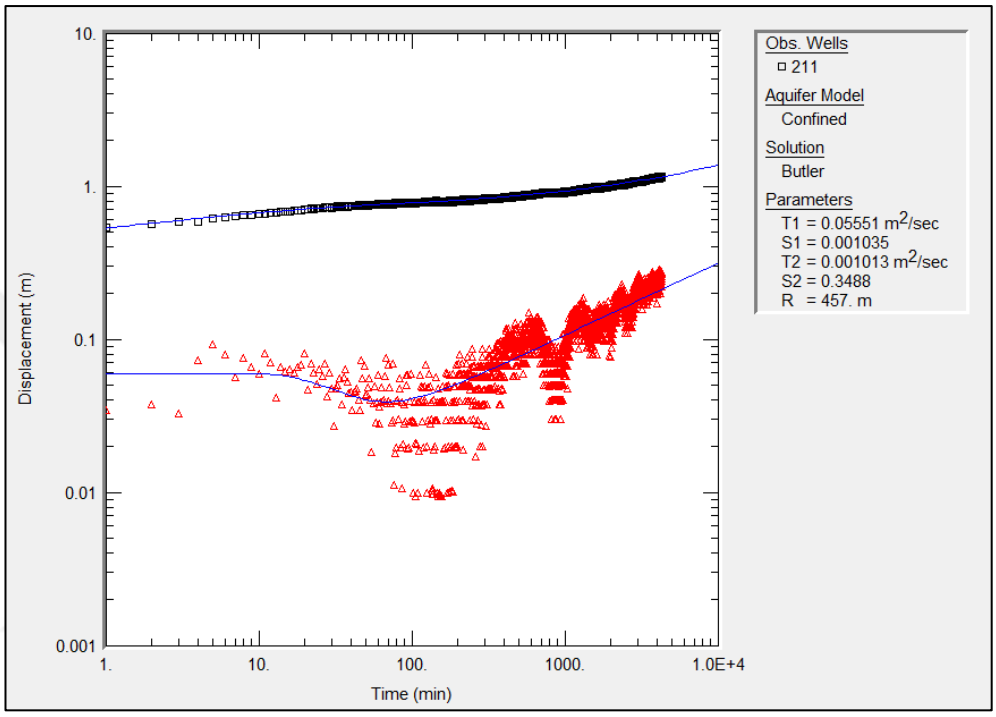


Figure 4.3. Butler (1988) analysis for the observation well 211 (81.1 m) of pumping well 256 in Scheme C. Derivative of the data is showed in red triangle

Some of the fitting do not coincide with the early time data. Butler (1988) solution was developed for confined aquifer, and because of the study area has unconfined aquifer type, this early time mismatching might be expected.

Also, some of the results showed extreme values that might be caused from this mismatching as well. T1, S1 refers to the properties of the material inside the disk configuration and T2, S2 refers to the outside of the disk (Figure 4.4).

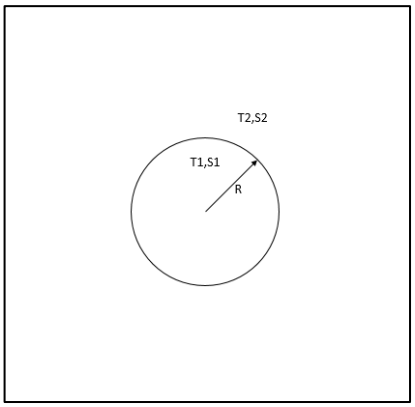


Figure 4.4. Disk properties located in the medium (Butler, 1988)

All results were obtained separately for each pumping well in each schemes. According to the hydrodynamic properties, wellbore effect can be observed as increase in transmissivity inside the disk. However storativity was seem to be effected otherwise (Table 4.1). These properties will be used to see the effect of disk existence to the recharge flow. Boundary of the disk will be decided according to the radius results.

Table 4.1. Hydrodynamic parameters of each scheme with disk material

	SCHEME A		SCHEME B		SCHEMEC	
	Average	Median	Average	Median	Average	Median
T1 (m^2/sec)	0.180	0.073	0.095	0.070	0.113	0.054
S1	0.045	0.005	0.078	0.007	0.024	0.001
T2 (m^2/sec)	0.004	0.001	0.002	0.001	0.003	0.001
S2	0.338	0.106	0.328	0.095	0.194	0.124

Radius results acquired from each observation well in a pumping test were considered to be the effect of that pumping well. Wide range of values for radius was observed. Descriptive radius as median for scheme A can be told to be 520 m from the pumping well (Figure 4.5).

Scheme B shows radius values of approximately 200 m, although well number 154 gives higher value (Figure 4.6). Representative radius values for scheme C is 620 m as median (Figure 4.7).

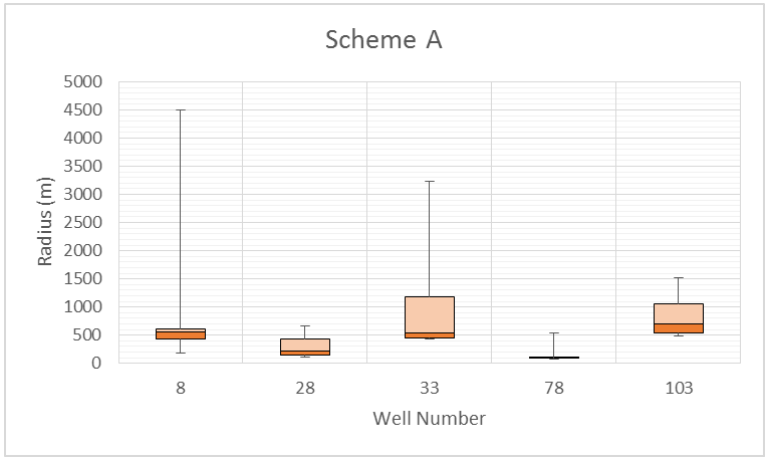


Figure 4.5. Boxplots of radii calculated from Butler (1988) approach for Scheme A

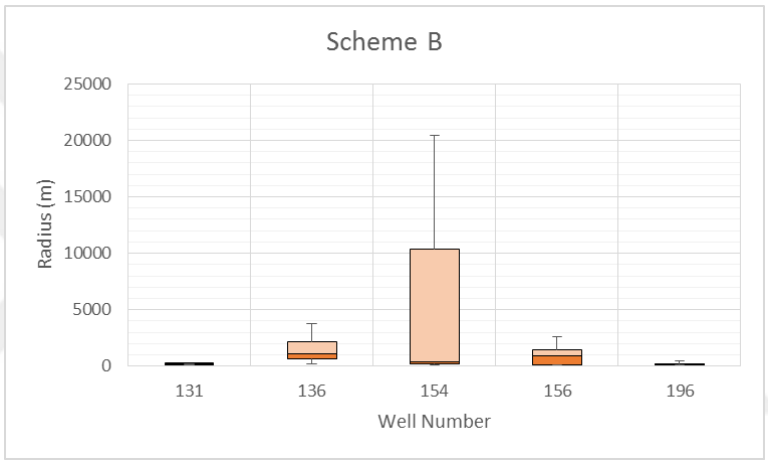


Figure 4.6. Boxplots of radii calculated from Butler (1988) approach for Scheme B

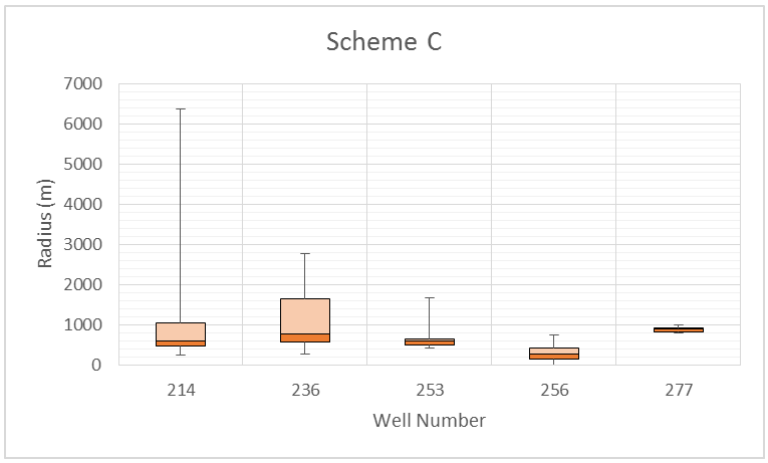


Figure 4.7. Boxplots of radii calculated from Butler (1988) approach for Scheme C

For each scheme, based on median of radii, merged disk regions was created. Merged radii of each well were used to see the boundaries of the disk. However, this type of region gave overestimated heterogeneity area because of the extreme values located in the results.

Median of all disk radii wells in each scheme used in schemes differently. It is assumed that each scheme will have the effect of two zone aquifer as their median radius from scheme center (Figure 4.8). This type of region is more reasonable in terms of changed material property.

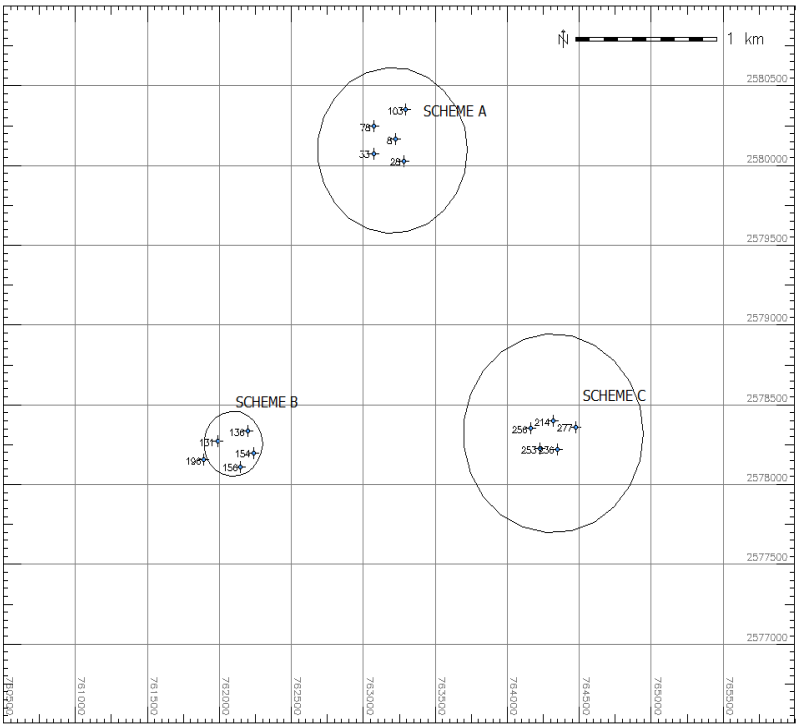


Figure 4.8. Disk regions with median of Butler (1988) radii from scheme as center

4.3 Heterogeneity Relation of the Techniques

Experimental results after sensitivity analysis of developed method were used to correlate with the any possible heterogeneity trend of the local facies. Method of anamorphosing was expected to give fractal heterogeneity map after using 2nd and 3rd order of rectifications, which was not the case. 1st order rectification results indicated

an anisotropy rather than heterogeneity. This heterogeneous medium indicating anisotropy results were tried to be applied to the real lithological data which has also relatively heterogeneous inside the sand unit as grain size. A trend that may exist in grain size groups may results in higher connectivity in their grouping direction. Therefore variogram analysis was important in that sense.

Spatial trend was observed in variogram. In fact, the trend of this relatively heterogeneous facies revealed that there is a similar anisotropy with anamorphosing delineation for Scheme C.

From the long term data, drawdown trend was observed which shows uncommon late-time property. Possible disk formation in terms of changing material properties of the nearby well region was a characteristics of this uncommon trend. Due to the numerous well drilled and developed, region was effected as developing large scale disk heterogeneity of each scheme. To understand this large scale heterogeneity effect from wellbores, application of Butler (1988) analytical solution was used. Solution gives hydraulic properties of the two-zone aquifer based on evaluation of each drawdown data. Zone properties and radius of possible disk formation were identified according to the pumping well (center of the disk). Drawdown trend, and radius of disks were compatible. Scheme with larger radius (scheme C), showed less increase in the late time (Appendix C).

5. TESTING OF HETEROGENEITIES ON RECHARGE

A basic flow model was constructed in Groundwater Vistas to observe the effects of the heterogeneities to flow during recharge. A simple model with all necessary components (top elevation, bottom elevation, boundary condition etc.) was introduced. Cell size around the schemes were arranged finer than other areas to see the effect in detail. Recharge of $3.2x10^{-5}$ m/s were used. This amount is the planned daily amount of water that will be artificially introduced. Artificial recharge will be applied through the infiltration basins located in the center of the schemes. This infiltration basins have diameter of 75 meter in reality, however in model it is accepted as 100 meter because of cell size restrictions. Top elevations of model were obtained from SRTM v2, bottom elevations were taken as 85 meter from the surface. Boundary conditions in the area were taken as constant-head with 106.4 meter which is the mean value of the static heads. Initial head of the system was accepted same as well. Two different heterogeneity case of artificial recharge was tested.

