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"Numerical Modeling of Managed Aquifer Recharge (MAR) Systems"

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ABSTRACT

Managed Aquifer Recharge (MAR) involves the deliberate addition of water to an aquifer with the intention of storing and subsequently recovering it. This method serves to replenish depleted groundwater reserves, enhance water quality, and address issues related to overdraft or contamination. MAR employs various techniques, including injection wells, infiltration basins, or spreading grounds, to introduce water into the subsurface, aiming to restore or sustain groundwater levels and enhance overall aquifer sustainability.

This thesis utilized numerical modeling to examine MAR, employing the finite-difference numerical code MODFLOW with the Visual MODFLOW GUI. The study focused on a typical MAR scenario involving an infiltration basin receiving water out of the the irrigation season and a well extracting water during the irrigation season. Simulation results demonstrated that water infiltration led to increased groundwater levels, consequently enhancing groundwater availability during the irrigation season. A sensitivity analysis explored influential factors, such as the size of the infiltration basin, the quantity of infiltrated water, the basin's shape, and its distance from the well. Additionally, a surplus effort was made to investigate the effect of these factors by employing different values of hydraulic conductivity to encompass a broader range of possibilities.

The findings highlighted that the volume of infiltrated water and the relative distance between the well and basin were the most impactful parameters on the production well's performance. Conversely, the shape of the basin had a negligible role in simulation outcomes, and, notably, the basin's area, when applying the same volume of water, exhibits minimal impact on the results. As the area decreases, there is a slight enhancement in the rise of water levels, albeit negligible. This observation still holds significance, as aligning with the importance of maintaining a minimal basin area due to land use considerations. In terms of efficiency, the simulated MAR method demonstrated the highest productivity in low-conductive aquifers.

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A COMALA; desidero esprimere la mia profonda gratitudine a te, La Mia Casa Lontano Da Casa. Nei primi giorni in cui ero una straniera a Torino, mi hai accolto. Più di un luogo, sei diventato il mio rifugio, un luogo in cui mi sentivo al sicuro e veramente a casa. Ti ringrazio con ogni lacrima che una straniera potrebbe versare lontano dal suo paese e dalla sua famiglia. Sei e sarai una parte importante della mia vita che non dimenticherò mai.

To Maman and Baba, my dearest parents,

Azizanam, this thesis is dedicated to you two.

With Eshgh (Love), Ami

1 Introduction

Climate change, fast urbanization, and population growth all contribute to fluctuations in water demand and supply [1]. Climate change is projected to disrupt the balance of water demand and availability, perhaps resulting in reduced water supply and changing water usage patterns. Rapid urbanization causes localized increases in water demand, making it difficult to satisfy the goals for providing safe and inexpensive water supply, particularly in dry regions. Population growth and urbanization patterns are also major drivers of rising water demand, while climate change is expected to reduce water supplies. These variables together contribute to water scarcity, where demand exceeds availability, providing challenges for sustainable water security and necessitating the development of alternate water sources [2]–[6]. Arid and semi-arid areas, for instance, are facing water depletion from surface water along with overexploitation of groundwater from increased abstraction [7], [8]. The practice of storing water in surface reservoirs is widespread, but it comes with several disadvantages, including the fact that there is high evaporation loss, the requirement for extended land areas, the accumulation of sediment, the possibility of structural failure, and the vulnerability to contamination [9], [10]. The dependence of communities on groundwater might vary seasonally or episodically. Groundwater is an important resource for human populations, especially during times of water scarcity. In certain areas, communities may rely on groundwater only during dry seasons or droughts, when surface water sources are limited. Furthermore, groundwater dependence might be episodic, resulting from specific events or situations, such as extended droughts or the depletion of surface water sources [11]. This unpredictability in dependence emphasizes the significance of sustainable groundwater management in ensuring human community resilience, particularly during periods of limited water availability [12]. Thus, during seasons of low demand or abundant availability, additional water can be preserved underground rather than on the surface [13]. This strategy involves deliberately storing water below during wet periods and recovering it when needed.

Managed aquifer recharge allows water to be "banked" underground, reducing the impact of evaporation and facilitating the recycling of water from multiple sources [14]. Managed Aquifer Recharge (MAR) involves purposefully injecting and storing water into an aquifer with the intention of subsequent recovery with environmental advantages. This comprehensive technique is versatile, finding applications in both potable water and wastewater treatment, often integrated with engineered treatment systems [15]. MAR serves various purposes, including supplying drinking water, providing process water for industries, supporting irrigation, and sustaining groundwater-dependent ecosystems. Effective pre-treatment before recharge and post-treatment after recovery ensure the suitability of the water for its intended use. MAR leverages natural subsurface processes like mechanical filtering, sorption, and biodegradation, eliminating the need for additional chemicals and demonstrating sustained effectiveness over extended periods [16].

MAR refers to a suite of methods that are increasingly being used to maintain, enhance, and secure the balance of groundwater systems under stress [17]. The MAR method and technology strategically contribute to tackling the environmental changes and extreme weather events resulting from climate change, overpopulation, pollution, and the increasingly prevalent challenges associated with global water scarcity [18], [19]. Numerous sites around the globe have already implemented this water management approach, which are extensively documented in scientific literature, showcasing its relevance and effectiveness [20]–[22].

Even countries with abundant water resources are facing water scarcity due to climate change, overpopulation, and pollution. Although there may be a number of specific reasons for this – e.g., aging infrastructure and distribution systems, pollution, political/economic conflict or mismanagement of water resources – it is clear that climate change and the resulting deteriorating social factors are providing increasingly unfavourable conditions for the supply of clean drinking water for the population, for maintaining a balanced water management framework, and for providing the basis for a liveable social environment. Furthermore, the significant increase in water consumption around the world, as well as the concomitant pollution of water, pose serious challenges to both developed and developing nations. For this reason, it is crucial also for developed societies to strengthen the framework for prudent and far-sighted water management [18].

The International Groundwater Resources Assessment Centre (IGRAC) [23] hosts an interactive map [24] that compiles over a thousand managed aquifer recharge (MAR) case studies from over 50 countries [25]. Figure 1-1 illustrates the Managed Aquifer Recharge (MAR) case studies and implemented projects worldwide in 2024. This method is becoming an increasingly attractive water management option for the replenishment of depleting aquifers, especially in arid and semi-arid regions with limited surface water supplies. More than 224 currently active Managed Aquifer Recharge (MAR) projects in 23 European countries exist providing significant volumes of water for drinking and irrigation purposes [26].

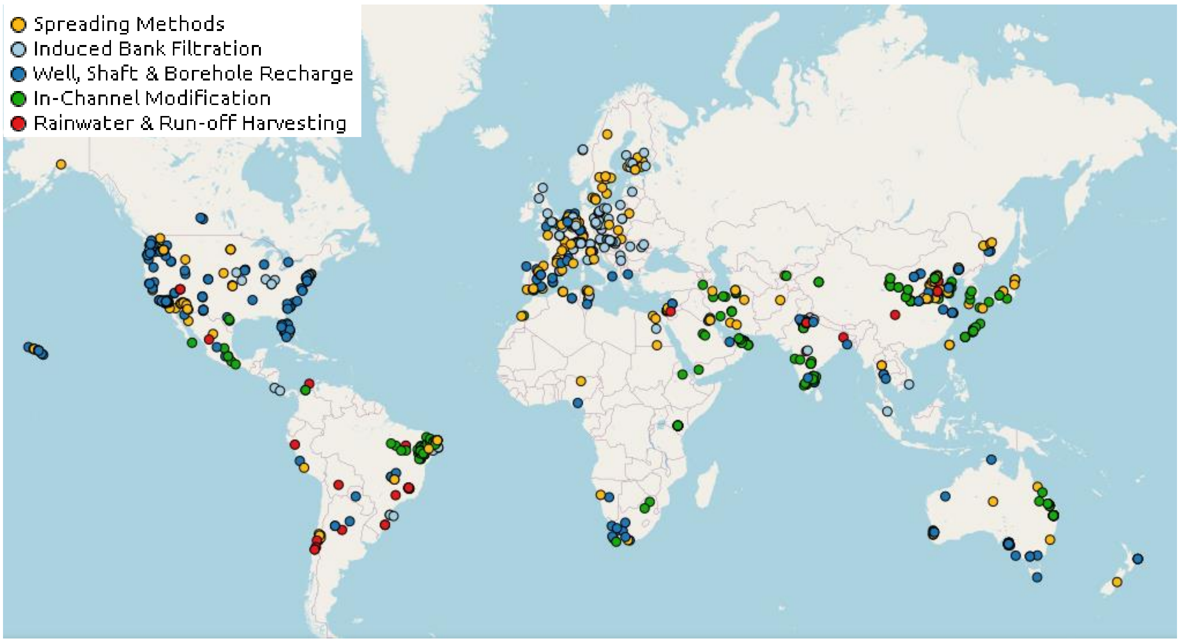


Figure 1-1 The global managed aquifer recharge inventory [25].

To conduct calculations for predicting groundwater flow, groundwater experts rely on computer models, which simulate and predict aquifer conditions based on established mathematical principles in hydrogeology. This modeling is crucial for ensuring that construction projects comply with environmental permitting requirements and for providing insights into necessary design modifications in advance. The technology is flexible and applicable to different scales, making it a valuable tool for managing groundwater resources and sustainable development. Groundwater models, with their ability to estimate flows and aquifer characteristics, are especially useful when direct measurements are unavailable. They also play a pivotal role in simulating the aquifer's response under hypothetical conditions. This comprehensive understanding of groundwater flow is fundamental to preventing adverse effects on nearby wetlands, bodies of water, or neighboring wells [27]–[29].

The need for simulation and modeling processes emanates from the importance of reducing the uncertainties and risks of failure of costly operations [30]. The process of simulation enables the anticipation of fluid displacement within reservoirs, providing engineers with valuable insights to develop economically efficient and less risky designs. To engage in simulation, a prerequisite is to possess an appropriate model. The model employed in simulation procedures should accurately mirror the behavior and properties exhibited by the real reservoir [31].

Modeling serves various purposes in the context of Managed Aquifer Recharge (MAR). It can be employed for scenario analysis, predicting future outcomes, comparing different MAR techniques, and evaluating various operational schemes. While adaptive approaches, such as trial and error, are valuable, modeling provides a systematic and efficient means to estimate the feasibility of a MAR method at a specific location. Due to its flexibility, a model-based preliminary assessment is often advisable before conducting pilot field experiments. This approach helps in optimizing resources, minimizing risks, and ensuring a more informed and strategic implementation of MAR methods [17,18]. Building a proper model for the means of simulation is a time-consuming process that necessitates a detailed dataset. However, the range of potential applications, such as scenario and sensitivity analyses, can justify the effort [32].

The most commonly used models for simulating groundwater flow are MODFLOW, FEFLOW, SEAWAT, HST3D and PHAST. The majority of applied models are not explicitly tailored for MAR applications. Nevertheless, the prevailing choice for groundwater flow and saturated flow modeling is MODFLOW as reported in the literature [33]. Therefore, in this study, we have opted to employ MODFLOW (Waterloo Hydrogeologic, United States Geological Survey (USGS) team, USA) to build the geological model and to address the objectives and parameters relevant to our investigation.

1.1 Managed Aquifer Recharge (MAR)

The primary goal of Managed Aquifer Recharge (MAR) is to augment the storage of groundwater, addressing the temporal disparity between local water demand and availability. This ensures a consistent and reliable supply of drinking or irrigation water throughout the year [33], [34].