5.1 Anamorphosing Anisotropy as Kx/Ky

In this model, anisotropy anomaly obtained from Anamorphosing method was introduced as Kx/Ky anisotropy. Firstly, extend of different property zones were constructed inside scheme regions and these results will be observed in figures 5.1 and 5.2. Property zones were also changed into broader region, yet change in recharge results was minor.

Scheme A and Scheme B have showed almost isotropic results. Because their direction is more variable, only the 0.92 value of anisotropy ratio accepted for K_x/K_y. For Scheme C anisotropy was taken as 0.84 and major axis showed almost 140° in clockwise orientation from north, so the grid of the model was rotated 40° clockwise. Rotation angle was chosen to have the long axis of anisotropy for Scheme C in vertical

(y-axis) for utilization of the K_x/K_y anisotropy. Transmissivity and storativity of the medium were taken as 0.012 m^2/sec and 0.072, respectively (Kurtulus & Avsar, 2016). No water mounding was observed for the configuration with planned recharge of $3.2x10^{-5}$ m/s (Figure 5.1).

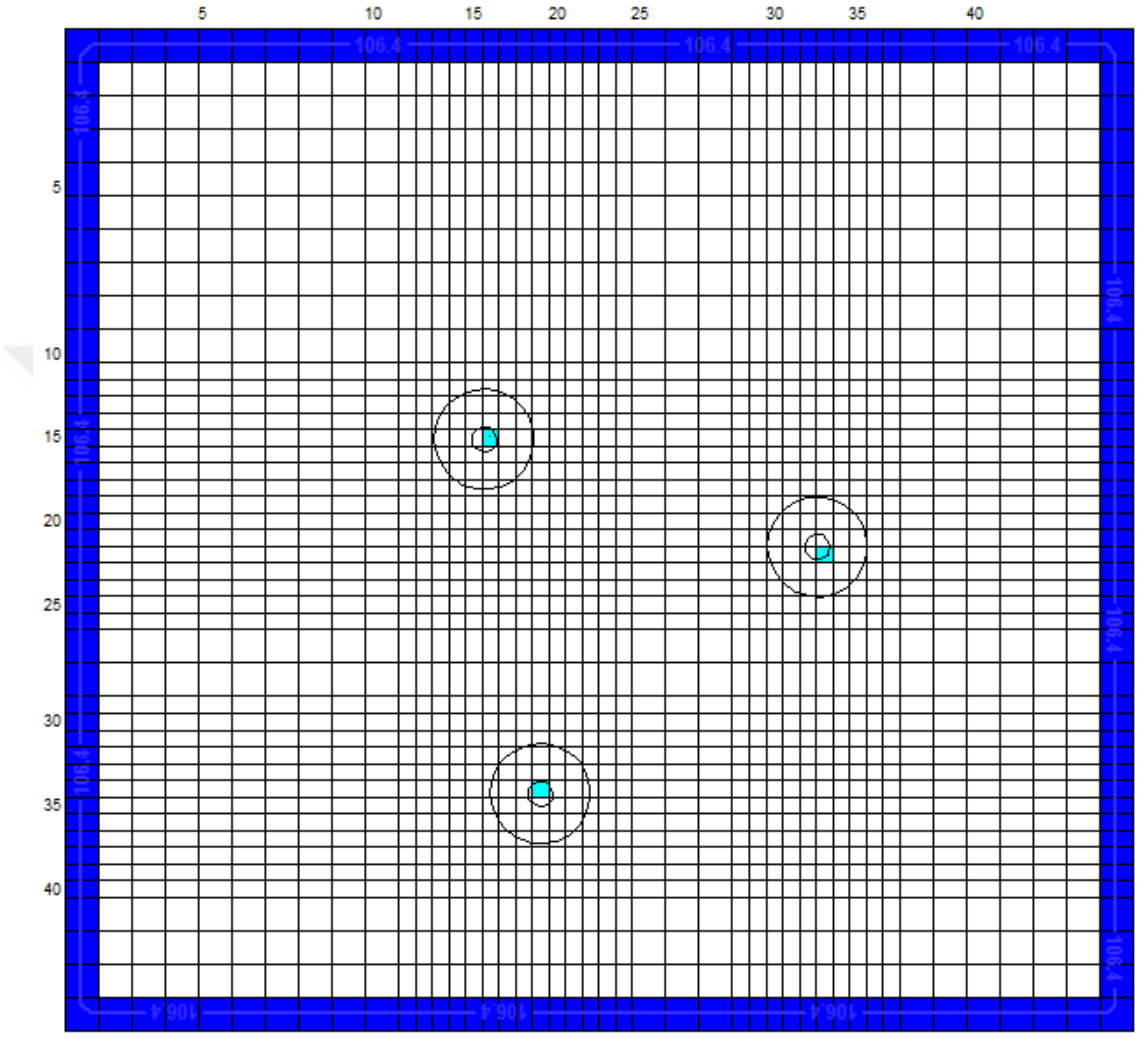


Figure 5.1. Anamorphosing effect on planned amount of artificial recharge

Recharge was increased up to $3.2x10^{-4}$ m/s to observe the anisotropy effect (Figure 5.2). According to that injected water plume extend is broader in the Scheme B through the center of the study area, due to the topographic effect. Extend is slower and restricted in Scheme C, due to the topography. Although anisotropy obtained is higher in this scheme, change in the propagation of the plume was minor compared to isotropic properties.

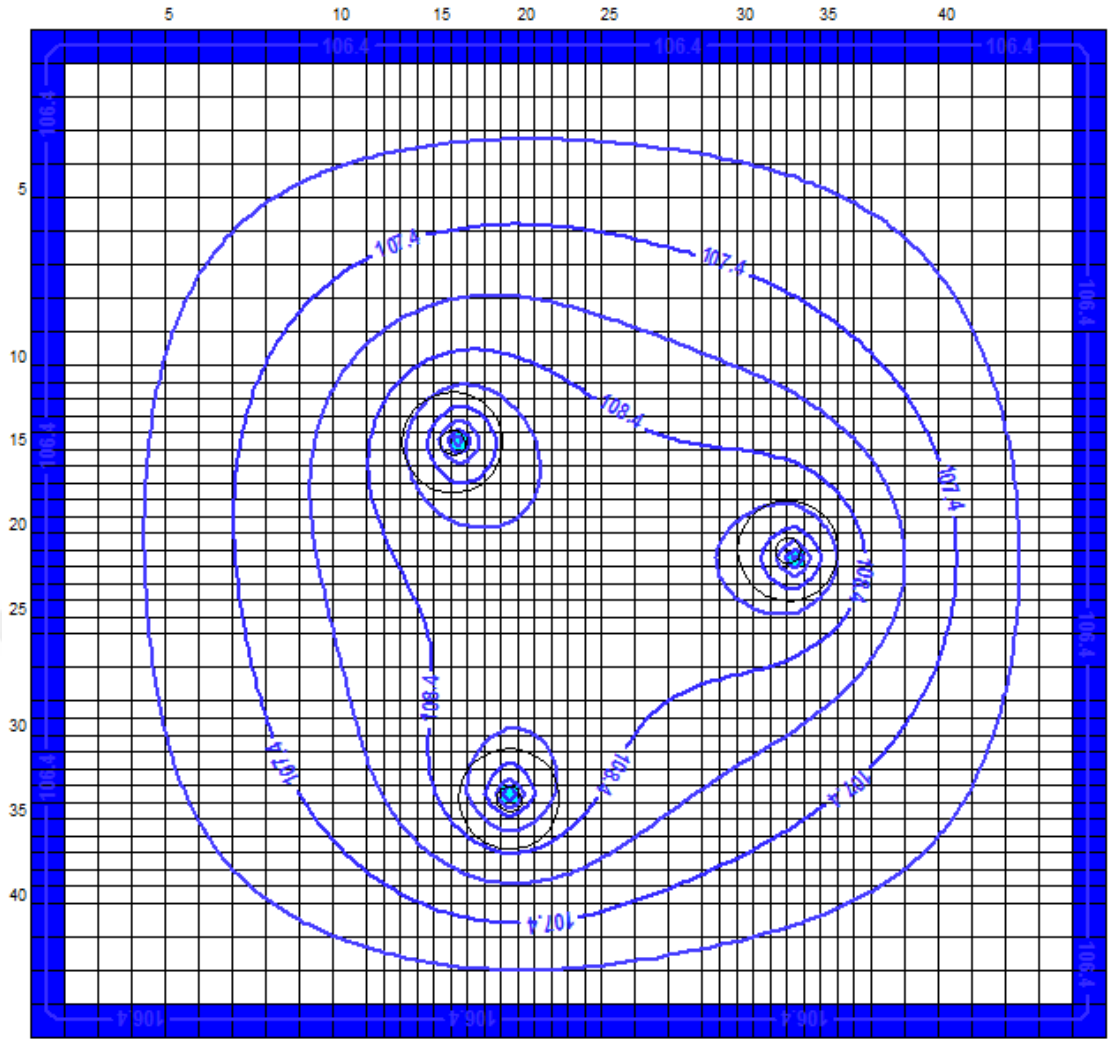


Figure 5.2. Anamorphosing effect on increased amount of recharge

5.2 Two-zone Aquifer as Disk Heterogeneity

Disk zonation heterogeneity acted as a barrier effect to the medium (Figure 5.3). For this configuration, mean of hydraulic properties that was calculated from Butler (1988) analysis of were used (Table 5.1). Water level increase only observed inside the disk formation with recharge of 3.2×10^{-5} m/s.

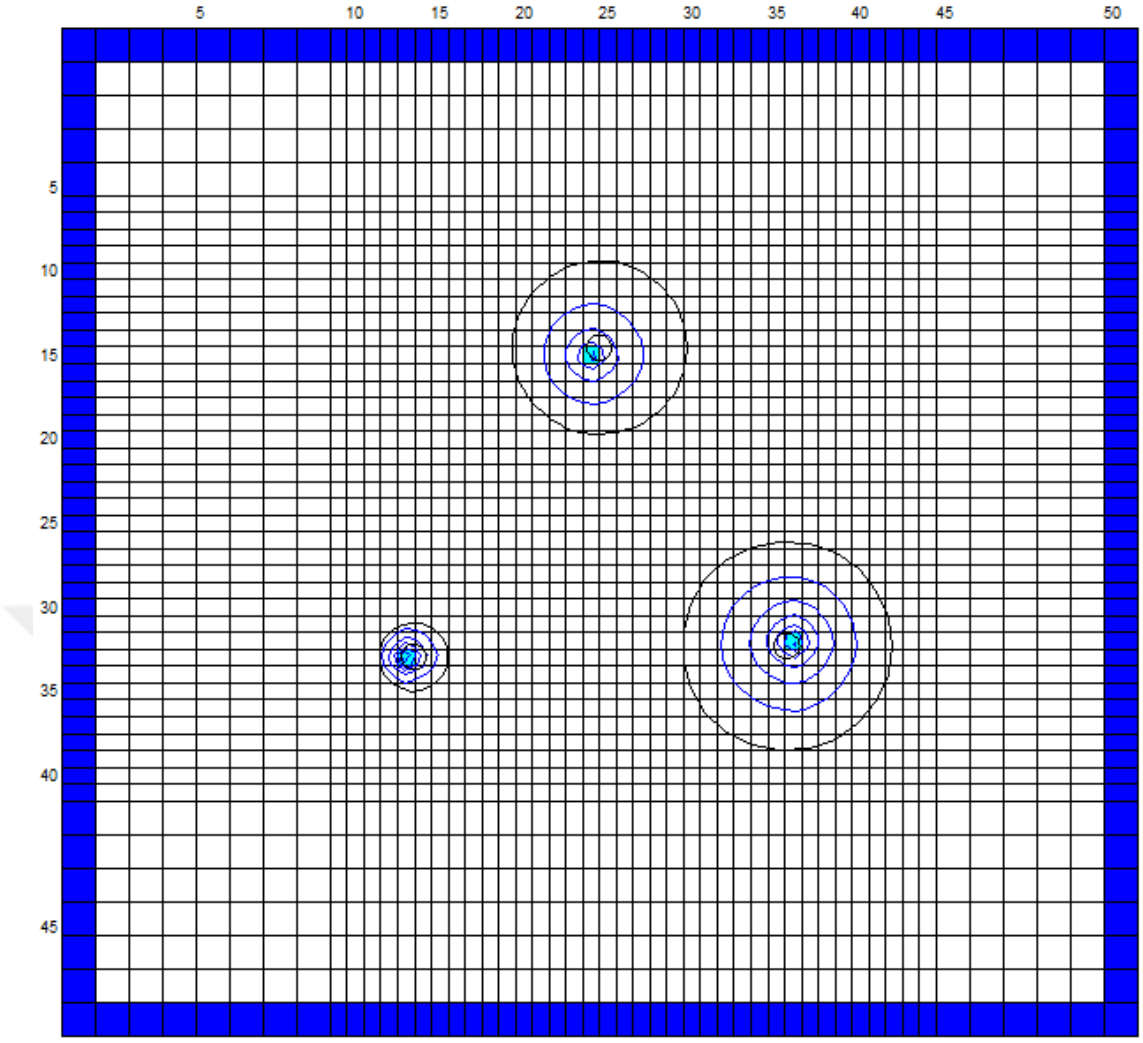


Figure 5.3. Disk effect on planned amount of artificial recharge

Table 5.1. Hydraulic properties used in Butler (1988) configuration

SCHEME	A	B	C
T1 (m^2/sec)	0.180	0.095	0.113
S1	0.045	0.078	0.024
T2 (m^2/sec)	0.004	0.002	0.003
S2	0.338	0.328	0.194

6. CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Two different heterogeneity survey approach was carried out on the pumping test data of water recovery and storage project in Liwa. A methodology developed to investigate the point to point connectivity implicated heterogeneity was one of the approach. Dynamic connectivity metrics was inferred from the substantial dataset of short term drawdown. They have been attempted to be used as a base information for heterogeneity map. Due to the constraints and/or key points, expected heterogeneity map demonstrated as an anisotropy map of the medium deducted from connectivity information. Second approach of heterogeneity investigation was applied to the unusual trend of the long term data. Potential effect of drilling and developing intense amount of wells in relatively small region was studied on the increasing slope of the late time drawdown dataset. Circular and well-ordered numerous recovery and monitoring wells in the schemes were evaluated as they might change the medium property so that they create barrier effect as large scale heterogeneity.

In terms of methodology for connectivity integration, two main parts were developed. First, Cooper Jacob (1946) solution and its assumptions was considered to determine appropriate point to point connectivity metrics. Secondly, defined point to point connectivity was used by cartographic anamorphosing method to generate spatial delineation of heterogeneity. For this method, a computer code was developed and simulations was utilized to deal with great amount of calculation and possibilities of results. It was concluded that developed method can be used to obtain spatial representation of a medium property. Regarding limitations, representation was achieved as anisotropy of the connectivity. Sensitivity analysis of the method showed that, for this study area, 100 to 150 pairs of drawdown data is optimal. Connectivity

metrics obtained from different time steps might show different properties, however at 600 minutes, representative values can be acquired.

Simulation number for different possibility arrangement of anamorphosing method was decided to be around 50 for most of the cases. According to the results of the determined scenarios, connectivity indicating anisotropy was correlated with the spatial anisotropy of the grain sizes of the lithology. Groups of facies were sampled at each 10 depths and their variogram analyses was realized. Scheme C showed high similarity between anisotropy characteristics of the anamorphosing result (0.84 to 141°) and anisotropy of the facies variogram (0.76 to 133°). Scheme A and Scheme B gave relatively more isotropic results after anamorphosing analysis as ratio of 0.92 for both and directions of 66° and 88°, respectively. 0.75 to 138° for Scheme A and 0.73 to 131° for Scheme B anisotropy characteristics of variogram analysis were found, which are not coincide with anamorphosing method.

Butler (1988) solution approach for long term data of each pumping tests were analyzed and radius of disks were obtained for corresponding pumping wells by AQTESOLV v4.5. Difference between the assumption of aquifer type for solution and study area aquifer type resulted in extreme values for each long term pumping test well. However median values showed reasonable results. Merged disks of boundary for individual schemes showed overestimated heterogeneity regions. Therefore, depictive mean values of disks for each schemes were used for investigation. Circular configuration of wells on the schemes could illustrate the validity of this type of heterogeneity. Although there are still noticeable differences in disk radii of schemes, their size trend show similarity with the trend of steepness in the late time drawdown curves. 520 meter for Scheme A, 204 meter for Scheme B and 625 meter for Scheme C are the radii of the disks based on scheme centers. Visual comparisons and trial results of trend steepness showed that Scheme C has the lowest derivative increase and Scheme B has the highest derivative increase.

Accordingly, based on these results, barrier boundary effect can be mentioned. However existence of this barrier zone explained as a consequences of wellbore

drilling and development. Therefore heterogeneity caused from this effect should be considered in terms of modelling.

To conclude, anisotropies obtained from anamorphosing method and heterogeneities investigated by two-zone aquifer system were tested in the artificial recharge case in Liwa aquifer. Anisotropy obtained from connectivity results showed minor changes in the propagation of the injected water plume. Application of the anisotropy to the model were done as most convenient way possible by rotating the grid based on direction of anisotropy and applying the ratio of K_x/K_y. Two zone aquifer case showed highly overestimated barrier effect without having any mounding outside the disk zone. However, its existence as changed material property should be taken into account. Planned amount of water volume that is recharged is suitable for the environment, however it might be underestimated to observe effects of the proposed techniques.

6.2 Recommendation

Expected spatial heterogeneity mapping of developed methodology was resulted in anisotropy features due to the consideration of the 1st order rectification, basically. 2nd and 3rd order rectification trials have showed uncommon and insignificant results for now, therefore they have not been presented. Reason for that can be explained by having restriction errors that were not studied in the scope. Detailed study on better coordinate computation might be carried out in further development.

Geological features in the study area contains units that have relatively high homogeneity. It was considered to be an applicable case for studying this kind of high sensitive heterogeneity modelling methods. Due to this high homogeneity that study area contains, it might have showed unstable results in Scheme A and Scheme B. Also high amount of pairs were necessary in anamorphosing. Method should be studied in other types of media.

After the application of Butler solution, it has been observed that hydraulic properties obtained for outside the disk region from this solution show high similarity with

conventional methods (Cooper Jacob, Neuman etc.) applied. Properties obtained for inside the disk region could be underestimated, yet matching of the late time cannot be ignored. Hydraulic properties obtained from the wells that are located outside the scheme can be used to compare the disk formation in further investigation.