Once the MAR site has been identified, taking into account constraints such as the availability of water, hydrogeological characteristics and regulations, five steps are usually necessary [35]:

- a preliminary evaluation of the feasibility of a recharge system at the chosen site based on existing data or modelling;
- designing the recharge system;
- carrying out a detailed study of the site in order to validate or supplement the results obtained in the first step;
- building a pilot or experimental system at a scale that makes it possible to carry out preliminary tests;
- extrapolation to an operational scale.

1.1.1 Applications of MAR systems

According to the reports from the United Nations 2021 [36], the present global scenario reveals the following key observations:

- Approximately four billion individuals, constituting nearly two-thirds of the world's population, experience severe water shortages for at least one month annually.
- Over two billion people reside in countries where water supplies are inadequate.
- It is anticipated that by 2025, half of the world's population might inhabit regions facing water scarcity.
- Projections suggest that by 2030, around 700 million individuals could be compelled to abandon their residences due to acute water shortages.
- Looking ahead to 2040, roughly one in four children worldwide is expected to inhabit areas impacted by severe water shortages.

These concerning findings have given rise to a new paradigm in recent years, emphasizing sustainable water management. Several strategic approaches, primarily centered around enhancing water-use efficiency, promoting water recovery, and advocating for water reuse and recycling, have been developed. The overarching goal of these approaches is to meet current water demands while safeguarding future water resources and ensuring their continued availability [36]. Managed water recovery, aligned with these principles, presents a promising opportunity to utilize reclaimed water for agricultural, industrial, or even domestic purposes. Implementing these strategies widely holds the potential for significant advancements in establishing a more sustainable framework for water management [37].

MAR emerges as a crucial solution, underscoring its strategic significance in confronting the multifaceted challenges of climate change, overpopulation, pollution, and the growing threat of global water scarcity. More specifically, this methodology finds practical application in supporting and enhancing groundwater quality, quantity, and environmental management efforts [38]. More specific objectives include [39]:

Water Quality:

- Enhancing water quality in degraded aquifers by addressing issues like nutrient reduction from agricultural pollution and preventing seawater intrusions.
- Reducing the concentration of geogenic pollutants such as fluoride or arsenic.
- Minimizing the need for extensive water treatment through the utilization of natural purification processes, such as riverbank filtration.

Water Quantity:

- Storing water in aquifers for future utilization, such as water supply.
- Addressing seasonal peak water demand induced by e.g. irrigation season, tourism activities.

- Elevating groundwater levels in over-exploited aquifers.

Environmental Management:

- Preventing storm runoff and soil erosion.
- Preserving environmental flows in rivers and streams.
- Mitigating floods and flood-related damages.
- Controlling seawater intrusions.
- Reducing land subsidence.
- Providing hydraulic control of contaminant plumes.
- Increasing groundwater levels to sustain or enhance the status of groundwater-dependent terrestrial ecosystems.

The adoption of MAR serves a dual role, addressing both environmental sustainability and economic considerations. It is utilized to alleviate water table drawdown, restrict seawater intrusion, and enhance depleted groundwater reserves by replenishing aquifers with surplus surface water [40]. This method not only aids in maintaining environmental sustainability through the replenishment of groundwater resources but also it possesses economical potential for securing a dependable water supply for diverse needs, encompassing agriculture and urban water demand [41].

Furthermore, MAR has gained recognition as a socially acceptable, cost-effective, robust, and environmentally friendly approach to water management. This highlights its capacity to address economic considerations while concurrently promoting sustainable water practices [41], [42]. Nevertheless, the economic feasibility of this technology hinges on precise siting and cost assessments, introducing elements of uncertainty into the implementation of MAR schemes. Despite the potential economic benefits, the absence of a definitive economic rationale for investing in the construction and operation of MAR systems has been acknowledged as a barrier to its widespread implementation [43].

Around the world, MAR initiatives have been established and executed with the aim of enhancing the resilience of groundwater resources. This mirrors the environmental advantages associated with deliberate groundwater replenishment. Furthermore, MAR has swiftly gained recognition as an effective approach for repurposing stormwater or treated sewage effluent, supporting both non-potable and indirect potable reuse. This, in turn, contributes significantly to the conservation of natural resources and the establishment of a sustainable water supply [44].

1.1.2 MAR type specification

The nature of the water designated for recharge is a crucial factor to contemplate, involving various sources such as stormwater, treated wastewater, or excess surface water. Each water source demands particular treatment processes to adhere to quality standards before the recharge process, and the design of the system must correspond with the selected water treatment methodology [45], [46]. The selected recharge method also has a substantial impact on the total design and efficiency of the MAR system. Choosing the right method for recharging depends on various factors like the permeability of the soil, characteristics of the aquifer, and the available space to implement the project [47]. Furthermore, the system design is significantly influenced by the intended use of the reclaimed water; Whether it's for uses like potable water, agricultural irrigation, or industrial uses, it is crucial to design the system to meet the specific requirements, ensuring both the quality and quantity of the recovered water that align with the final applications [48]. Therefore, the selection of the recharge method and the design of the system must align with the specific characteristics of the site and the quality of the water source to ensure the effectiveness and sustainability of MAR projects.

Essentially, creating a successful MAR system requires a thorough understanding of various factors, including geography, hydrogeology, water source, treatment, recharge method, and intended use. These elements work together to shape the design of a sustainable and efficient MAR system that is customized to meet the specific characteristics and needs of the particular location.

Based on Dillon et al. 2009, the MAR method can be classified into the main following technologies [1]:

- Aquifer Storage and Recovery (ASR): Utilizing the same well for injection and extraction, the ASR technique involves directly replenishing surface water into an aquifer for later recovery and usage. This technique is considered economical and has a negligible influence on the environment. ASR, with controlled recharge, has proven particularly helpful for saline aquifers, as seen in the Netherlands, where it has successfully reduced groundwater salinity. The main goal of ASR is to store water in aquifers for future use as drinking water, and the utilization of treated wastewater for urban stormwater storage and agriculture.
- Aquifer Storage Transfer and Recovery (ASTR): represents a more specialized iteration of Aquifer Storage and Recovery (ASR) technology, introducing a distinct approach to water management. This method revolves around the recharge of water into a designated

well for subsequent storage and retrieval from a separate well. ASTR distinguishes itself by its focus on enhancing water quality through the prolonged residence time of water within the aquifer. This extended duration facilitates additional purification processes through the natural deposits within the aquifer, presenting a technical solution that holds particular significance for urban drinking water supply.

- The Shallow (Vadose Zone) Wells: involves deploying near-surface wells within the vadose zone, also referred to as dry wells. These wells strategically tap into the substantial space between the topographic surface and the saturated zone of groundwater. This method serves various purposes, including facilitating drainage in mountainous regions, mitigating soil erosion, and efficiently recovering rainwater that has accumulated over time. By harnessing the extensive space available in the vadose zone, these shallow wells contribute significantly to sustainable water management practices, addressing specific environmental challenges in regions characterized by uneven topography and variable precipitation patterns.
- Rainwater Harvesting: diverts rainwater to a well, facilitating its natural seepage into groundwater for later extraction through pumping. This efficient process filters rainwater, contributing to a balanced hydrological cycle in urban areas. By capturing and utilizing rainwater, this technique ensures a sustainable water supply and helps alleviate strain on conventional sources.
- Bank Filtration: employed along the banks of rivers and lakes, is a water management technique that stimulates the infiltration of surface water into associated coastal or floodplain aquifers using pumping mechanisms. This approach enhances the natural filtration process, resulting in a considerable improvement in the quality of the extracted water. The high-quality water obtained through Bank Filtration makes it an ideal technological solution for meeting the drinking water needs of riverside settlements. This method not only ensures a reliable and clean water supply but also minimizes the environmental impact, making it a sustainable choice for communities situated along water bodies.
- Infiltration Basins: serve as widely adopted devices to capture stormwater runoff and replenish groundwater. These methods entail the utilization of shallow basins filled with permeable materials for the storage and infiltration of water. The efficacy of these technologies is heavily reliant on soil textural properties and subsurface heterogeneity, with their performance being influenced by factors such as vadose zone thickness and

the distribution of subsurface heterogeneity. Infiltration basins are prominent among MAR techniques, aiming to optimize infiltration into unconfined aquifers by evenly spreading and retaining water across mostly level terrain. These techniques prove particularly suitable for unconfined aquifers characterized by permeable sedimentary rocks and fractured crystalline rocks, exhibiting enhanced effectiveness in flat or gently sloped terrains where infiltration is facilitated, and clogging is minimized.

- Infiltration Ditches and Channels: involve water seeping through the bottom of ditches, requiring a smaller occupied area compared to infiltrating basins. This method has a reduced risk of clogging due to a lower occurrence of algal blooms and the increased permeability of channel deposits compared to sediments in quiet-water conditions.
- Dune Filtration: employs the infiltration of surface water to a shallow depth through drilled wells in constructed lakes within coastal dunes, a technique predominantly practiced in the Netherlands. This approach is primarily employed for water purification and to establish a reliable drinking water supply.
- Leaky Dams: constructed as low-head dams on intermittent, mostly mountainous streams, facilitate water infiltration into aquifers, mitigating seasonal floods and decelerating the stream's flow rate.
- Sand Storage Dams: constructed in the beds of intermittent mountain streams and smaller watercourses, enable the natural accumulation of sediment. This retention of rainwater improves groundwater recharge and serves as a source of drinking water along the river, with the added benefit of evaporation avoidance or reduction in this method. The construction of these dams is a carefully planned intervention to harness the natural process of sediment retention, transforming it into a sustainable method for creating localized aquifer-like conditions.

Each MAR approach is specifically constructed to complement the specific geological, hydrological, and environmental characteristics of its intended location, offering a variety of strategies for long-term groundwater resource enhancement. The selection of a particular MAR technique is inextricably tied to a thorough understanding of elements like as soil composition, aquifer dynamics, and the broader objectives of regional water management. This personalized approach guarantees that the chosen technology blends perfectly with the natural circumstances of the area, maximizing efficacy while reducing any environmental consequences. The thorough examination of these various criteria highlights the adaptability and precision required when implementing MAR efforts to meet the unique needs and constraints of each location.

1.2 Simulation and Modeling

Numerous operational systems are intricately linked and influenced by both variability and complexity, encompassing both combinatorial and dynamic aspects. Predicting the performance of systems facing any one of these challenges is challenging. When systems are potentially subject to all three—variability, interconnectedness, and complexity—the difficulty in making accurate predictions becomes even more pronounced, if not seemingly impossible. Simulation models, however, possess the capability to explicitly represent the intricacies of variability, interconnectedness, and complexity within a system. Consequently, simulations enable the anticipation of system performance, facilitate the comparison of various system designs, and allow for the assessment of the impact of alternative policies on overall system performance [32].

A model is a simplified representation of an actual system and the phenomena occurring within it. It serves to simulate, in an approximate manner, the relationships between the system's excitation and response that are of interest [49].

Modeling serves a multifaceted set of objectives, each playing a crucial role in various applications. These objectives encompass a broad spectrum of purposes and functions, contributing to the effectiveness and utility of the modeling process. Some of the key objectives are summarized as follows:

- Anticipating the system's response to management decisions;
- Estimating various resources by comprehensively understanding the characteristics of the system under study;
- Supplying essential information for regulatory compliance;
- Furnishing insights for designing monitoring networks or field experiments through the prediction of the system's future behavior.

The diagram below illustrates a step-by-step flowchart outlining the necessary procedures for constructing a model that is prepared for simulation.