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APPENDICES

Appendix A. Short Term Well Pairs and Drawdown Data

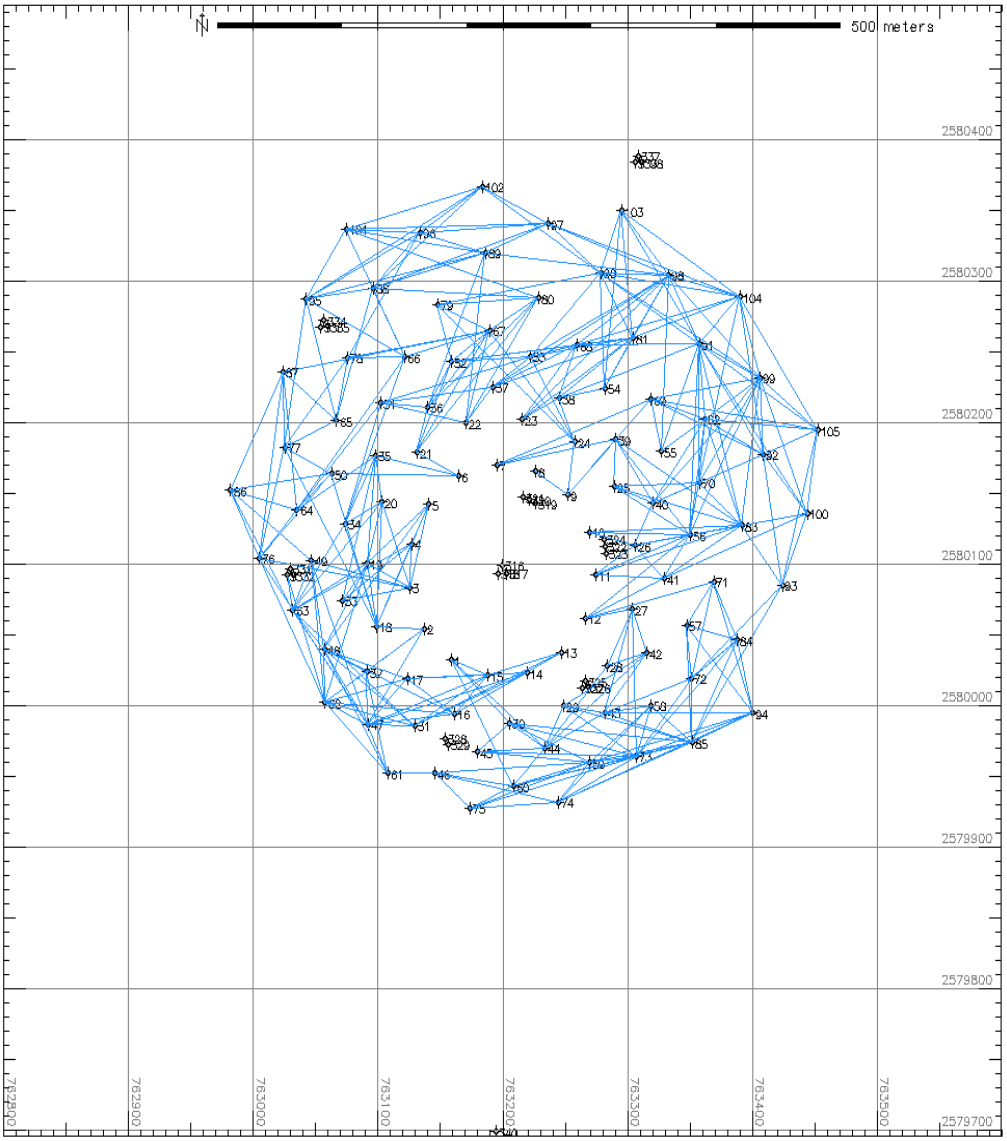


Figure A. 1. All the pairs and true radii for the scheme A at 600 minutes

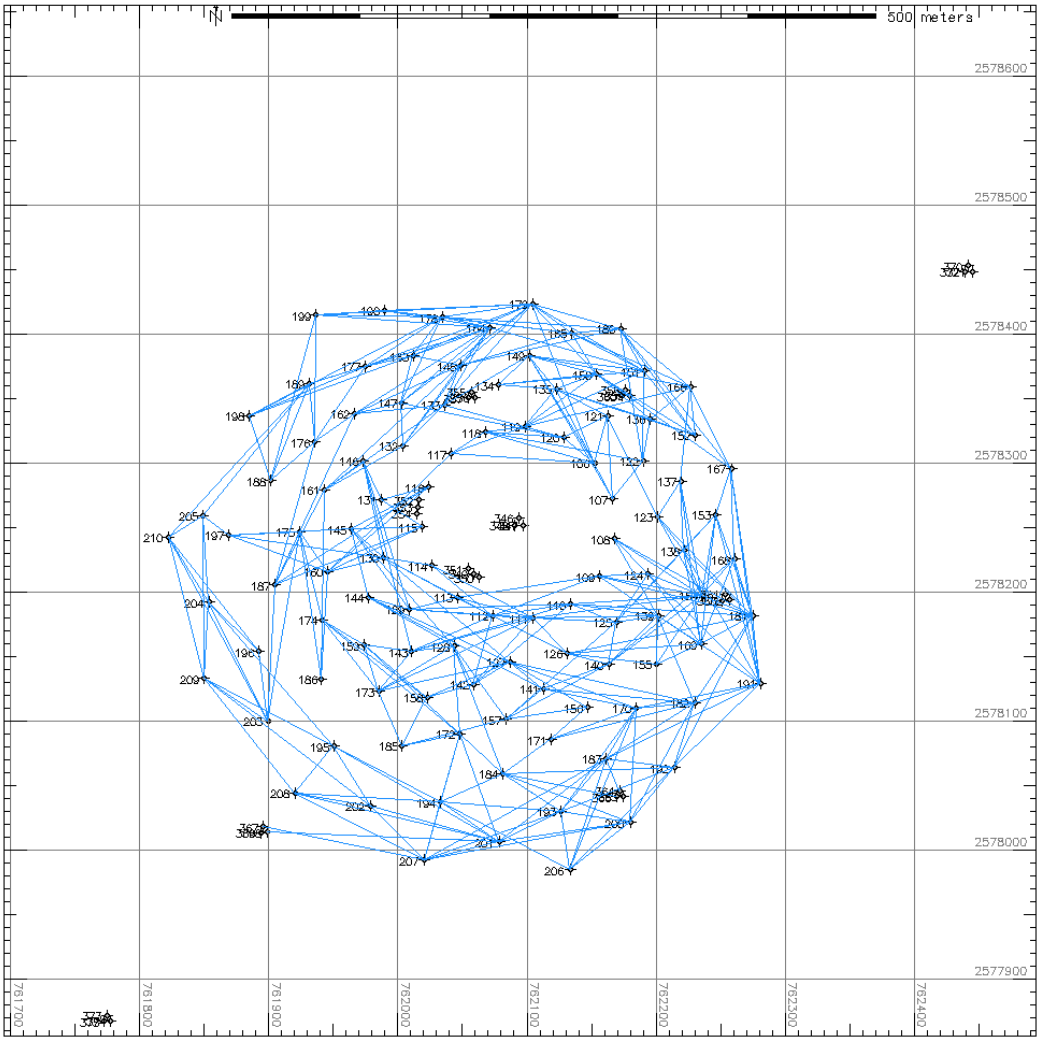


Figure A. 2. All the pairs and true radii for the scheme B at 600 minutes

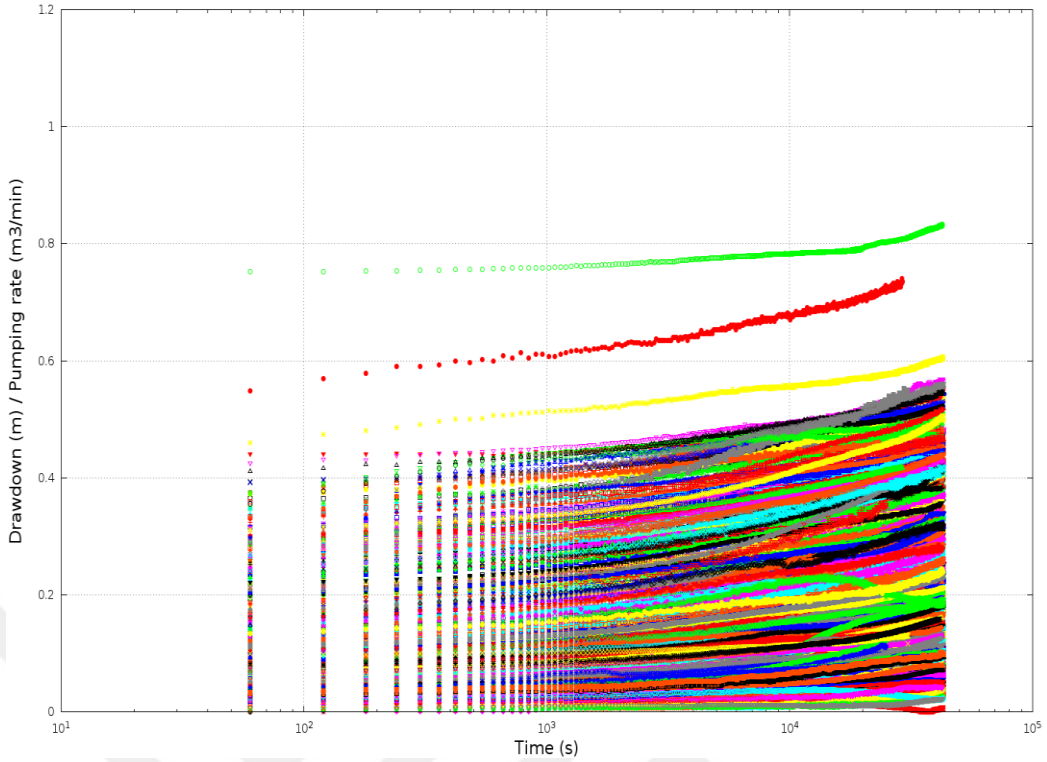


Figure A. 3. Short term data of Scheme A used for the analyses

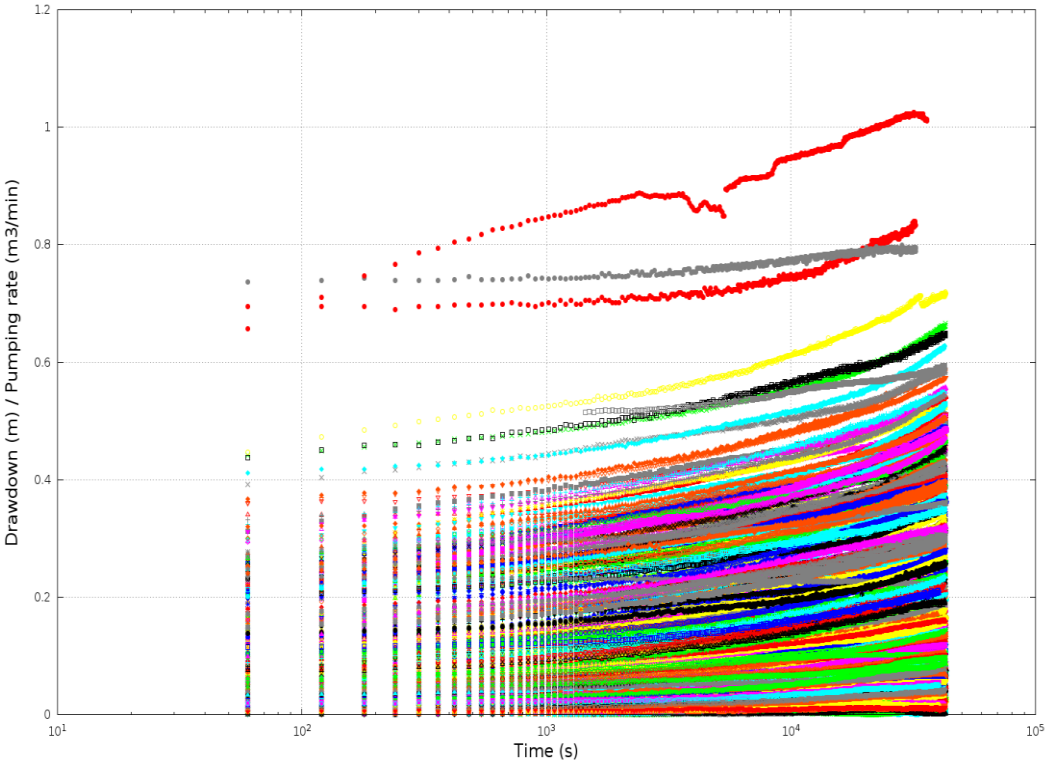
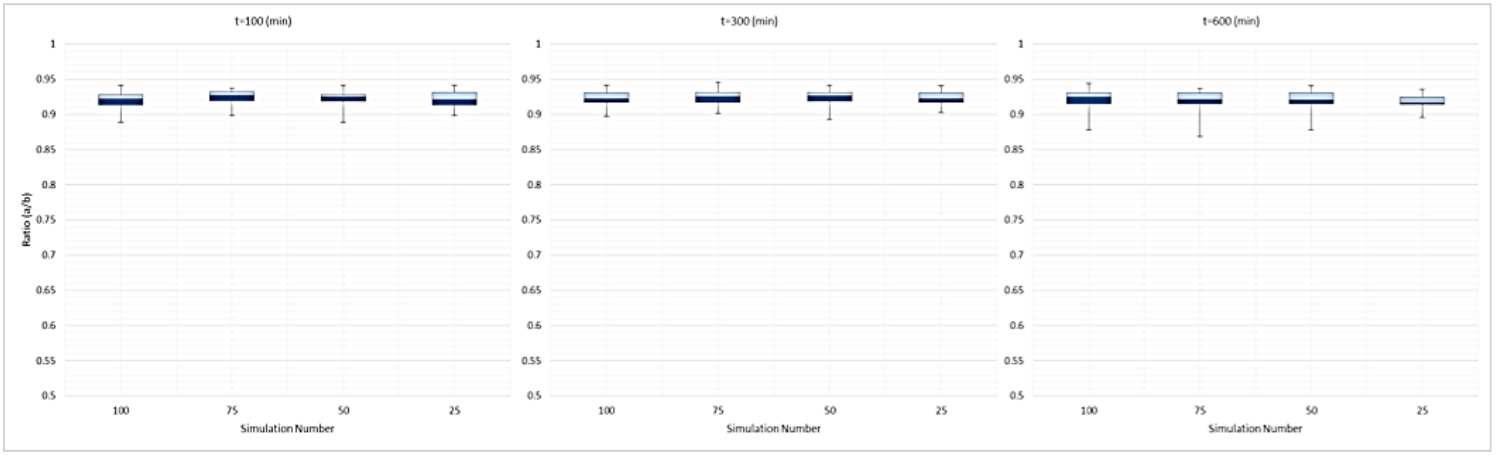


Figure A. 4. Short term data of Scheme B used for the analyses

Appendix B. Boxplots of Anamorphosing Scenarios



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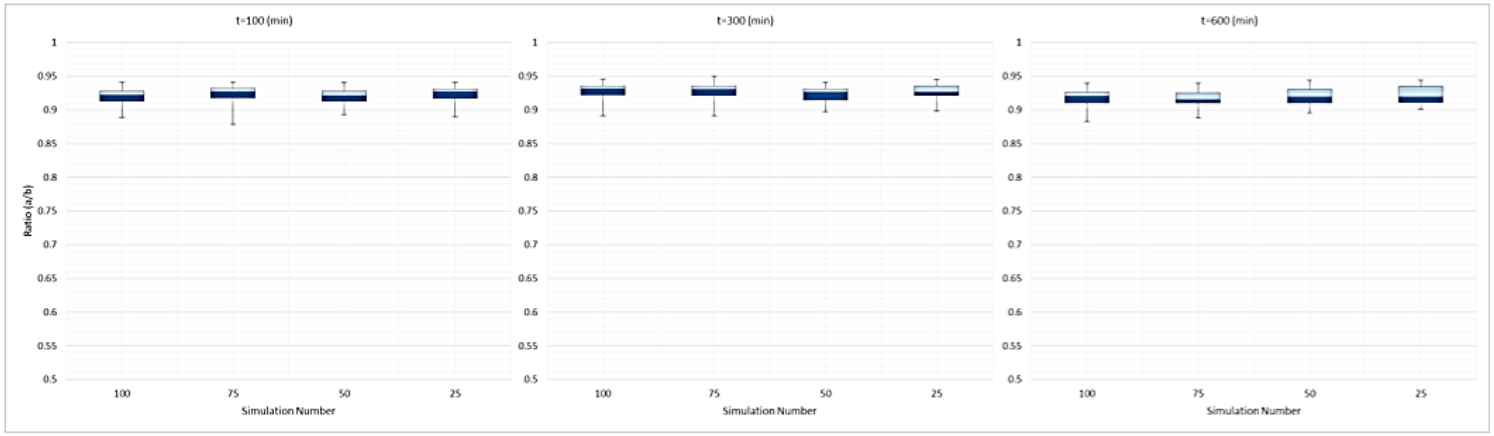
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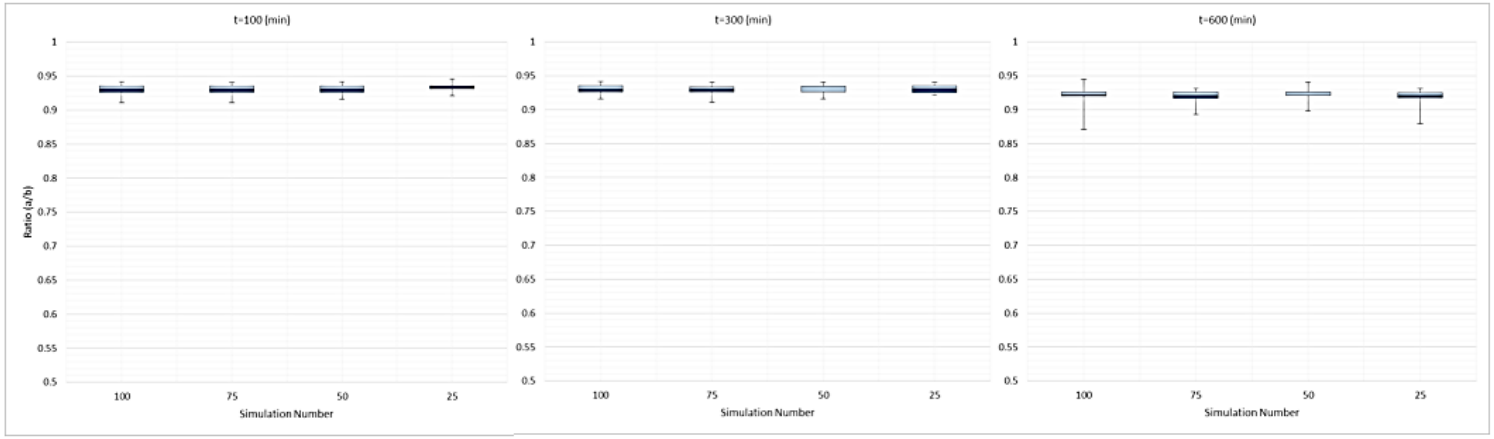
b)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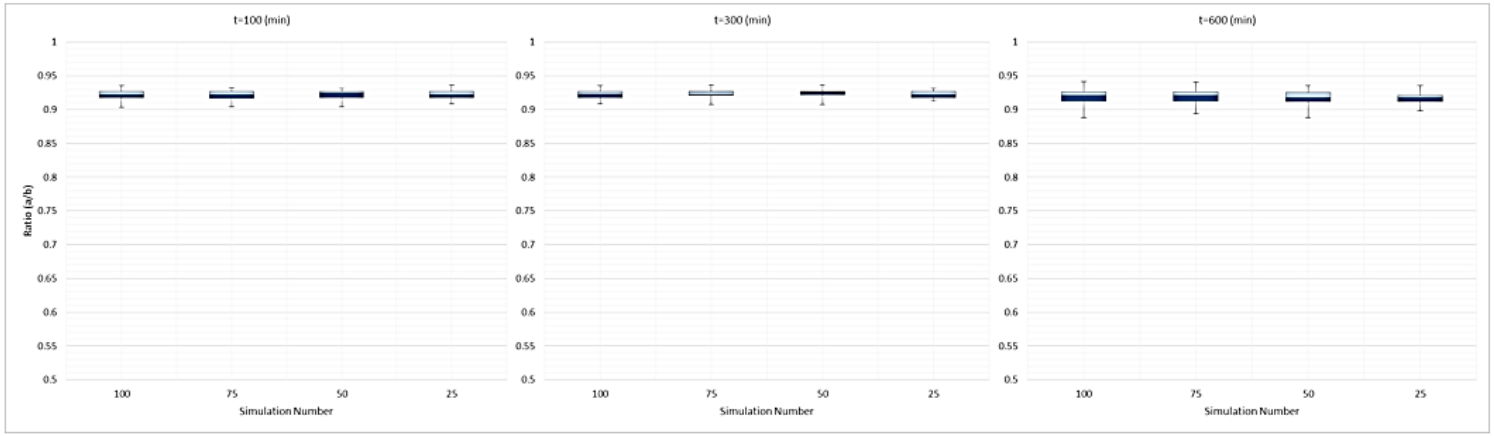
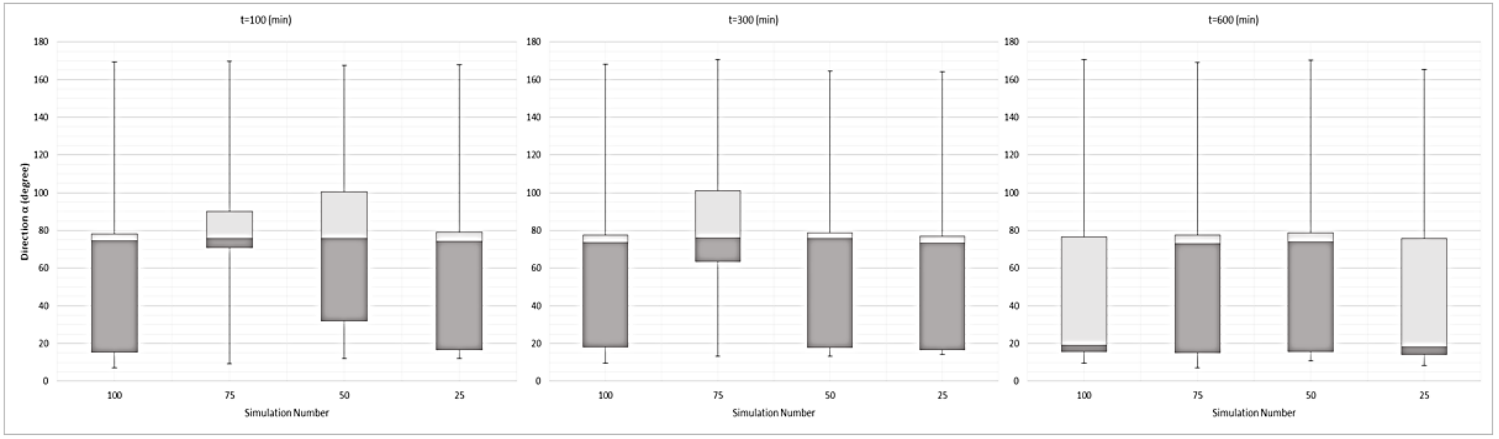


d)

Figure B. 1. Boxplot of anisotropy ratios simulated from scheme A. Case A (a), Case B (b), Case C (c) and Case D (d) with corresponding scenarios of simulation number and time step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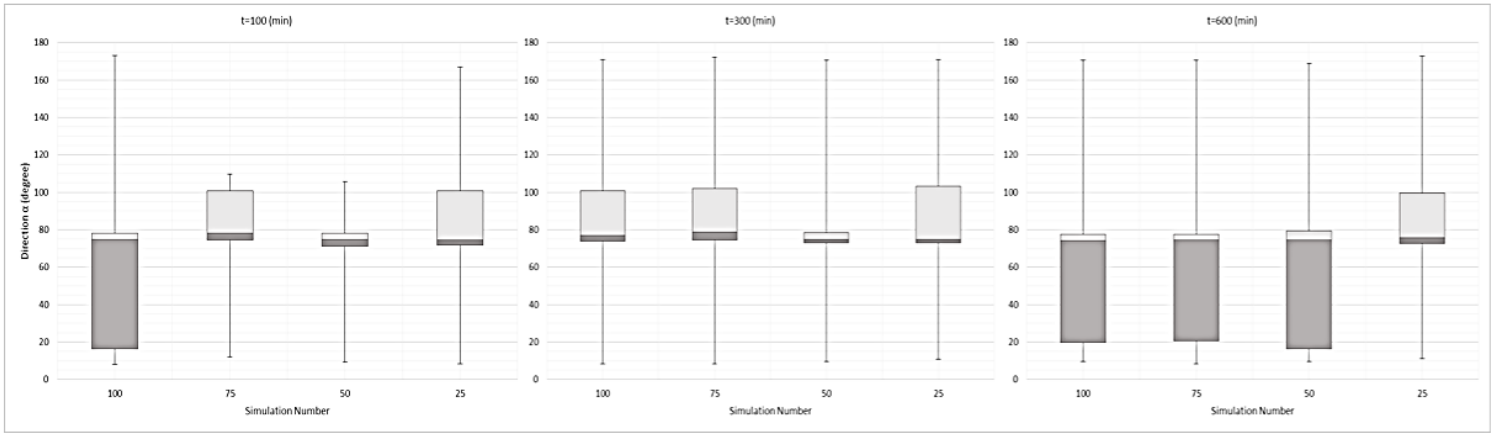
80
100
120
140
160
180
100
75
50
25
Simulation Number

a)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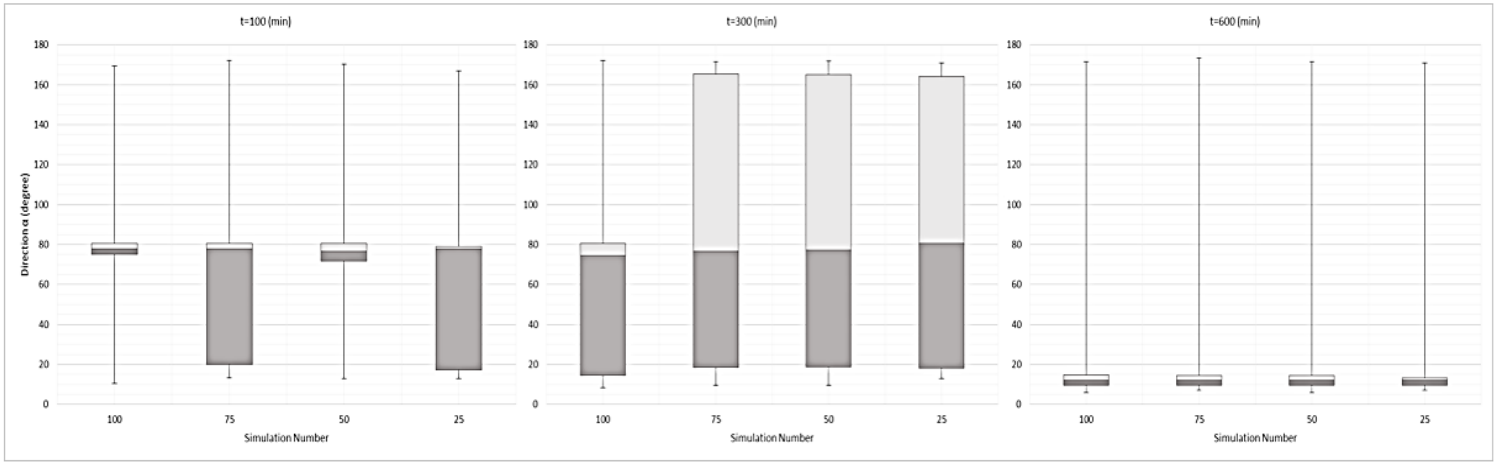
75
50
25
Simulation Number

b)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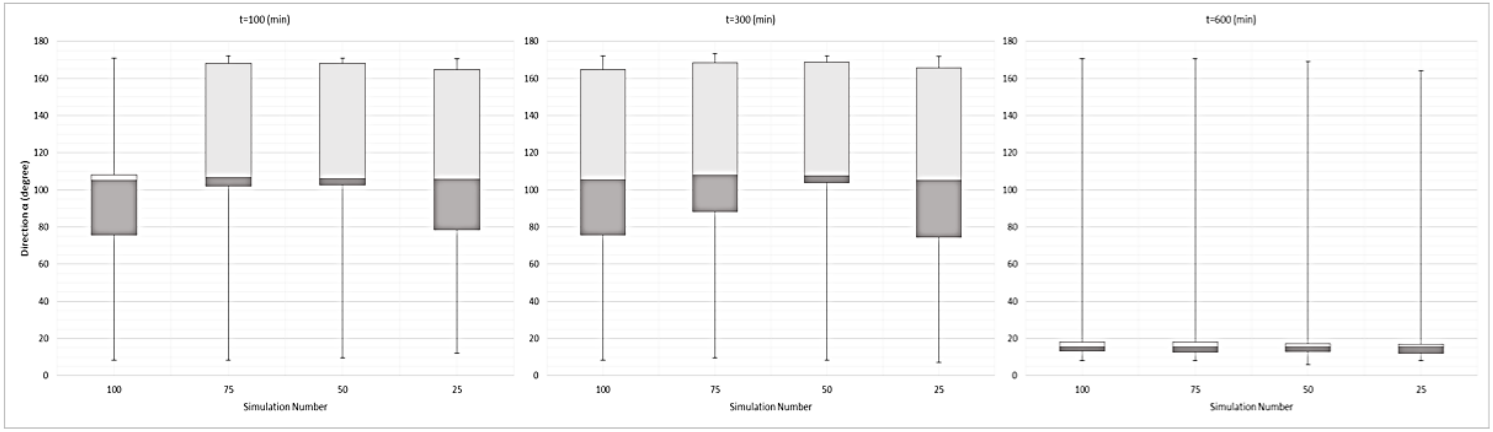
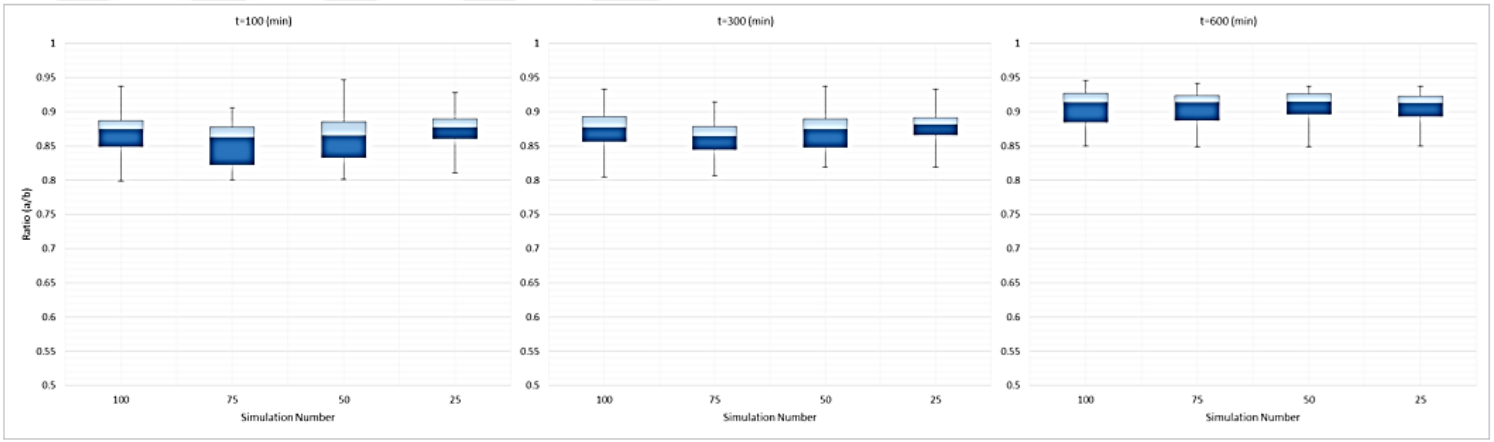
Simulation Number

c)



d)

Figure B. 2. Boxplot of direction angles simulated from scheme A. Case A (a), Case B (b), Case C (c) and Case D (d) with corresponding scenarios of simulation number and time step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Ratio (a/b)
Simulation Number
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75
50
25