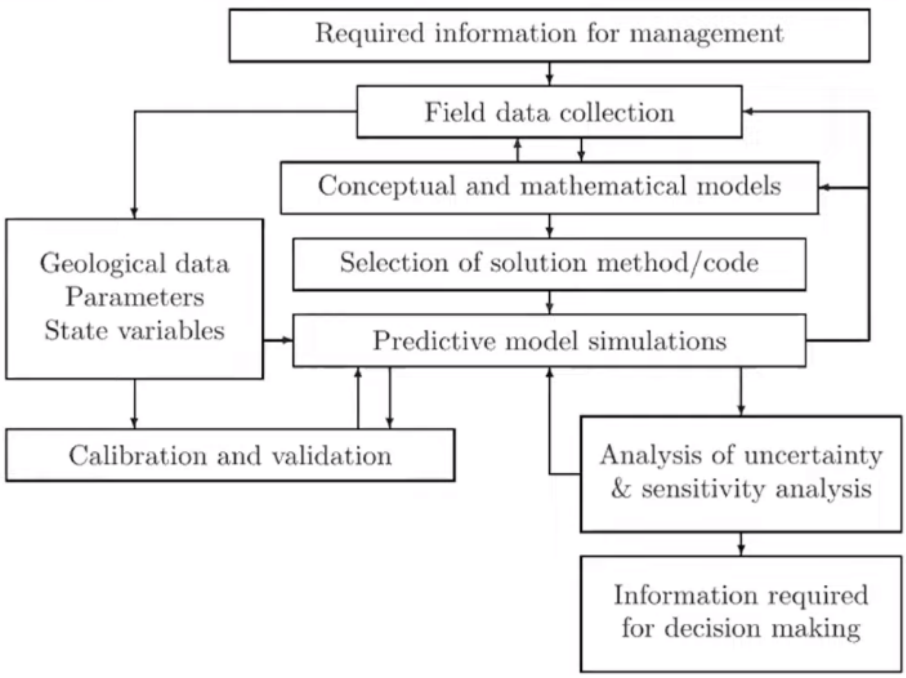


Figure 1-2 Flowchart depicting the process of constructing a simulation model [49].

1.3 Off-Season Groundwater recharge

Emphasizing the importance of sustainable groundwater management, the water resources community notes that over one-fourth of the world's population and 40% of global agricultural production rely on unsustainable groundwater extraction [50]. The increasing demand for water, driven by factors such as population growth, rising living standards, and the expansion of irrigated agriculture, contributes to groundwater overexploitation in regions where surface water is only available seasonally or scarce [2]. Simultaneously, climate change models predict an escalation in the magnitude and frequency of extreme precipitation events, including multi-year droughts and floods [51].

Options for increasing reservoir storage in developed regions are limited and prohibitively expensive. Projected increases in demand call for new long-term water storage to help sustain agriculture, municipalities, industry, and ecological services. MAR is becoming an integral component of water resources around the world. However, MAR faces challenges, including infrastructure costs, difficulty in enhancing recharge, water quality issues, and lack of available water supplies [52], [53].

More specifically, regarding agricultural lands an off-season irrigation approach has been introduced over a decade ago, a promising MAR approach, toward enhancing recharge to aquifers within agricultural lands during periods of excess surface water, referred to as Ag-MAR [54]–[56]. This approach also known as agricultural groundwater banking, on-farm recharge, or flood-flow capture [54], during non-cultivation season, seeks to redirect surplus surface water directly onto farmland during periods of the rainy season, snowmelt, or reservoir releases with the goal of replenishing groundwater. The implementation of Ag-MAR across extensive agricultural areas has several benefits where much larger quantities of recharge can be achieved, in contrast to localized methods like well injection, which are constrained by well capacity and groundwater mounding [52]. Furthermore, Ag-MAR represents a secondary use of agricultural land that is primarily used for agricultural production [57]. However, The impacts of Ag-MAR on crop yield and health, encompassing post-flooding considerations such as pest management [57]; the percolation of legacy nitrogen, salts, pathogens, and naturally occurring inorganic contaminants like arsenic (As) into groundwater [54], [58]; and the potential waterlogging of agricultural lands near Ag-MAR sites, giving rise to hypoxic or anoxic conditions [59].

In the context of this research, we have explored the concept of off-season recharge, deviating from the conventional Ag-MAR approach by initiating the recharge process upstream of the farmland. The key distinction lies in the introduction of a strategically positioned recharge basin, located at a distance from the agricultural fields. This approach offers a notable advantage over Ag-MAR by virtue of the basin being located away from agricultural fields. This spatial separation eliminates the potential issue of pesticide infiltration associated with Ag-MAR. Moreover, the distance between the basin and the farmland facilitates the natural purification of infiltrated water as it traverses this spatial gap.

What sets this methodology apart is firstly, the placement of the basin, situated away from the farmland, in contrast to Ag-MAR, where the farmland itself serves as the infiltration site, and secondly, its intentional alignment with the non-farming season, spanning from October to April. This time frame corresponds to periods of heightened precipitation, resulting in elevated surface water levels and, at times, potential flooding. This deliberate synchronization with the non-farming season provides a distinctive opportunity to leverage and strategically channel excess water. Precisely during this period of increased precipitation and surface water abundance, our approach involves injecting surplus water into the basin. The objective is to facilitate the percolation of this water through the soil layers to reach the underlying aquifer. By doing so, we aim to make optimal use of and strategically manage the excess water, capitalizing on its potential to replenish the aquifer underground.

Moreover, this off-season recharge mechanism allows the surplus water, injected during periods of agricultural inactivity, to gradually traverse the intervening distance and eventually reach the pumping well situated within the farmland. By strategically implementing this distant recharge basin upstream of the agricultural land, we aim to effectively address issues related to groundwater depletion and counteract head loss in the pumping well.

The objective of this research is not only the utilization of excess water resources but also to strategically contribute to the sustainable management of groundwater in agricultural settings. The deliberate timing and spatial considerations in the off-season recharge strategy aim to ensure that the replenishing water efficiently compensates for groundwater depletion, ultimately enhancing the overall resilience and productivity of agricultural systems.

1.4 Groundwater Modeling

Groundwater modeling is an essential process that involves converting intricate physical flow systems into mathematical representations. This methodology provides a conceptual understanding of hydrological challenges, enabling researchers and practitioners to analyze and address complex groundwater dynamics [60]. These models play a pivotal role in simulating and predicting conditions within aquifers, offering a comprehensive depiction of natural groundwater flow in the environment. Groundwater flow models, essentially mathematical depictions of groundwater movement through aquifers, are indispensable tools despite not capturing the full complexity of real-world systems. They prove invaluable in estimating flows and aquifer characteristics, enabling the simulation of responses under hypothetical scenarios. This capacity aids in identifying sensitive areas, where additional hydrologic insights can enhance understanding [61], [62].

Groundwater modeling's role is indispensable in comprehending and managing groundwater resources. It furnishes critical insights for decision-making in water management and environmental protection, underscoring its paramount importance in sustainable resource utilization. The development of a conceptual model is a pivotal stage in groundwater modeling, undergoing mathematical analysis to produce a simplified representation of the hydrogeological system. This streamlined version facilitates the prediction, testing, and comparison of various feasible alternatives [63].

The demand for predicting the regional impacts of human activities on groundwater systems has driven significant advances in regional groundwater flow modeling. The availability of innovative software packages and increased computational power have further fueled interest in this field [64]. To analyze regional groundwater flow systems, transient groundwater models are employed, simulating conditions at a broader scale. These mathematical equation-based computer-generated models provide scenarios based on specific assumptions and input values. The effectiveness of regional groundwater models relies on accurate input parameters and boundary conditions. Variations in these inputs can lead to dramatic changes in model output, emphasizing the need for precision in model calibration [65].

The versatility and comprehensiveness of groundwater modeling are underscored by its key advantages and diverse applications across various domains [64], [66]–[68]:

1. **Environmental Permitting:** Groundwater modeling serves a pivotal role in ensuring compliance with stringent environmental permitting requirements. By providing early insights during the project planning phase, it facilitates proactive design modifications to align with regulatory standards, ensuring sustainable and environmentally responsible practices.
2. **Prediction and Testing:** The predictive capabilities of groundwater modeling extend to systematically assessing and comparing viable alternatives. This functionality proves invaluable in evaluating the potential impacts of proposed projects on critical parameters such as groundwater elevation, surface water elevation, or streamflow volume. The ability to simulate different scenarios aids in informed decision-making.
3. **Understanding Hydrogeological Systems:** At its core, groundwater modeling offers a conceptual understanding of complex hydrogeological systems. By translating the intricacies of natural groundwater flow into mathematical terms, the modeling process generates a simplified version of the system, facilitating easier comprehension and aiding in the interpretation of complex groundwater dynamics.
4. **Assessment of Hydrological Changes:** Groundwater models provide a powerful means of assessing the effects of hydrological changes. This includes predicting variations in water table levels, evaluating the impact of groundwater withdrawals on nearby streams, and forecasting potential saltwater intrusion scenarios. Such assessments contribute to effective water resource planning and management.
5. **Water Management Planning and Supporting Informed Decision-Making:** Urban water management plans benefit significantly from the integration of groundwater models. These models ensure coherence among critical factors such as aquifer properties, recharge and discharge rates, and groundwater levels. This holistic approach enhances the overall efficiency of water resource management strategies in urban areas.
6. **Identifying Sensitive Areas:** Groundwater models excel in pinpointing sensitive areas where additional hydrological information could greatly enhance system understanding.

Identifying these areas allows for targeted efforts in data collection and monitoring, further refining the accuracy of the model and its predictions.

7. **Estimation of Aquifer Characteristics:** Groundwater models play a pivotal role in estimating flows and aquifer characteristics, especially in situations where direct measurements are unavailable. This capability contributes to a more comprehensive understanding of groundwater dynamics, aiding in effective resource management and sustainable utilization.
8. **Quality Aspects:** Advanced groundwater models incorporate chemical quality aspects, enabling the prediction of chemical fate and movement. This functionality is particularly valuable in assessing potential environmental impacts in diverse scenarios, encompassing natural landscapes, urban environments, and hypothetical situations.
9. **Avoidance of Unforeseen Challenges:** Understanding hydrogeological systems through modeling allows project managers to anticipate and plan for unforeseen challenges. This foresight helps avoid unexpected setbacks and the associated costs that may arise due to issues like unexpected changes in groundwater levels or subsurface conditions.
10. **Long-Term Cost Savings:** While there may be an initial investment in groundwater modeling, the long-term cost savings it facilitates can outweigh these initial expenses. Accurate predictions and informed decision-making during the planning phase can prevent costly modifications and adjustments during and after project implementation.

In summary, groundwater modeling emerges as a cornerstone in the endeavor to address a wide spectrum of challenges, ranging from navigating complex environmental permitting processes to conducting nuanced assessments of hydrological changes. Its versatility and capacity to provide detailed insights position it as an invaluable asset in the broader context of understanding, managing, and preserving groundwater resources for sustainable and responsible utilization. Moreover, the economical aspects of groundwater modeling lie in its capacity to optimize project design, mitigate risks, ensure compliance, and enhance the efficient utilization of resources. Offering an in-depth insight into the dynamics of groundwater, modeling emerges as an indispensable instrument for projects aiming to attain both economic effectiveness and enduring sustainability.

Various software tools have been designed for MAR applications, alongside those utilized in broader hydrogeological studies. While some tools are purpose-built for MAR, the majority of models employed are not exclusively developed for such applications. Notably, MODFLOW stands out as the most widely utilized groundwater flow model in this context [69]. Visual MODFLOW serves as a Graphical User Interface for the USGS MODFLOW, functioning as a commercial software widely favored by hydrogeologists due to its user-friendly features. Primarily designed for creating Groundwater flow and contaminant transport models, this software is utilized to simulate various conditions and scenarios [70].

The Modular Finite-Difference Flow Model (MODFLOW) software was introduced by the U.S Geological Survey (USGS) and the 'Waterloo Hydrogeologic' company in August 1994. This software utilizes finite-difference methods for solving groundwater flow and contaminant transport models [71]. Notably, MODFLOW is categorized as "free public domain software" in terms of its source code. Visual MODFLOW, an application of MODFLOW, streamlines the modeling process by accepting input files in various formats such as Excel files, Surfer grids, GIS, and AutoCAD data. This characteristic enhances user-friendliness and reduces execution time.

A notable feature of Visual MODFLOW is its capability to interpret raw text and binary output files generated by MODFLOW. It transforms this data into color/contour maps and charts, providing a visual representation that facilitates easy analysis and interpretation of model results. Visual MODFLOW comes in two variants: Classic and Flex. While both types share similarities, the key distinction lies in their approach. Classic employs a numerical approach, whereas Flex utilizes a conceptual approach.

Leveraging well-established tools like MODFLOW in MAR modeling confers significant advantages. As outlined in the comprehensive review conducted by Ringleb et al. [33], MODFLOW emerges as a versatile and extensively utilized software tool across various modeling objectives and applications in managed aquifer recharge. This powerful software is employed in different stages of MAR, covering a spectrum of applications, including well, shaft, and borehole recharge. Its versatility extends to diverse aspects such as design, optimization, feasibility assessments, water quality analyses, exploration of geochemical processes, groundwater management strategies, evaluation of recovery efficiency, addressing saltwater intrusion concerns, and determining residence times within aquifers. Furthermore, MODFLOW proves to be highly adaptable, demonstrating its efficacy across different MAR methods. Its extensive history of diverse applications and comprehensive documentation enhances its reliability and usability in the realm of Managed Aquifer Recharge, making it a powerful and preferred choice in our research.

2 Methodology

2.1 Model Design in MODFLOW

As mentioned before, in the context of this study, the widely acclaimed MODFLOW, a three-dimensional finite-difference model [69], has been used. Operating based on Darcy's law, MODFLOW governs the flow rate within saturated systems. Its capability to simulate both steady and transient flows makes it a versatile choice, accommodating various aquifer configurations, including confined, unconfined, or a combination of confined and unconfined layers. Three-dimensional groundwater flow is described by the following partial differential equation:

$$\frac{\partial}{\partial x}\left[K_x \frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_y \frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_z \frac{\partial h}{\partial z}\right] \pm W = S_s \frac{\partial h}{\partial t} \qquad \text{Eq (2.1)}$$

where K_x, K_y and K_z are the hydraulic conductivity values along the x, y, and z coordinate axes parallel to the major axes of hydraulic conductivities; h is the potentiometric aquifer head; W is the volumetric flux per unit volume representing sources (W is negative for flow out) and/or sinks (W is positive for flow in) of water; S_s is the specific storage of the porous medium; and t is time. K_x, K_y and K_z, and S_s are functions of space (x, y, z) while W is a function of space and time (x, y, z, t) [72].

In this study, the Visual MODFLOW 2011.1 version was employed. For the flow model, five numeric engines were accessible, including USGS MODFLOW-96 from WHI, USGS MODFLOW-2000 from WHI, USGS MODFLOW-2005, USGS SEAWAT 2000, and MODFLOW-SURFACT from HGL. Among these options, USGS MODFLOW-2005 was selected for simulation, specifically defined for a saturated domain with constant density [71].

2.1.1 Properties and Initial Data

The fundamental requirement for groundwater modeling entails the creation of mathematical frameworks and the inclusion of varied hydrogeological properties. This encompasses the spatial distribution of hydraulic conductivities, static groundwater head, and the coefficients of individual aquifers.

We established a hypothetical groundwater model domain within the Visual MODFLOW framework, defining an area measuring 3 km by 1 km with a thickness of 50 m. Within the scope of this investigation, the process of model discretization was carried out utilizing a grid with dimensions of 10 × 10 meters, resulting in 300 columns (number of grids along the x direction) and 100 rows (grids along the y direction). The model consisted of two stratigraphic layers, spanning a combined area of 3 square kilometers and featuring an impressive 30,000 cells organized across two layers. Figure 2-1 illustrates the planar view of the model within the MODFLOW software workspace.

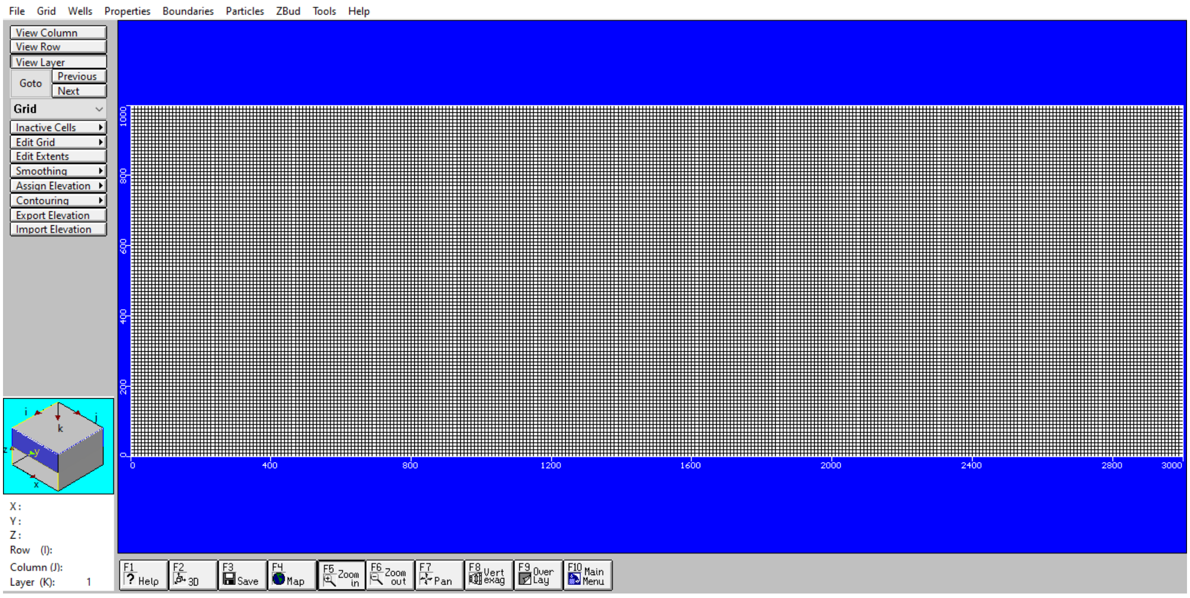


Figure 2-1 Planar view of the model in MODFLOW workspace.

The first layer represents an unconfined aquifer, while the second layer serves as an aquitard. The underlying layer comprises relatively impermeable bedrock, functioning as the model's bottom. Layer 1, representing the unconfined aquifer, is consistently 40 m thick, while Layer 2, acting as the aquitard, has a uniform thickness of 10 m. Table 2-1 provides details on the spatially uniform hydraulic properties of the aquifer. The figure below displays the cross-sectional view of the model, including both the aquifer and the aquitard sections. The dark blue portion represents the aquitard, which is characterized as a scarcely conductive layer.

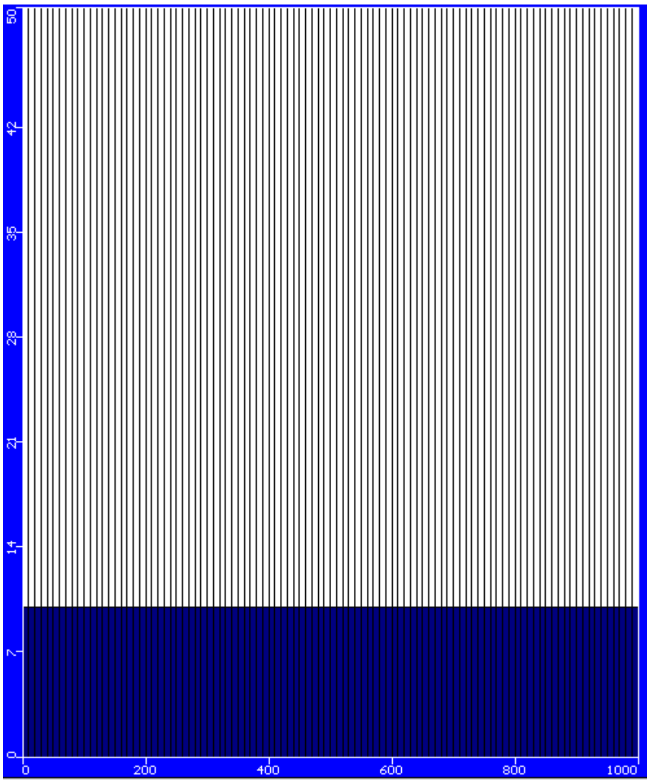


Figure 2-2 Cross-sectional view of the model in MODFLOW workspace.

2.1.2 Boundary conditions

The groundwater flow pattern is considered to move from the west of the model towards the well, located in the eastern part of the model where the agricultural field is situated. Consequently, the model area is delimited by no-flow boundaries assigned to the north and south. As a fundamental boundary condition, the static groundwater level is specified at both the western and eastern boundaries of the model. Constant hydraulic head as the first type boundary condition was adopted.

In particular, the hydraulic head at the western boundary is established at a value of 40 m, indicating the static groundwater level in that specific region. In contrast, a constant value of 31 m for hydraulic head is assigned to the eastern boundary. This boundary condition configuration is designed to simulate the expected groundwater dynamics within the model area, taking into account the directional flow toward the agricultural field in the east and establishing a foundational framework for the analysis of groundwater behavior. The values for the mentioned boundary conditions are also summarized in Table 2-1.

Table 2-1- Model Parameters Used in Visual MODFLOW Framework

Model Input Variable	Value
Aquifer zone model parameters	
Horizontal hydraulic conductivity (K_x, K_y)	$10^{-3} m\ s^{-1}$
Ratio of vertical to horizontal $(K_z/K_{x,y})$ hydraulic conductivity	1.0
Specific yield (S_y)	0.2
Specific storage value (S_s)	$10^{-4}\ m^{-1}$
Effective porosity (φ_e)	0.15
Aquitard zone model parameters	
Horizontal hydraulic conductivity (K_x, K_y)	$10^{-10} m\ s^{-1}$
Ratio of vertical to horizontal $(K_z/K_{x,y})$ hydraulic conductivity	10^{-1}
Boundary conditions	
Western boundary: Constant Hydraulic Head	$40\ m$
Eastern boundary: Constant Hydraulic Head	$31\ m$
Northen and Southern boundary: No Flow	$q = 0$

In this study, we incorporated a pumping (irrigation) well near the hypothetical agricultural field downstream of the model, operating at a consistent pumping rate. Additionally, an infiltration basin upstream has been established, designed to convey water through the underlying aquifer to reach the pumping well. The cultivation period was defined from May to September, spanning 155 days, while the infiltration basin operated for seven months, from October to April, totaling 210 days.

To improve the clarity of alterations around the pumping well and conduct a more detailed analysis of drawdown data, we implemented a refined spatial resolution. More specifically, we reduced the size of the cell containing the well and its neighboring cells by a factor of 2, encompassing also three cells on each side (north, south, east, and west). This adjustment resulted in a total of seven cells being included in both rows and columns within this downscaled area. Consequently, our focused analysis was performed on a grided model featuring 307 columns and 107 rows, enabling a more intricate examination of groundwater drawdown patterns in the immediate vicinity of the pumping well. The before and final griddings are illustrated in the figures below.