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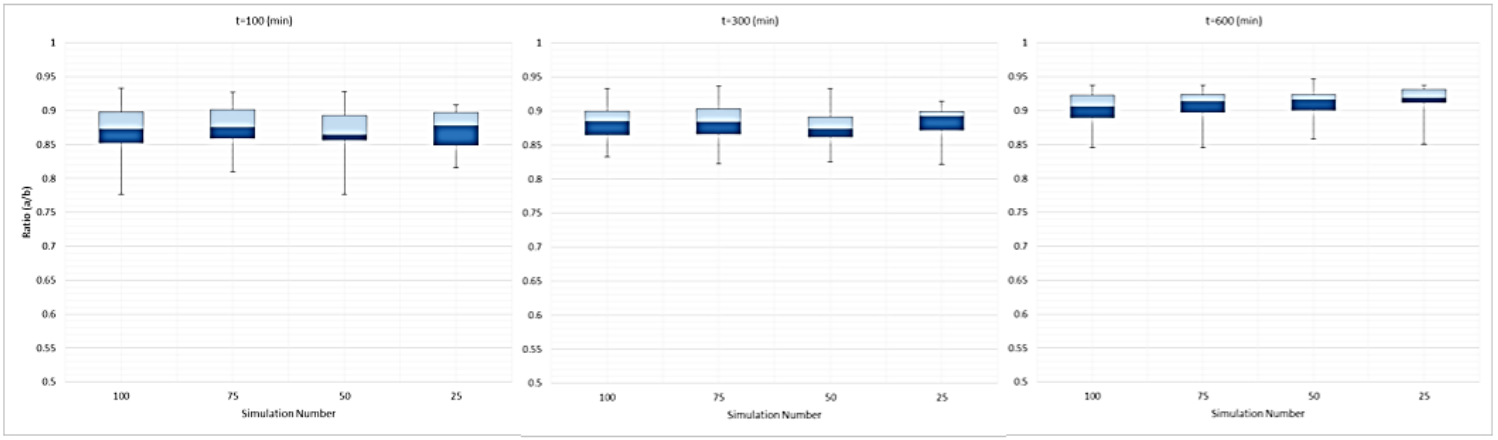
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Ratio (a/b)
Simulation Number
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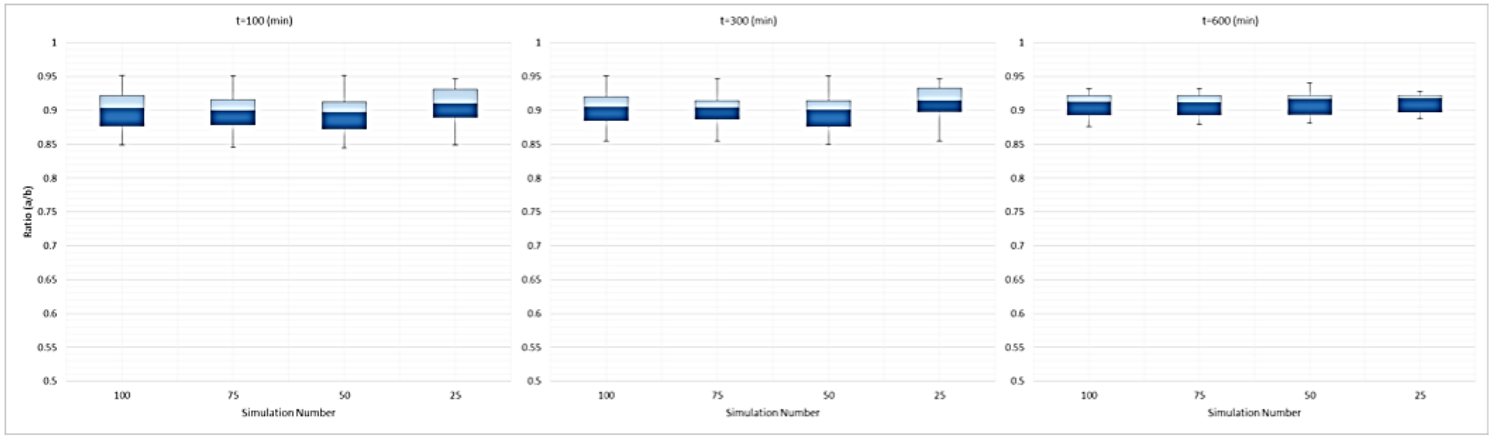
75
50
25

b)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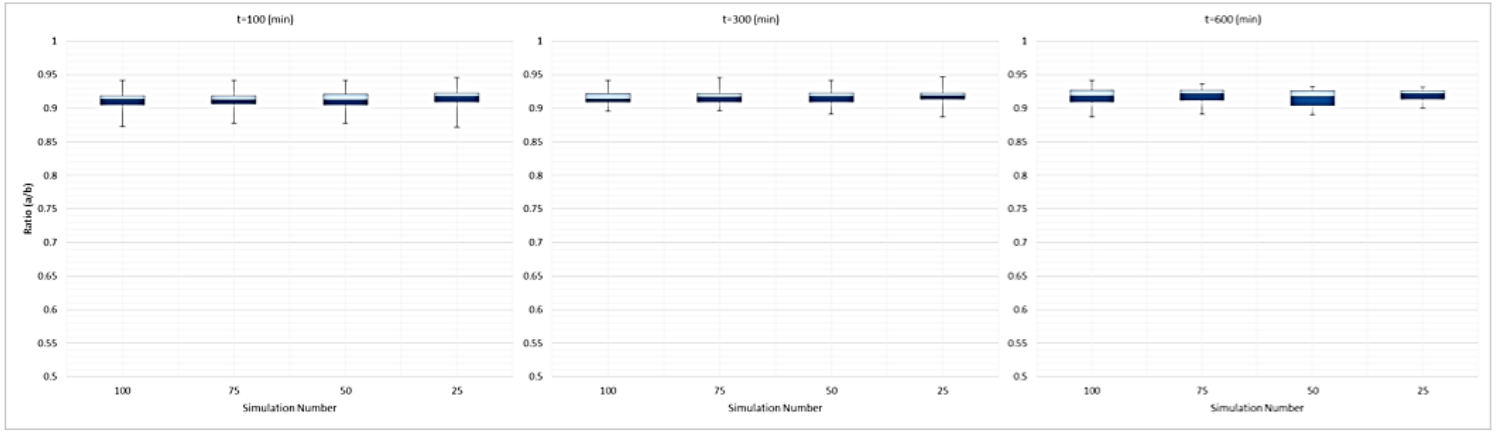
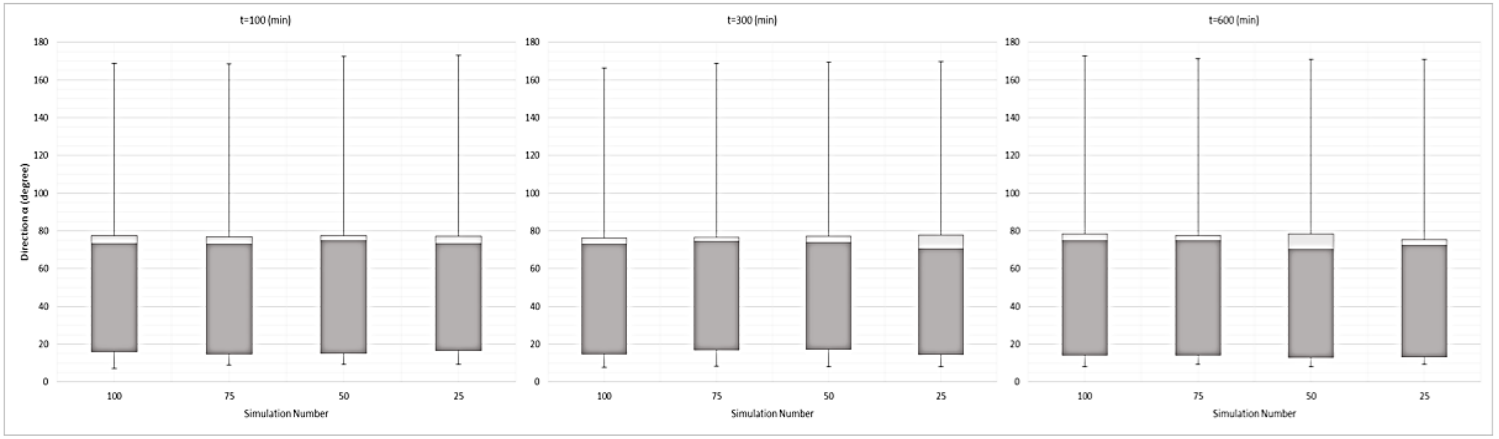
100
75
50
25
Simulation Number

c)



d)

Figure B. 3. Boxplot of anisotropy ratios simulated from scheme B. Case A (a), Case B (b), Case C (c) and Case D (d) with corresponding scenarios of simulation number and time step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100
75
50
25
Simulation Number

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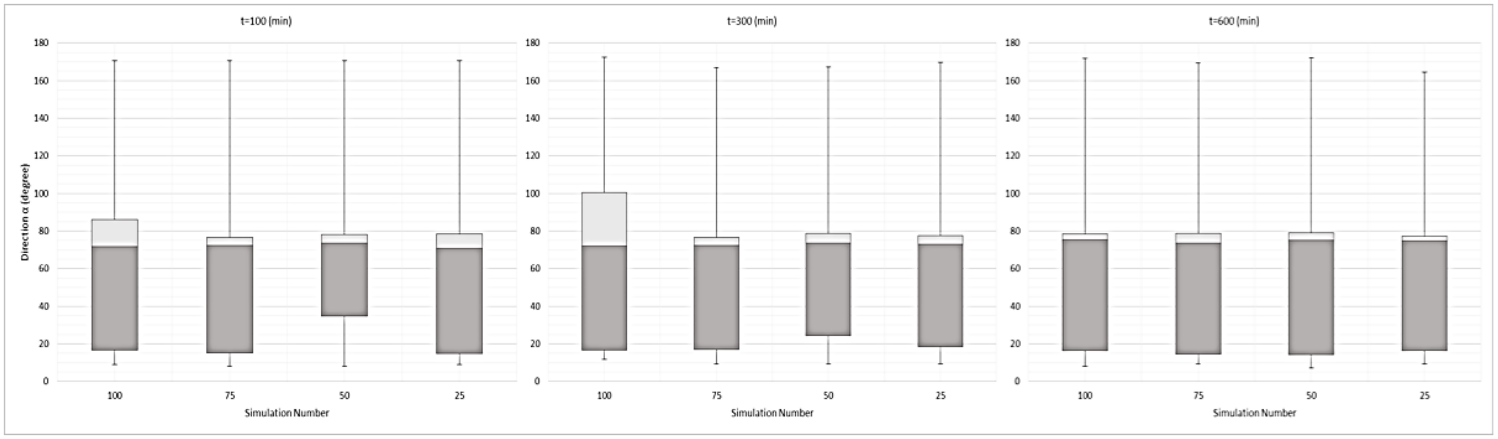
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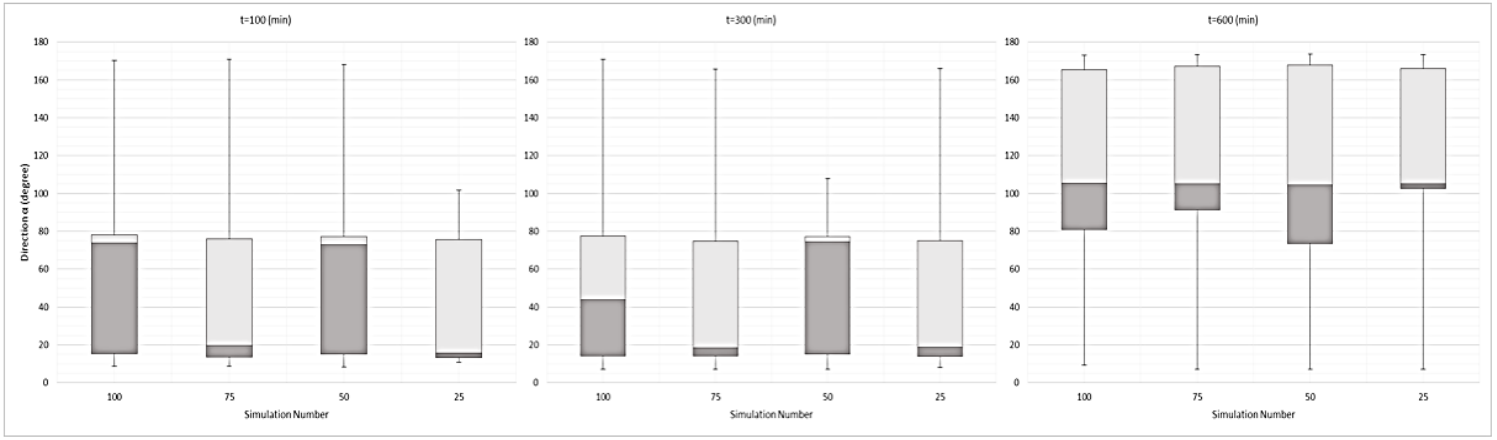
Simulation Number

b)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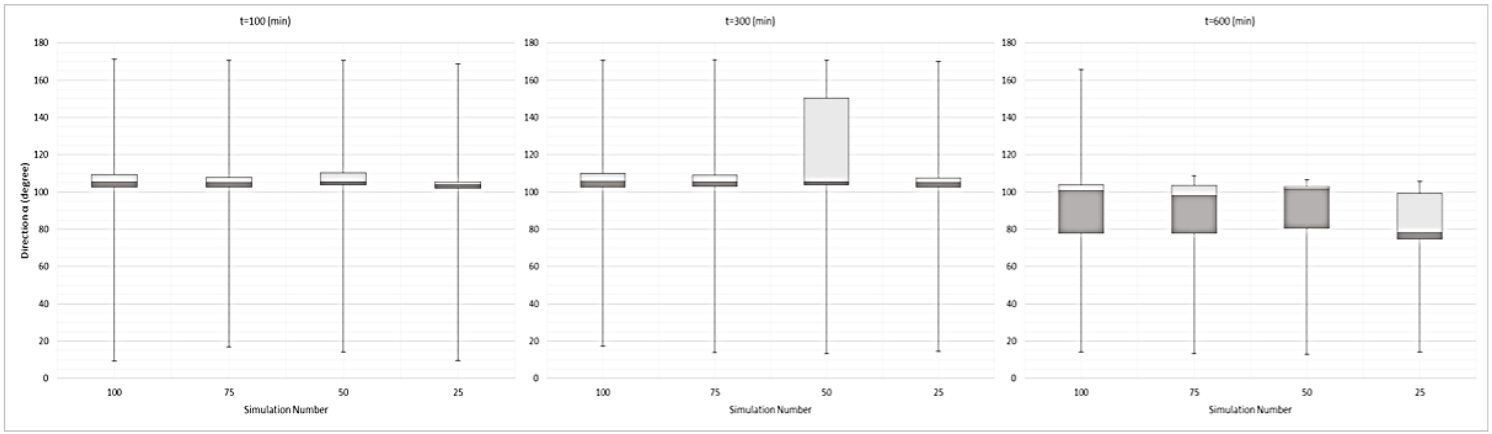
25
Simulation Number

c)



d)