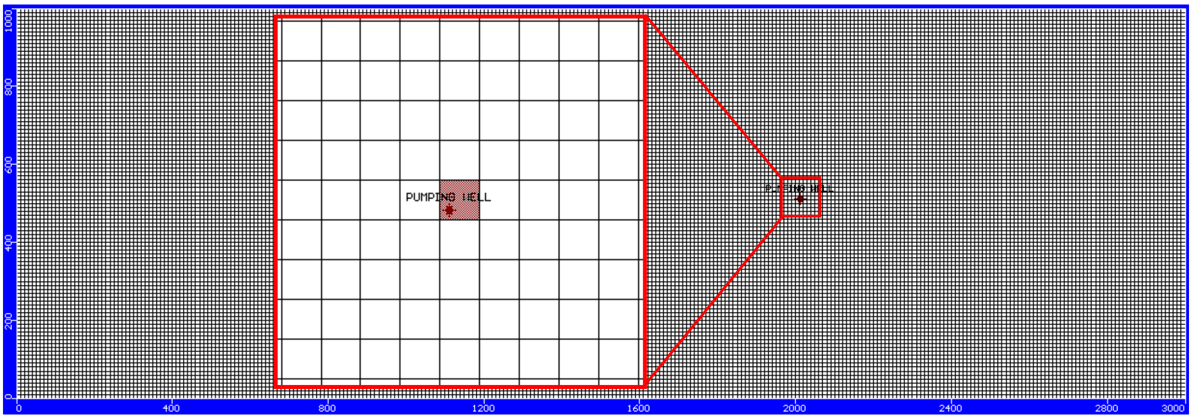


Figure 2-3 Model gridding before downscaling the area around the well.

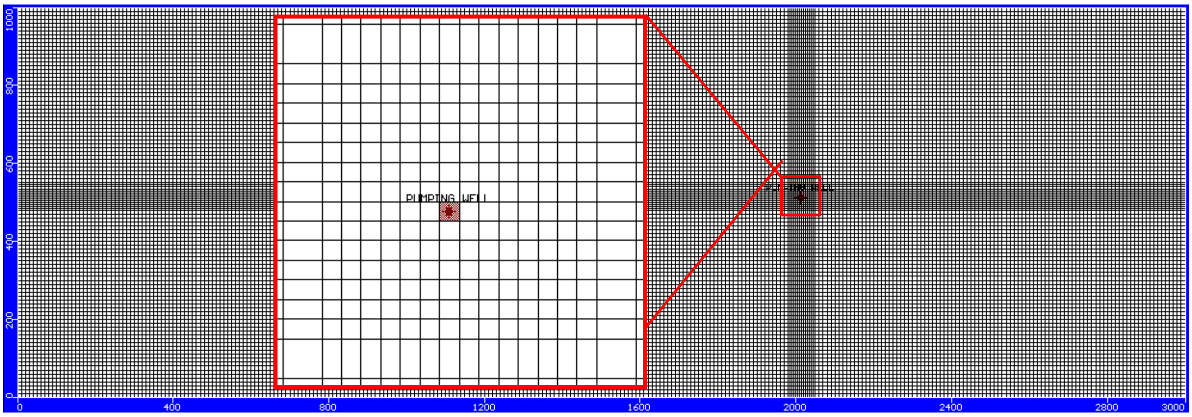


Figure 2-4 Model gridding after downscaling the area around the well.

To conduct a thorough sensitivity analysis, we explored various factors, encompassing hydraulic properties, the positioning, shape, and dimensions of the recharge basin, along with the rates of infiltration. The simulation was carried out over a substantial duration of 20 years, allowing for a comprehensive exploration of the system dynamics and the impact of different recharge scenarios and groundwater flow on the pumping and agricultural conditions. This extended simulation period enhances our understanding of the long-term effects and sustainability of the proposed groundwater management approach.

2.2 Model (Sensitivity Analysis) Scenarios

Sensitivity analysis is a valuable tool in the application of a new model, especially when there is limited information and literature about it. It helps in determining how different values of an independent variable affect a particular dependent variable under a given set of assumptions. Here are some key points about the application of sensitivity analysis [73]–[75]:

Model Simplification: Sensitivity analysis can aid in simplifying the model. By identifying factors that don't significantly impact the output, the model can be streamlined, making it easier to analyze the inputs.

Identifying Key Elements: It helps in determining which elements have the greatest impact on the model's output, thus providing insights into the most critical components of the model. By systematically varying input parameters over a reasonable range and observing the model's response, researchers can discern which parameters have a substantial impact on the model outcomes. This aids in prioritizing and focusing attention on the most influential aspects of the model.

Robustness Testing: Sensitivity analysis can be used to determine whether the results are robust. This is particularly important when dealing with a new model where uncertainties exist.

Communication of Results: It assists in communicating the results to stakeholders, including upper management, by providing a clear understanding of how changes in input variables affect the model's output.

Decision-Making Support: Sensitivity analysis provides valuable information for decision-making, especially in scenarios where there is limited information about the model. It helps in understanding the potential impact of different variables on the model's output.

Optimizing Model Performance: Sensitivity analysis aids in optimizing the performance of the new model. Understanding which parameters drive the model's behavior allows researchers to fine-tune and optimize those aspects. This iterative process enhances the model's predictive capabilities, especially when dealing with limited prior knowledge.

Guiding Future Research: In the context of a new model, sensitivity analysis serves as a guide for future research directions. It not only informs researchers about the crucial parameters requiring further investigation but also helps set priorities for additional data collection and experimental studies. This ensures that subsequent research efforts are targeted and aligned with the model's sensitivities.

In summary, sensitivity analysis is a powerful tool that can be particularly useful when dealing with a new model where there is limited information and literature. It can aid in simplifying the model, identifying key elements, testing robustness, and supporting decision-making and communication of results.

In the subject of groundwater modeling, model sensitivity is a function of groundwater response to changes in model inputs, such as groundwater recharge and aquifer hydraulic properties [60]. The purpose of the sensitivity analysis is to demonstrate the sensitivity of the model simulations to uncertainty in values of model input data. The sensitivity of one model parameter relative to other parameters is also demonstrated. Sensitivity analyses are also beneficial in determining the direction of future data collection activities. Data for which the model is relatively sensitive would require future characterization, as opposed to data for which the model is relatively insensitive. This strategic approach not only ensures the accuracy of the model in handling sensitive data but also translates to significant benefits in terms of both time and cost savings, particularly for insensitive data. This streamlined process contributes to efficient resource utilization, enhancing overall project efficiency and resource management [76], [77].

In the forthcoming sections, we will provide detailed explanations of the scenarios outlined in this study. Additionally, we will elaborate on the variables selected for conducting sensitivity analyses to assess their impact on the response of the production well to various changes.

2.2.1 The Base Model

The initial simulation model, executed with properties outlined in Table 2-1, featured a strategically placed well at coordinates 2012.5 m and 512.5 m in the x and y directions, respectively. The meticulous selection of well coordinates ensured its central positioning within a corresponding cell when the model was gridded. This well was specifically designed for water extraction during agricultural activities, spanning approximately 155 days annually from May to September.

The first simulation focused solely on water production, deliberately omitting the inclusion of the water infiltration and the recharge basin. This intentional exclusion aimed to evaluate alterations in the hydraulic head within the well and the corresponding water levels in the underlying aquifer. The simulation spanned an extensive period of 7300 days, equivalent to 20 years, providing a comprehensive perspective on the long-term effects and dynamics associated with the operation of the production well.

In this study, the simulation year has been divided into two periods, which are defined as follows:

1. Starting from October 1st until the end of April: Spanning a duration of 7 months or 210 days, this period corresponds to the operation of the recharge basin. During this timeframe, no pumping activities occur at the well.
2. Second period, commencing in May and concluding at the end of September: Spanning approximately 155 days, this timeframe coincides with the agricultural season. Consequently, it aligns with the operation of the well, and during this period, there is no infiltration occurring at the basin.

Each model was simulated starting in October, with no irrigation and no well production for the initial 7 months, and the pumping rate was considered equal to zero during this period. Subsequently, for the remainder of the simulation year, starting in May, the well started pumping for 5 months until the end of September. For the sake of conducting a thorough sensitivity analysis and facilitating a more comprehensive comparison, a pumping rate of 100 liters per second (approximately 8640 m^3/d) has been taken into account to observe a noticeable drawdown.

The screen level of the well was established with a length of 10 meters, ranging from 11 to 22 meters with respect to the bottom of the model. This configuration was chosen to align with the expansion of the aquitard, which extends from 0 to 10 m from the bottom of the model. The figure below provides a schematic illustration of the well and the relative position of the screen alongside the visual representation of the pumping rate schedule, showcasing the periodical production from the well.

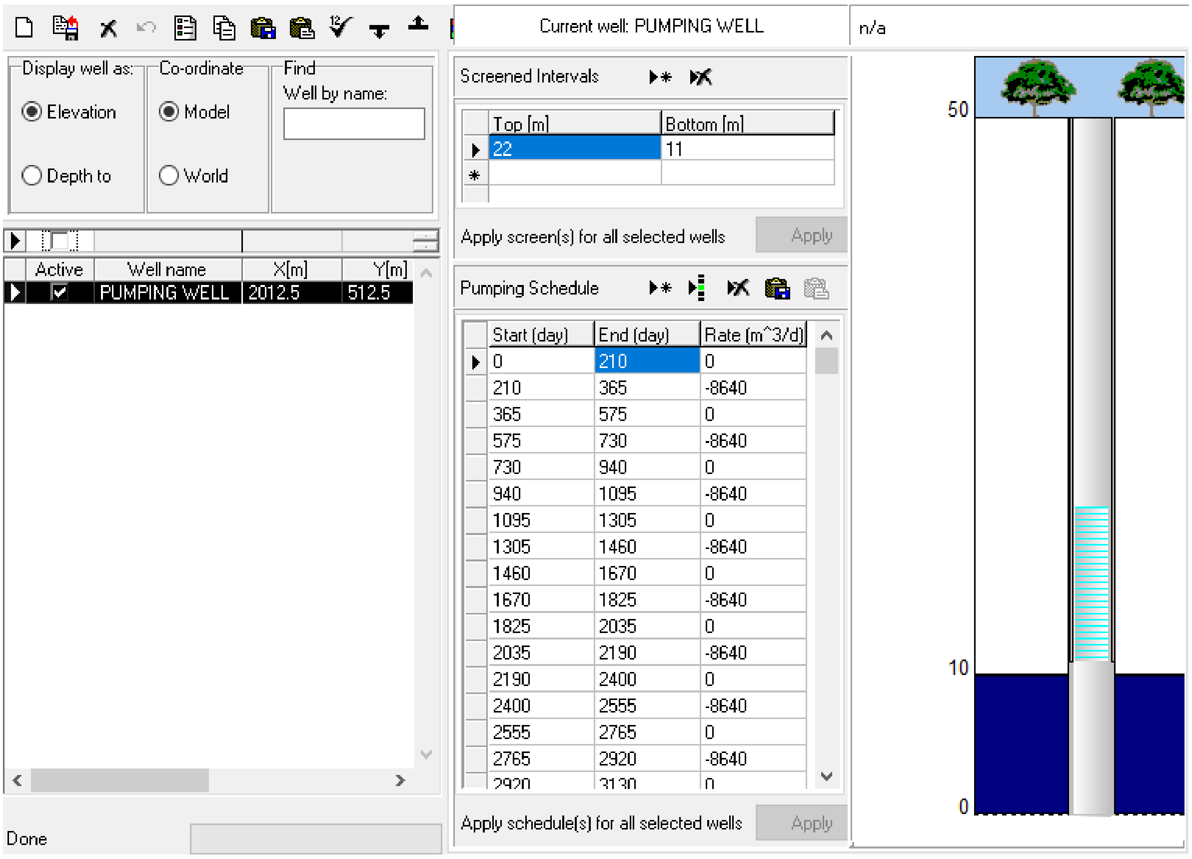


Figure 2-5 Well schematic and the adopted pumping rate schedule over 20 years (7300 days).

2.2.2 The Definition of The Recharge Basin

In this part, the modification implemented in relation to the base model involved the introduction of a recharge basin. Taking into account the established boundary conditions and the natural flow direction within the model, a recharge basin was strategically placed in the proximity of the western boundary. This adjustment was made with the understanding that the infiltrated water from the basin (on the western side) would follow a course toward the pumping well (on the eastern side) and subsequently contribute to the water source for the farmland.

An attempt was made to symmetrically define the basin in relation to the placement of the well. To this matter, the basin was expanded from 450 to 550 meters along the x-direction (groundwater direction) and from 400 to 600 meters along the y-direction (transversal to the flow direction). Therefore, a rectangular area has been created, measuring 100 meters by 200 meters, equivalent to a total of 20,000 square meters. Figure 2-6 illustrates the schematic representation of the basin and its relative position with respect to the well within the MODFLOW working space.

This figure also highlights two monitoring wells that have been purposefully introduced in the system, with one strategically placed precisely at the location of the pumping well to monitor the water level within the well. The second monitoring well is positioned at the center of the recharge basin, serving to assess the level of rise in the water level and the groundwater mounding right under the infiltration basin during and at the end of each infiltration period.

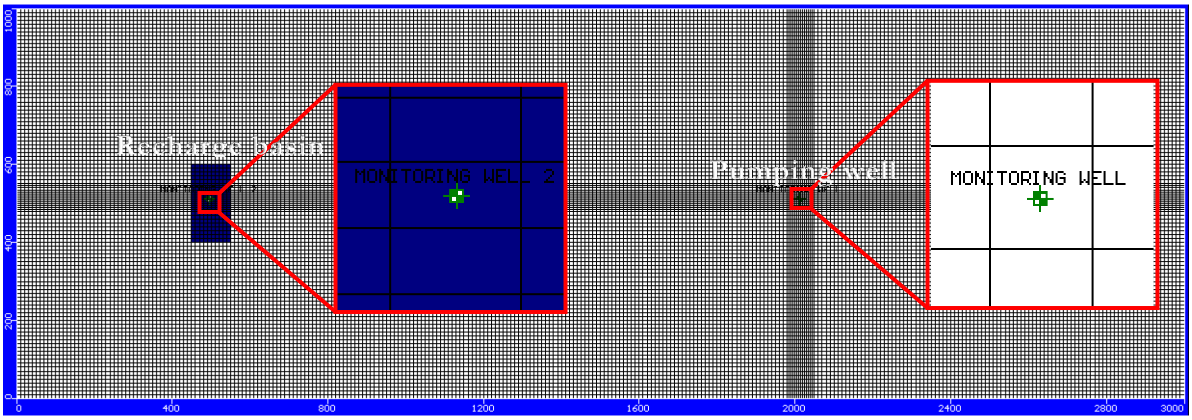


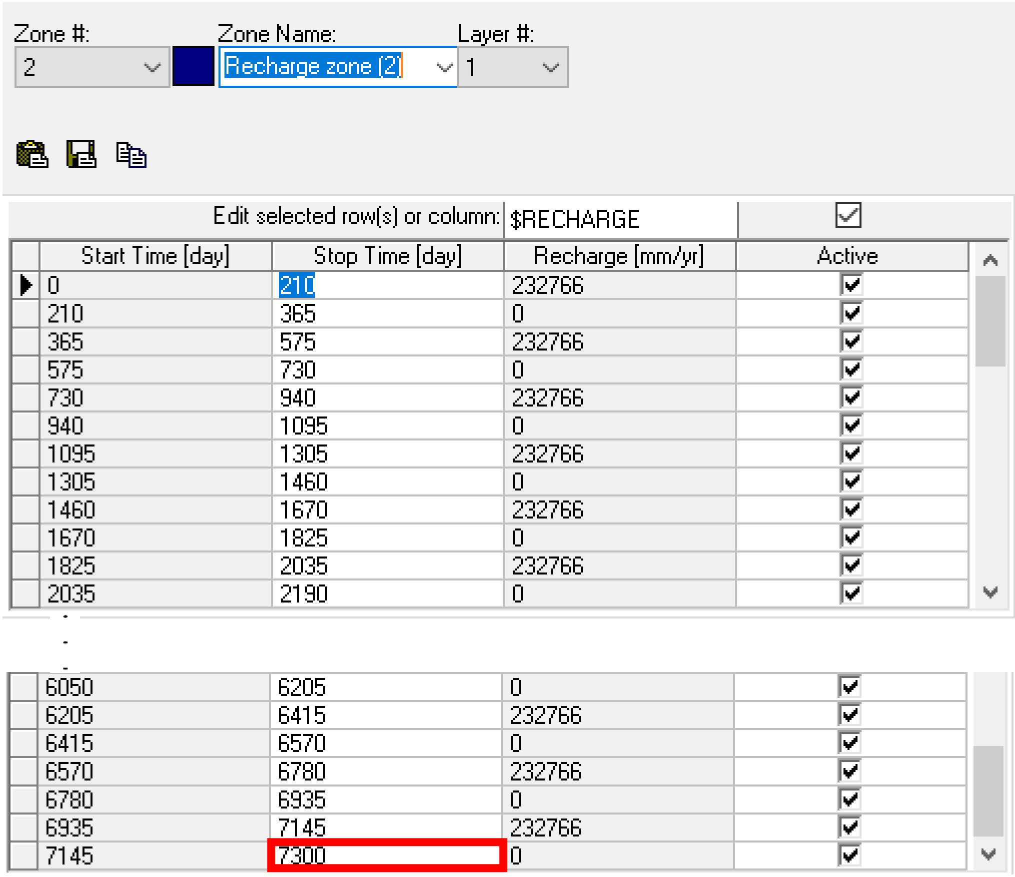
Figure 2-6 Positioning of the production and monitoring wells and the recharge basin.

The basin recharging rate is derived from the well's pumping rate, focusing on the volume of extracted water from the pumping well over 155 days. More specifically, the same amount of extracted volume from the well is considered to be recharged underground during the off-agricultural season, for 210 days and covering an area of 20,000 square meters of the recharge basin. Table 2-2 illustrates the procedure for determining the infiltration rate.

Table 2-2- Calculation of the basin's infiltration rate

Parameters	Units	Value
Pumping rate	m3/s	0.1
Irrigation season length	d	155
Overall volume abstracted	m3	1339200
Ratio of volume infiltrated to volume abstracted	-	1
Infiltration season length	d	210
Infiltration volume rate	m3/s	0.07381
Infiltration basin width	m	100
Infiltration basin length	m	200
Infiltration rate	m/s	7.38E-06
	mm/y	116383
Ratio of volume infiltrated to volume abstracted	-	2
Infiltration rate	m/s	3.69E-06
	mm/y	232766

In the initial attempt to define the basin, the infiltration rate was established at 116383 mm/year, initiating the trial to observe and analyze the impact of this adjustment on the model's behavior and dynamics. However, in order to enhance the visibility of changes on the final hydraulic head at the well and for a more thorough investigation into the effects of various parameters on drawdown, the recharge volume was set to be twice the extraction volume, as also calculated in the table above. Henceforth, the basin infiltration rate of 232766 mm/year has been employed for the remainder of the study. The simulation time commenced on October 1st, with a defined recharge schedule for the basin, set in opposition to the operation time of the pumping well. During the period when the recharge basin is actively infiltrating water, the pumping well remains inactive. In a synchronized manner, as the infiltration basin completes its recharge process at the end of April, a strategic alignment is observed where the pumping well starts its pumping activities concurrently with the initiation of agricultural activities in May. This orchestrated synchronization ensures a coordinated approach, allowing the pumping well to play an integral role in supporting agricultural needs as the planting season begins. Figure 2-7 provides a visual representation of the recharge schedule for the basin. By comparing this schedule to Figure 2-5, the counter-sequential operation of the well and basin becomes apparent.



Zone #: 2 | Zone Name: Recharge zone (2) | Layer #: 1

Edit selected row(s) or column: $RECHARGE

Start Time [day]	Stop Time [day]	Recharge [mm/yr]	Active
0	210	232766	✓
210	365	0	✓
365	575	232766	✓
575	730	0	✓
730	940	232766	✓
940	1095	0	✓
1095	1305	232766	✓
1305	1460	0	✓
1460	1670	232766	✓
1670	1825	0	✓
1825	2035	232766	✓
2035	2190	0	✓
.			
.			
.			
6050	6205	0	✓
6205	6415	232766	✓
6415	6570	0	✓
6570	6780	232766	✓
6780	6935	0	✓
6935	7145	232766	✓
7145	7300	0	✓

Figure 2-7- Basin recharge schedule over 20 years (7300 days).

2.2.3 Change in The Shape of The Recharge Basin

As a preliminary try, we aimed to examine the influence of the basin's shape, while maintaining a constant area, on the ultimate hydraulic head observed in the well. This exploration serves as a foundational step in understanding how variations in the geometric configuration of the basin may impact the groundwater level.

Two distinct alternative shapes were examined in this investigation. The first involved elongating the basin along the transversal direction of groundwater flow, while the second sought to mimic a shape resembling an arc. The deliberate choice to maintain a consistent area while altering the shape allows for a focused assessment of the influence of shape alone on the observed hydraulic head. The figures below offer a visual representation of the simulated basin shapes, providing a clear depiction of the spatial modifications under consideration.

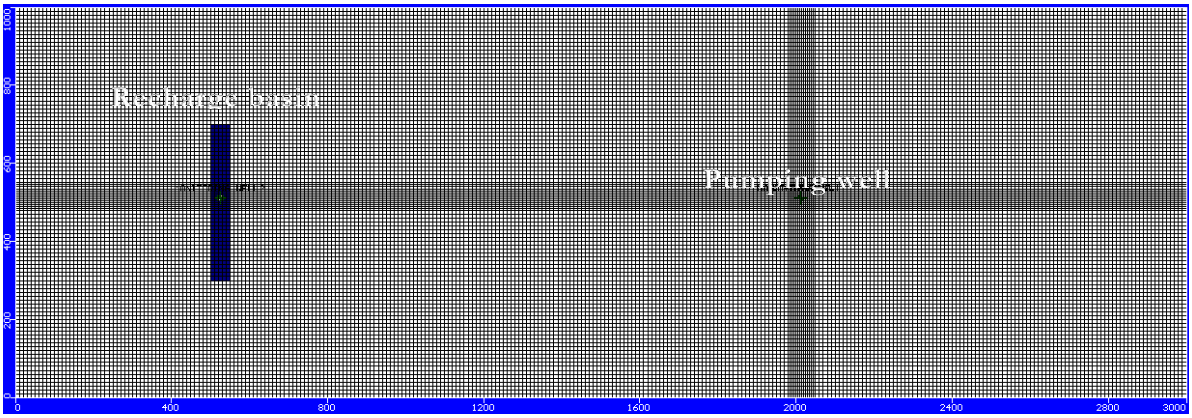


Figure 2-8 MODFLOW model schematic with the first proposed shape of the altered recharge basin.