Figure B. 4. Boxplot of direction angles simulated from scheme B. Case A (a), Case B (b), Case C (c) and Case D (d) with corresponding scenarios of simulation number and time step

Appendix C. Long Term Drawdowns and Butler Results

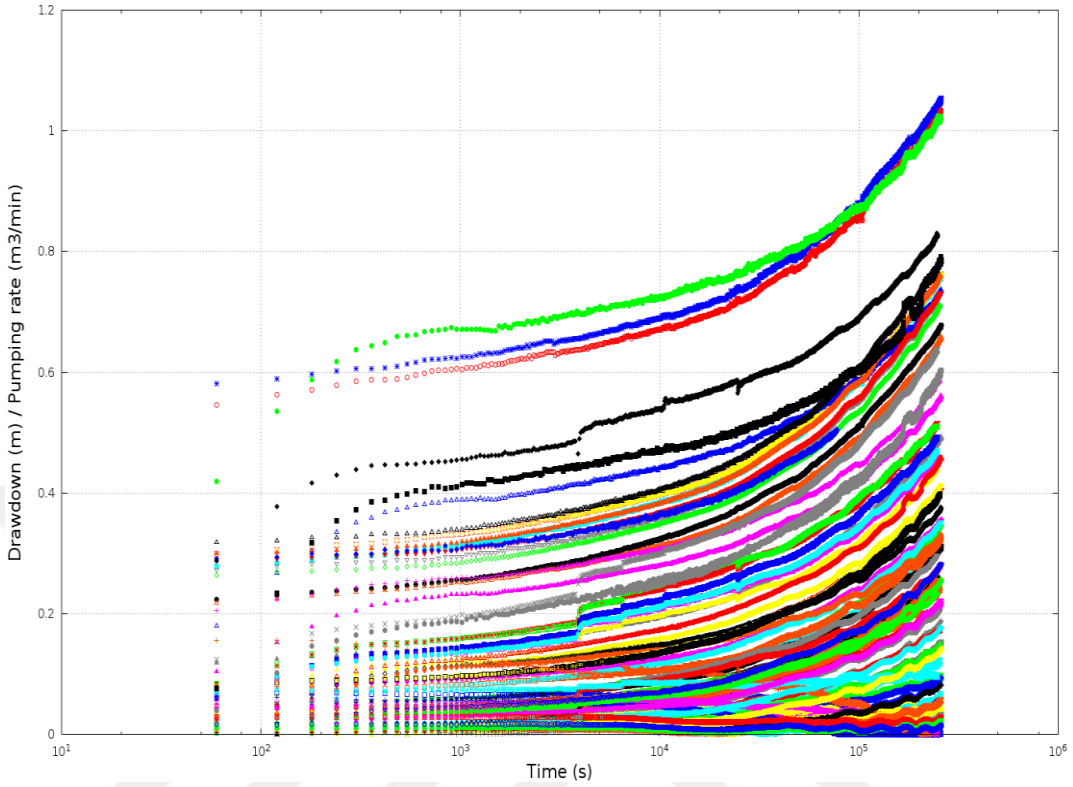


Figure C. 1. Long term data of Scheme A used for the Butler analyses

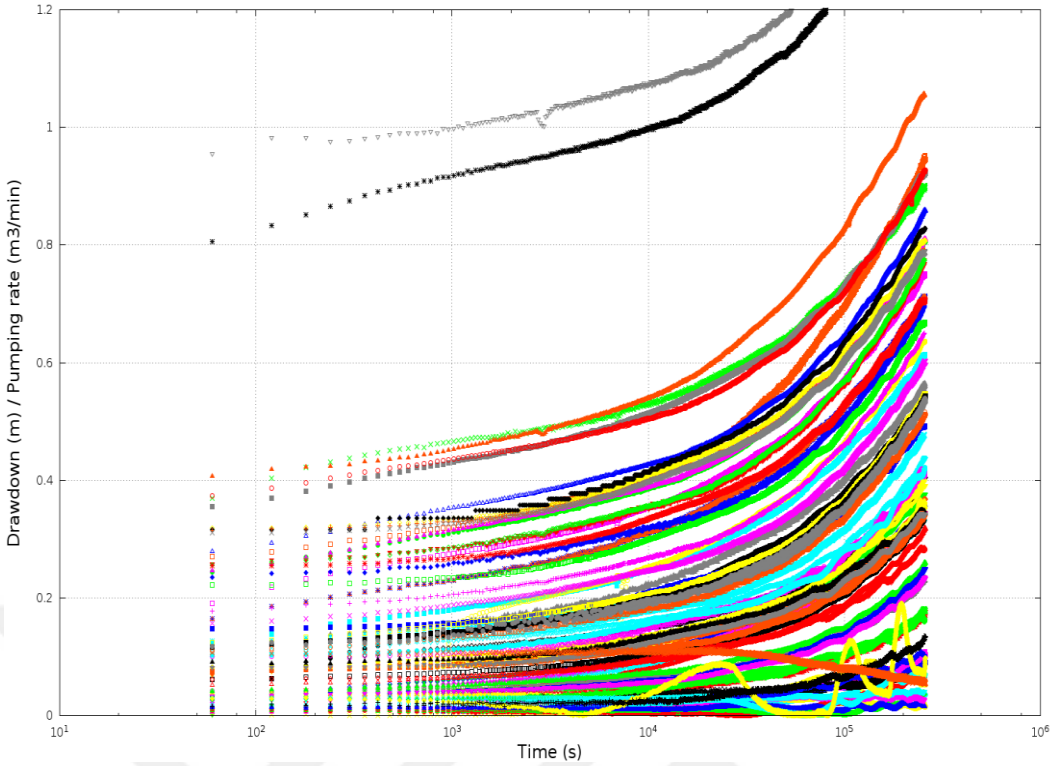


Figure C. 2. Long term data of Scheme B used for the Butler analyses

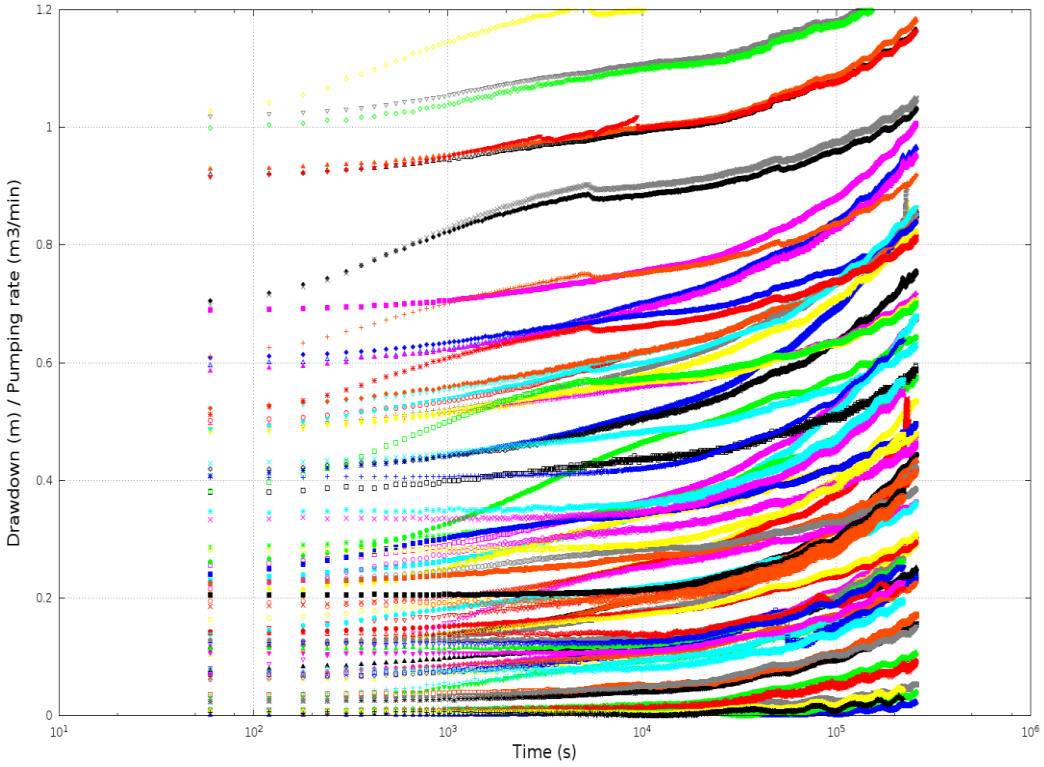


Figure C. 3. Long term data of Scheme C used for the Butler analyses

Table C.1. Butler results for Scheme A

Pumping Wells in SCHEME A		Observation Well	***320***	***319***	***7***	***9***	***23***	***24***	***38***	***22***	***317***	***322***	***54***	***323***	***81***
	8	T1 (m^2/sec)	0.030	0.051	0.072	0.059	0.055	0.062	0.101	0.171	0.154	0.272	0.278	0.130	0.900
		S1	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.002	0.007	0.003	0.002	0.083	0.024
		T2 (m^2/sec)	0.028	0.001	0.001	0.001	0.001	0.004	0.001	0.000	0.001	0.000	0.000	0.023	0.004
		S2	0.000	0.100	0.049	0.020	0.039	0.002	0.078	0.100	0.173	1.000	0.429	0.002	0.050
		R (m)	4504	335	590	601	552	1027	521	617	396	546	699	188	430
		Observation Well	***42***	***43***	***27***	***11***	***14***	***44***	***10***						
	28	T1 (m^2/sec)	0.036	0.054	0.135	0.115	0.098	0.079	0.351						
		S1	0.005	0.011	0.043	0.006	0.041	0.319	0.119						
		T2 (m^2/sec)	0.000	0.005	0.001	0.001	0.000	0.007	0.003						
		S2	1.000	0.010	0.514	0.100	1.000	0.200	1.000						
		R (m)	668	416	170	449	212	103	117						
		Observation Well	***19***	***18***	***49***	***48***	***63***	***332***	***331***	***2***	***64***	***1***	***77***	***15***	
	33	T1 (m^2/sec)	0.038	0.043	0.053	0.052	0.058	0.061	0.073	0.154	0.145	0.412	0.408	1.000	
		S1	0.007	0.004	0.001	0.001	0.000	0.000	0.000	0.003	0.005	0.009	0.015	0.020	
		T2 (m^2/sec)	0.008	0.005	0.003	0.003	0.002	0.002	0.000	0.000	0.000	0.000	0.022	0.000	
		S2	0.002	0.003	0.003	0.002	0.002	0.001	0.009	1.000	0.709	1.000	0.001	0.994	
		R (m)	436	532	934	1074	1478	2923	3239	563	461	427	501	430	
		Observation Well	***335***	***334***	***51***	***65***	***66***	***95***	***87***	***88***					
	78	T1 (m^2/sec)	0.027	0.037	0.047	0.046	0.052	0.056	0.055	0.060					
		S1	0.011	0.196	0.196	0.196	0.196	0.196	0.196	0.196					
		T2 (m^2/sec)	0.013	0.007	0.007	0.007	0.007	0.007	0.007	0.007					
		S2	0.000	0.096	0.106	0.106	0.106	0.106	0.106	0.106					
		R (m)	533	79	95	95	95	105	101	106					

Table C.1.(Cont'd)

Pumping Wells in SCHEME A		Observation Well	***338***	***90***	***97***	***80***	***81***	***68***	***89***						
	103	T1 (m^2/sec)	0.036	0.099	0.151	0.425	0.414	0.517	0.743						
		S1	0.002	0.000	0.000	0.001	0.001	0.004	0.011						
		T2 (m^2/sec)	0.000	0.000	0.000	0.000	0.000	0.000	0.000						
		S2	0.093	0.767	0.866	0.986	1.000	0.829	1.000						
		R (m)	1514	529	557	1073	1030	696	483						