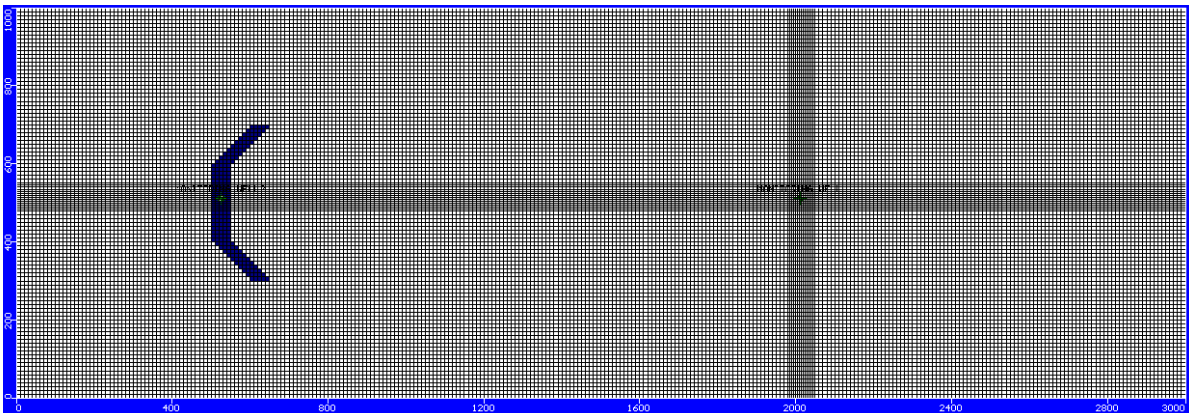


Figure 2-9 MODFLOW model schematic with the second proposed shape of the altered recharge basin.

2.2.4 Change in The Dimensions of The Recharge Basin

This section delves into the contribution of recharge from upland catchment areas to the pumping well domain, considering two pivotal components: the volumetric amount of recharge and the timing of its delivery. The primary objective here is to investigate the effects of adjusting the size of the recharge basin, while ensuring a constant recharge rate—essentially maintaining the same volumetric amount of recharge over the designated basin area. A deliberate emphasis was placed on achieving symmetry in the configuration of the basin relative to the placement of the well.

To examine how altering the size of the basin influences groundwater response and the hydraulic head in the well, the basin's dimensions have been deliberately adjusted. This systematic modification includes both increases and decreases in size. The analysis encompasses four proposed changes in the basin area, and the corresponding parameters are presented in the table below.

Table 2-3- Variations in basin area and corresponding recharge values

N. of realization	Basin area (m^2)	Infiltration recharge rate ($mm/year$)
Base model	100 × 200	232,766
1	200 × 300	77,588
2	50 × 100	931,064
3	40 × 60	1,930,716
4	20 × 30	7,758,870

The dimension of the recharge basin was transformed considering the fact every new defined basin area is capable of infiltrating the same volume rate of water over its own area. Notably, as the area decreases, to accommodate the same volume of water, the infiltration rate proportionally increases. To assess whether the increased infiltration rate remains within the permissible limits of the aquifer thickness, a monitoring well has been strategically established at the center of the infiltration basin. Furthermore, it is noteworthy to mention that, in order to maintain consistency and prevent alterations in the relative distance between the well and the basin area, the position of the front of the basin has been kept uniform across all models.

The applied changes encompassed variations in both the expansion and reduction of the basin's dimensions. Despite the dual approach, a keen awareness of the influential role of land use prompted a more pronounced inclination towards decreasing the overall basin area. This preference is evident in Table 2-3, where three simulations were conducted involving a decrease in the model's area. This directional shift in focus not only can prioritize the imperative of maintaining consistency in water infiltration but also will underscore the balance between the ecological sustainability of the solution and the practical implications of land utilization. However, it is important to note that the reduction in the area can only be carried out up to a certain point. As mentioned before, this limitation arises due to the escalating volumetric rate of water over the specified area, reaching a threshold where surpassing the thickness of the aquifer becomes a constraint.

The purpose of this investigation is to assess how changes in the spatial extent of the recharge basin can influence the overall dynamics of the groundwater system, with particular attention to its interaction with the pumping well and the subsequent impact on aquifer behavior.

2.2.5 Change in The Relative Distance of The Recharge Basin and The Well

In MAR methods like Aquifer Storage, Transfer, and Recovery (ASTR), the usual practice involves maintaining a relatively short distance, typically around 90 meters or less, between the injection well and the extraction well. This ensures that the extraction well remains within the storage "bubble" radius created by the recharge well, as both wells operate simultaneously [78].

In the context of the current study, wherein the schedules for infiltration and pumping are counter-sequential, therefore, there is a deliberate temporal gap designed to allow the infiltrated water sufficient time to traverse its path toward the pumping well. In this distinctive scenario, the conventional significance of the bubble radius concept comes under scrutiny. The customary practice of maintaining a short distance between the injection and extraction points, as encapsulated by the "bubble" radius, may not directly apply due to the intentional temporal offset between the two processes.

Given the counter-sequential nature of the infiltration and pumping processes, we have conducted an investigation into the impact of altering the relative distance between the infiltration basin and the well. The aim was to assess how and to which extent, the variations in this distance could influence the performance of the pumping well and, consequently, the observed hydraulic head in the well. This departure from the conventional approach allows for a more nuanced understanding of the dynamics in scenarios where the injection and production phases are not concurrent, providing valuable insights into the system's behavior under different operational conditions.

2.2.6 Change in The Hydraulic Conductivity

During this phase, numerical models were developed to delve into the intricate dynamics of groundwater flow, considering the intertwined influences of artificial recharge resulting from human activities and alterations in hydraulic conductivity reflecting changes in the medium's characteristics. The primary focus is on comprehensively understanding how these dual factors shape the behavior of groundwater over time and space.

The investigation is particularly geared towards examining the changes in the hydraulic head map and the drawdown experienced in the irrigation well throughout an extensive 20-year simulation. By analyzing these key parameters, the aim is to gain a deeper insight into the interplay between artificial recharge and variations in hydraulic conductivity, shedding light on the intricate patterns and potential consequences for groundwater resources.

To ensure meaningful comparisons with previous simulations, the temporal aspects of the well's production schedule and the recharge activities in the infiltration basin are synchronized. This synchronization serves to create a consistent framework, allowing for a thorough assessment of how the current combined influences compare with the outcomes of earlier simulations. By maintaining temporal alignment, one can identify any deviations, improvements, or patterns that emerge in the simulated groundwater behavior over the two-decade period. In this context, after doubling the hydraulic conductivity in one attempt to $2 \times 10^{-3} m\, s^{-1}$ (see Table 2-1.), the subsequent trial involved halving the hydraulic conductivity (to $5 \times 10^{-4} m\, s^{-1}$).

The scenarios mentioned in the previous sections, involving alterations in the shape, size, and relative distance of the basin from the well, will be simulated using the three specified values of hydraulic conductivity.

3 Discussion and Results

In this chapter, the simulation results are presented employing a qualitative approach, utilizing figures, for example, to illustrate the hydraulic head of the production well over a simulated period of 20 years. Additionally, we adopt a quantitative approach by presenting the results in tables for a more detailed examination. The primary aim of this study is to discern the influence of various model parameters and other pertinent factors on the aquifer system, with a particular focus on the response of the hydraulic head at the production well.

Our overarching objective is to pinpoint the variable(s) that most significantly influence the hydraulic head gain in the production well. This identification is crucial as it enables an increase in the production rate to a level where we attain the same final hydraulic head at the well as in the model without a basin. This objective will serve as a central focus in subsequent analyses.

Moreover, we endeavor to showcase the effectiveness of this Managed Aquifer Recharge (MAR) method in capturing surplus water during periods of abundance. This involves the infiltration of excess water through a basin, strategically located away from the production well. The basin allows for the storage and downstream flow of water in the underlying aquifer. At a designated distance, the stored water can be extracted and utilized during periods of necessity. The focus of this study is particularly on the agricultural season, highlighting the practical utility of MAR in aligning water availability with the demands of agricultural activities.

In the upcoming sections, we will delve into the impact of various variables on homogeneous realizations, with a focus on the final hydraulic head value at the production well after 20 years of simulation. To assess the sensitivity of this value, we have selected three different values for hydraulic conductivity. Our approach involves examining the effects of key factors discussed in the previous chapter. These factors encompass the introduction of the basin, alterations in its recharge rate, and modifications to the shape, area, and distance of the well-basin configuration. Initially, our analysis will concentrate on a model with a homogeneous hydraulic conductivity set at 0.001 m/s. We will systematically explore how each factor influences the final hydraulic head under this hydraulic conductivity value. Subsequently, we will repeat the investigation with the hydraulic conductivity doubled in one iteration and halved in another. This dual approach allows us to comprehensively evaluate the sensitivity of the model to changes in hydraulic conductivity, providing insights into how variations in this parameter may interact with other influential factors.

3.1 Model Outcomes With Base Model's (Moderate) Hydraulic Conductivity

This section provides a comprehensive discussion of the simulation outcomes for predefined scenarios in the previous chapter, focusing on the models characterized by a hydraulic conductivity of 0.001 m/s as specified in Table 2-1. The sensitivity analysis in the model encompasses crucial variables including the area, shape, rate, and distance of the basin from the well, each detailed in Table 3-1. This comprehensive set of parameters is essential for evaluating how variations in these factors influence the dynamics of the simulation. The table not only provides a thorough breakdown of the defined input variables but also presents insightful simulation results. Within this context, the simulation outcomes are reported in terms of the initial head, final head, and drawdown in the abstraction well.

These parameters serve as pivotal indicators, providing a holistic insight into the evolution of the groundwater system throughout the 20-year simulation period. Additionally, they offer valuable information on the anticipated gain or increase in the final hydraulic head at the well. This dual perspective not only captures the overall system dynamics but also quantifies the specific improvements or changes in the hydraulic head resulting from the introduction of the basin into the system under various scenarios, contributing to a more nuanced understanding of the model's behavior over the extended simulation timeframe.

Table 3-1 Model scenarios' input variables and simulation results over a period of 20 years.

	Base model	Introducing the basin		Change in the shape of the basin		Change in the area of the basin				Change in the relative distance of the basin and the well								
N. of model	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Description	(No basin)	1:1 infiltration rate	2:1 infiltration rate	Alongated transversal to flow	With shape of an arc	Increase in area	Decrease in area	Decrease in area	Decrease in area	Basin farther from well by 400 m	Basin farther from well by 200 m	Basin closer to well by 200 m	Basin closer to well by 400 m	Basin closer to well by 600 m	Basin closer to well by 800 m	Basin closer to well by 1000 m	Basin closer to well by 1200 m	Basin closer to well by 1400 m
Distance of basin and well (m)	1462.5	1462.5	1462.5	1462.5	1462.5	1462.5	1462.5	1462.5	1462.5	1862.5	1662.5	1262.5	1062.5	862.5	662.5	462.5	262.5	62.5
Basin rate (mm/y)	-	116383	232766	232766	232766	77588	931064	1939716	7758870	7758870	7758870	7758870	7758870	7758870	7758870	7758870	7758870	7758870
Basin area (m^2)	-	100x200 =20000	100x200 =20000	50x400 =20000	50x400 =20000	200x300 =60000	50x100 =5000	40x60 =2400	20x30= 600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600
Initial head (m)	34.150	34.580	35.007	35.051	35.098	35.006	35.050	35.059	35.076	34.384	34.730	35.424	35.777	36.135	36.502	36.898	37.388	38.422
Final head (m)	27.742	27.916	28.080	28.096	28.111	28.079	28.096	28.099	28.105	27.841	27.980	28.212	28.302	28.368	28.409	28.425	28.411	28.370
Draw down (m)	6.408	6.664	6.927	6.955	6.987	6.928	6.954	6.960	6.971	6.543	6.750	7.212	7.475	7.767	8.093	8.473	8.977	10.052
Final head difference from base model (m)	-	0.17371	0.33866	0.35387	0.36930	0.33759	0.35374	0.35691	0.362726	0.099386	0.237787	0.470566	0.560102	0.625927	0.667673	0.683275	0.668941	0.628445

3.1.1 Effect of Introducing The Basin

Two scenarios were established for this examination. The first scenario featured an infiltration rate where the ratio of volume infiltrated to volume abstracted was set at 1 (1:1 infiltration ratio). In the second simulation, the same basin was employed, but the infiltration volume was doubled in comparison to the volume abstracted (2:1 infiltration ratio). The figures presented below illustrate the plot of the hydraulic heads versus time recorded during 20 years of simulation of the base model with no infiltration and the two mentioned realizations with different infiltration rates. These data are recorded in the monitoring well, which is positioned at the same location as the production well.