Table C.2. Butler results for Scheme B

Pumping Wells in SCHEME B		Observation Well	***353***	***145***	***146***	***115***	***116***	***130***	***132***	***161***				
	131	T1 (m^2/sec)	0.032	0.057	0.050	0.080	0.069	0.069	0.052	0.082				
		S1	0.000	0.005	0.003	0.003	0.025	0.083	0.011	0.009				
		T2 (m^2/sec)	0.001	0.000	0.001	0.001	0.001	0.001	0.000	0.000				
		S2	0.192	0.453	0.328	1.000	0.894	1.000	0.587	1.000				
		R (m)	170	226	150	111	79	91	175	182				
		Observation Well	***359***	***360***	***358***	***121***	***122***	***152***	***151***	***166***	***167***	***180***	***135***	***346***
	136	T1 (m^2/sec)	0.020	0.058	0.042	0.045	0.069	0.062	0.073	0.155	0.112	0.106	0.357	0.430
		S1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.108	0.001	0.000
		T2 (m^2/sec)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.001	0.000
		S2	0.043	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.019	0.019	0.019
		R (m)	670	464	711	748	1377	2076	2440	3770	565	168	1451	3465
		Observation Well	***361***	***362***	***138***	***168***	***181***	***124***	***153***	***123***	***108***	***191***	***110***	
		T1 (m^2/sec)	0.048	0.028	0.080	0.075	0.064	0.059	0.077	0.088	0.118	0.116	0.215	
		S1	0.000	0.000	0.000	0.000	0.000	0.011	0.075	0.375	0.314	0.148	0.154	
		T2 (m^2/sec)	0.003	0.001	0.000	0.003	0.004	0.007	0.007	0.005	0.001	0.000	0.001	
		S2	0.000	0.000	0.000	0.000	0.000	0.002	0.010	0.083	1.000	1.000	1.000	
		R (m)	9050	20460	16010	11750	1752	362	177	85	96	146	161	

Table C.2.(Cont'd)

Pumping Wells in SCHEME B		Observation Well	***141***	***140***	***170***	***171***	***183***	***126***	***157***	***127***	***192***	***193***	***200***	
	156	T1 (m^2/sec)	0.061	0.048	0.052	0.054	0.069	0.071	0.073	0.077	0.095	0.100	0.124	
		S1	0.000	0.000	0.000	0.000	0.000	0.000	0.021	0.208	0.179	0.235	0.324	
		T2 (m^2/sec)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.004	0.002	0.002	
		S2	0.075	0.062	0.042	0.030	0.016	0.564	0.682	0.051	0.200	0.721	0.900	
		R (m)	898	1090	1477	1865	2604	1392	283	124	119	109	103	
		Observation Well	***209***	***187***	***186***	***204***	***203***	***174***	***159***	***195***	***144***	***173***		
	196	T1 (m^2/sec)	0.072	0.070	0.065	0.063	0.069	0.065	0.135	0.172	0.214	0.222		
		S1	0.005	0.050	0.067	0.138	0.132	0.129	0.257	0.323	0.326	0.343		
		T2 (m^2/sec)	0.000	0.003	0.002	0.004	0.006	0.004	0.001	0.001	0.001	0.001		
		S2	0.334	0.062	0.130	0.077	0.026	0.059	0.900	0.900	0.900	0.900		
		R (m)	475	176	156	112	124	120	113	115	112	114		

Table C.3. Butler results for Scheme C

Pumping Wells in SCHEME C		Observation Well	***215***	***213***	***230***	***229***	***244***	***245***	***243***	***376***	***377***	***274***	***392***	***296***	***297***
	214	T1 (m^2/sec)	0.039	0.039	0.056	0.070	0.081	0.091	0.089	0.083	0.075	0.236	0.206	0.718	0.553
		S1	0.000	0.000	0.000	0.000	0.001	0.006	0.007	0.033	0.016	0.001	0.000	0.000	0.000
		T2 (m^2/sec)	0.001	0.001	0.000	0.000	0.000	0.001	0.001	0.002	0.001	0.000	0.000	0.000	0.000
		S2	0.075	0.079	0.236	0.037	0.439	0.126	0.183	0.100	0.045	0.282	0.282	0.282	0.282
		R (m)	482	502	1051	1019	598	384	385	256	525	621	1415	3353	6368
		Observation Well	***383***	***384***	***382***	***250***	***221***	***220***	***235***	***237***	***266***	***219***	***280***		
	236	T1 (m^2/sec)	0.030	0.027	0.026	0.023	0.030	0.032	0.036	0.030	0.031	0.056	0.053		
		S1	0.001	0.059	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.023	0.001		
		T2 (m^2/sec)	0.000	0.022	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000		
		S2	0.120	0.000	0.046	0.049	0.062	0.077	0.100	0.116	0.256	1.000	0.252		
		R (m)	783	440	589	574	905	719	1744	2776	1952	286	1560		

Table C.3.(Cont.)

Pumping Wells in SCHEME C		Observation Well	***215***	***213***	***230***	***229***	***244***	***245***	***243***	***376***	***377***	***274***	***392***	***296***	***297***
	253	T1 (m^2/sec)	0.040	0.017	0.018	0.015	0.017	0.015	0.027	0.033	0.039	0.032	0.042	0.075	0.077
		S1	0.038	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		T2 (m^2/sec)	0.001	0.002	0.001	0.002	0.001	0.003	0.001	0.001	0.001	0.001	0.001	0.000	0.000
		S2	0.389	0.100	0.105	0.100	0.246	0.100	0.110	0.110	0.141	0.122	0.431	0.398	0.434
		R (m)	457	508	623	503	485	441	603	606	653	627	505	667	1669
		Observation Well	***390***	***255***	***270***	***227***	***211***	***242***	***212***	***258***	***213***	***273***			
	256	T1 (m^2/sec)	0.023	0.020	1.000	0.051	0.056	0.078	0.098	0.135	0.182	0.611			
		S1	1.000	0.001	0.001	0.001	0.001	0.004	0.008	0.135	0.003	0.001			
		T2 (m^2/sec)	0.040	0.001	0.036	0.002	0.001	0.001	0.002	0.003	0.009	0.011			
		S2	0.606	0.228	0.000	0.218	0.349	0.190	0.315	0.649	0.330	0.302			
		R (m)	1	694	0	388	457	758	325	237	155	178			
	277	Observation Well	***262***	***289***	***290***	***299***	***233***	***278***	***217***	***298***	***312***	***291***			
		T1 (m^2/sec)	0.038	0.046	0.044	0.056	0.077	0.084	0.141	0.137	0.157	0.218			
		S1	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005			
		T2 (m^2/sec)	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001			
		S2	0.150	0.151	0.132	0.019	0.026	0.028	0.040	0.048	0.053	0.056			
		R (m)	808	815	836	839	917	884	931	932	1003	1014			

Appendix D. Sample Comparison of Curve Matching

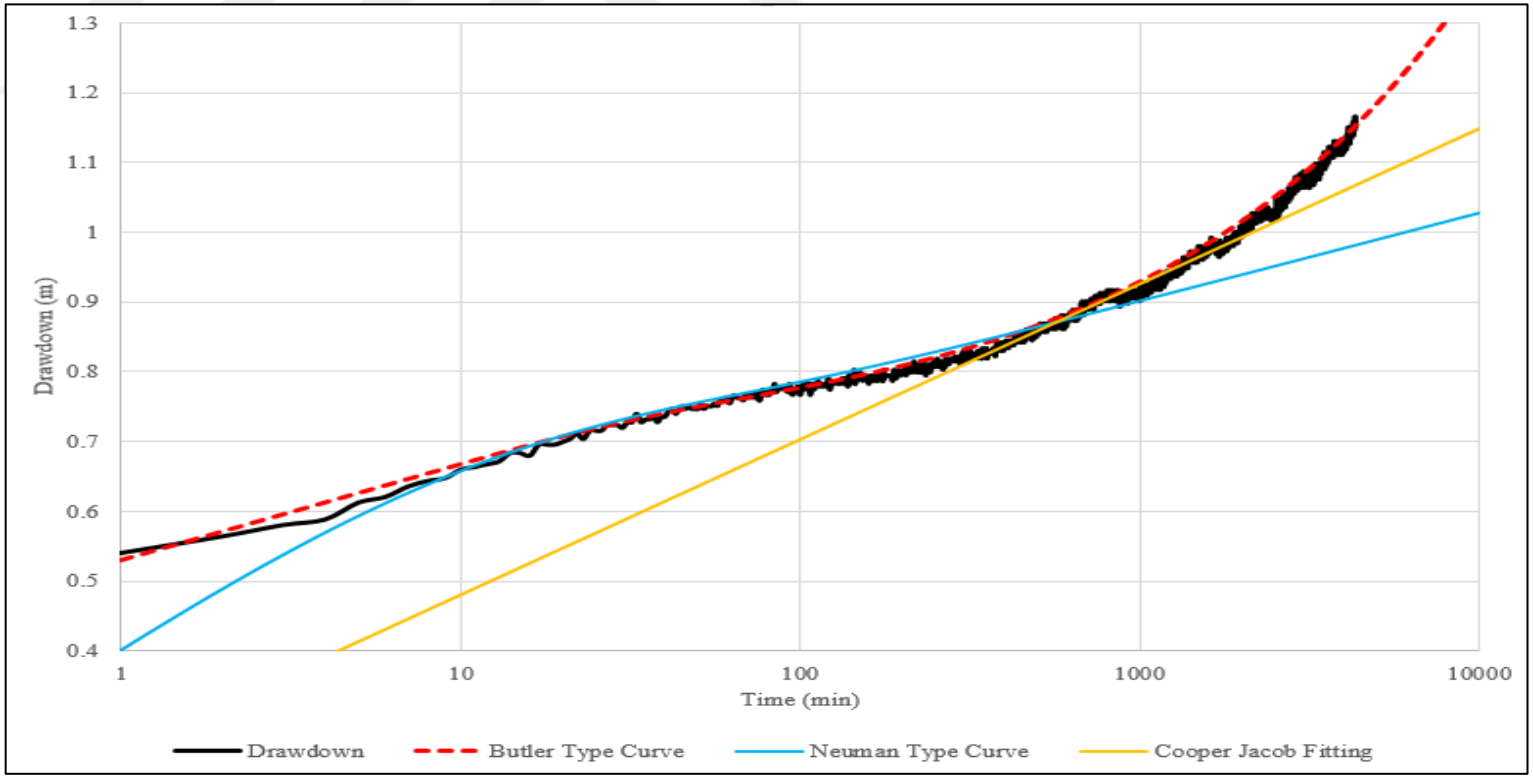


Figure D. 1. Match comparison for observation well 211 (81.1 m) of pumping well 256 in Scheme C

CURRICULUM VITAE

Personal Information

Engin Günay

engin.egunay@gmail.com

+90 506 298 93 88

Work Experience

10/2016–01/2017 Hydrogeologist

AECOM, Ankara (Turkey) / Dewatering Studies of Gökırmak Copper Mine (Consultancy for groundwater well install, sampling and monitoring of surface water and groundwater, carrying pumping tests and their analyses out)

02/2016–09/2016 Hydrogeology Internship

IC2MP-Poitiers (France) / Script development about well pair connectivity for anisotropy evaluation (Heterogeneity Investigation of Liwa Aquifer, UAE)

09/2014–08/2015 Junior Geologist

Zetas Zemin Teknolojileri A.S, Istanbul (Turkey) / Pumping Test Evaluation (Strategic Water Storage / Recovery Project in Liwa, UAE)

07/2014–08/2014 Geology Internship

Ekoflytech Ltd. Sti., Ankara (Turkey) / Experience about Hydrogeology and Remote Sensing

08/2012–08/2012 Geology Internship

TPIC - Turkish Petroleum International Company, Ankara (Turkey) / Experience about fieldwork (field mapping and exploration)

Education and Training

09/2015–04/2017 Geological Engineering (Turkey) & Hydrogeology and Associated Transfers (France)

Muğla Sıtkı Kocman University, Mugla (Turkey) & Universite de Poitiers, Poitiers (France) / Joint MSc. Thesis is about investigating the connectivity and heterogeneity using the multiple pumping test data in an arid region aquifer (United Arab Emirates).

09/2009–06/2015 Geological Engineering

Middle East Technical University, Ankara (Turkey) / Graduation Project: Remediation System Design for Groundwater Contamination in Gömec. CGPA: 2.79

02/2014–07/2014 Earth Sciences (Erasmus Program)

Utrecht University, Utrecht (Netherlands) / Certificate of "Learning ArcGIS desktop (for ArcGIS 10)" and "Learning ArcGIS Spatial Analyst"

09/2004–06/2009 Highschool Graduation

Cagrıbey Anatolian Highschool, Ankara (Turkey)

Personal Skills

Mother tongue: Turkish

Other language(s): English / Middle East Technical University, Certificate of English Proficiency Exam and Toefl score of 87.

Computer skills: Autodesk AutoCad, MicroImages (TntMips), Rockworks, ArcGIS 10.1, AquiferWin32, AQTESOLV, Surfer 10, Mathcad, JChess, Hydrus-1D, Scilab 5.5.2, SPSS, Mapinfo 11.0, MODFLOW 2.8 (Visual Modflow), Grounwater Vistas (Modflow, Pest, Modpath, MT3D), JChess, Grass 6.4.4 using Linux (Script writing and development for Grass work)

Poster on International Symposium: Kurtulus B., Avsar O., Yaylım T.N., Gunay E., Estimation of Hydraulic Properties of Liwa Aquifer from an Unconfined Pumping Test Data and Evaluation of Data by using Boulton(1963) and Neuman(1975) models, International Symposium on Eastern Mediterranean Geology (ISEGM), Mugla, Turkey, 13-17 October, 2014.