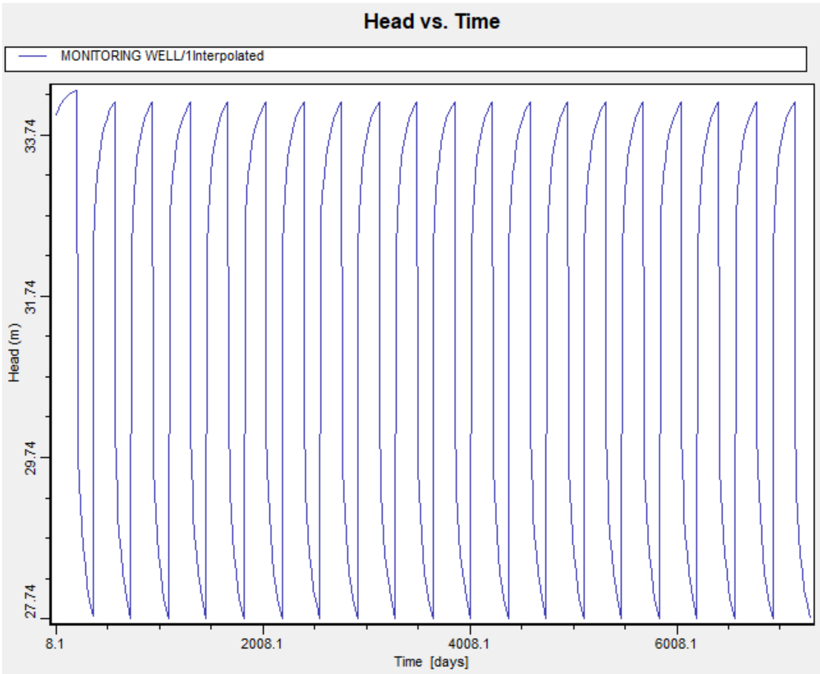


Figure 3-1 Hydraulic head vs time for the base model (no basin).

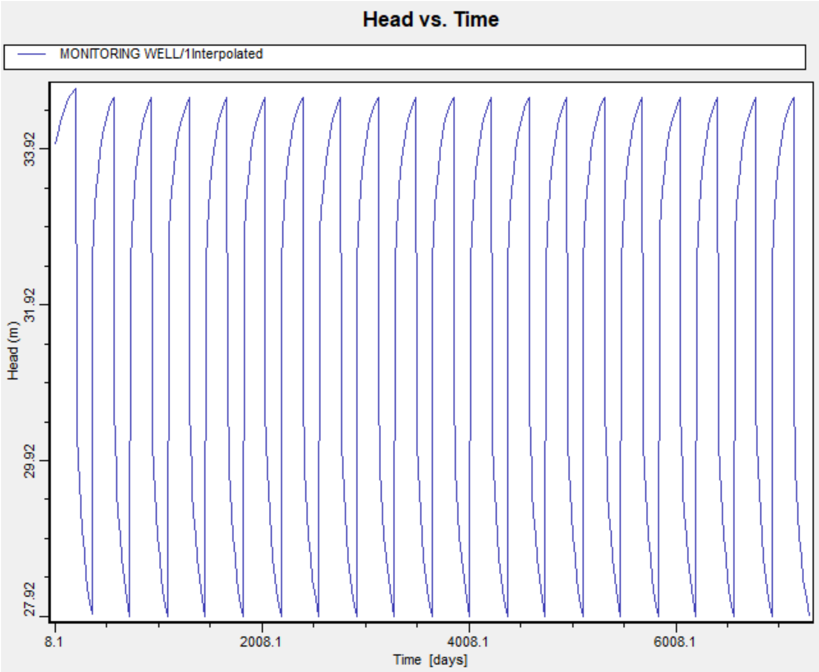


Figure 3-2 Hydraulic head vs time for the model with 1:1 infiltration ratio.

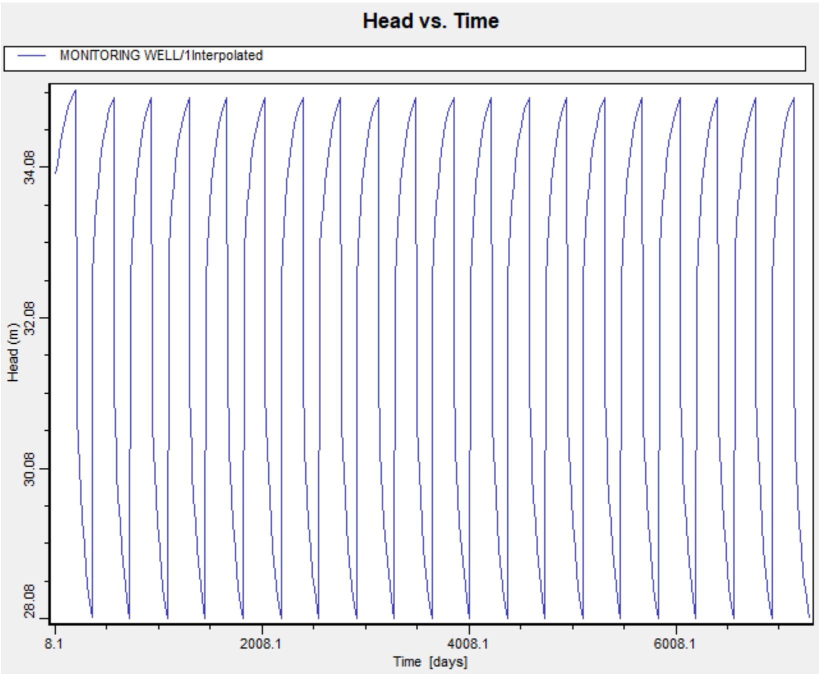


Figure 3-3 Hydraulic head vs time for the model with 2:1 infiltration ratio.

The figure below displays the recorded head at both the basin and the production well in the model with 2:1 infiltration ratio, during the 7300 days of simulations, highlighting a crucial observation. At the initiation of the simulation, the head at both the basin and the well increases, synchronizing with the onset of infiltrating water. However, after a cycle of infiltration, the head at both locations decreases. This decline corresponds to the production phase when water is extracted from the well. Additionally, during this period, the infiltration basin becomes inactive, causing water under the basin area to flow towards the well due to the disparity in pore pressure induced by the well's abstraction.

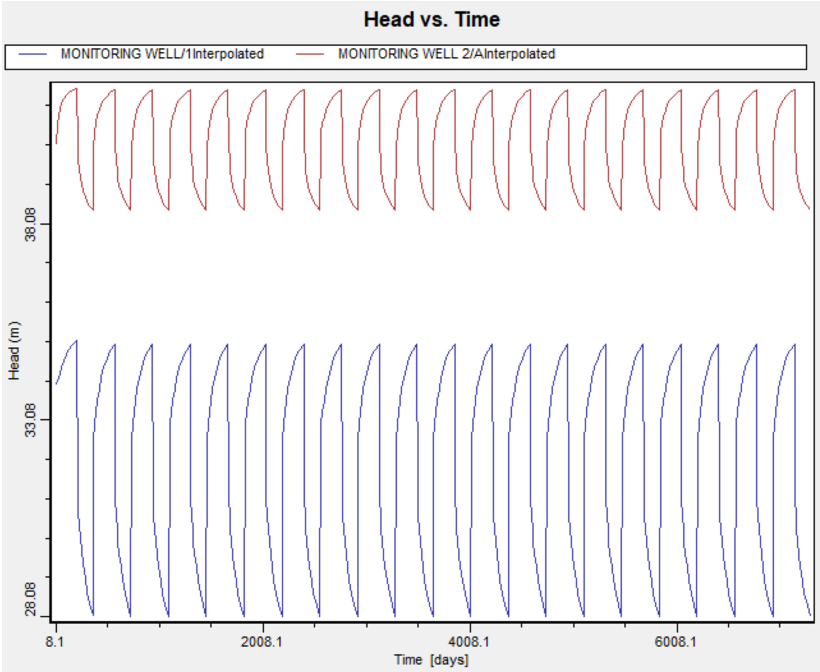


Figure 3-4 Hydraulic head data recorded at the monitoring wells placed at the basin (in red) and the production well (in blue).

Figure 3-5 Figure 3-6 display the simulation outcomes in terms of equipotential lines of the hydraulic head and the direction of groundwater flow through velocity arrows for both the base model and the model with a 2:1 infiltration ratio of the basin. These results are presented after 210 days, aligning with the conclusion of the first period of the basin's infiltration, during which the pumping well remains inactive.

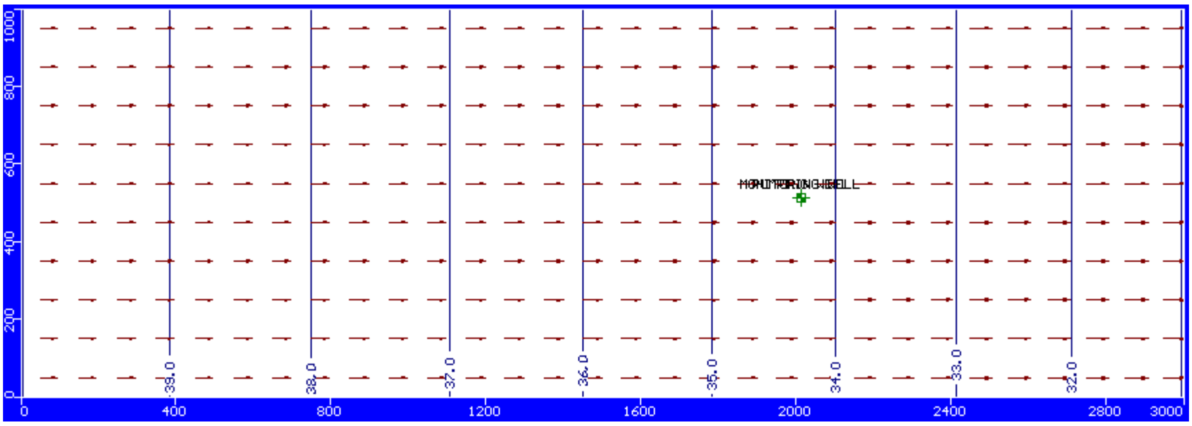


Figure 3-5 Equipotential lines and velocity arrows for the base model after 210 days.

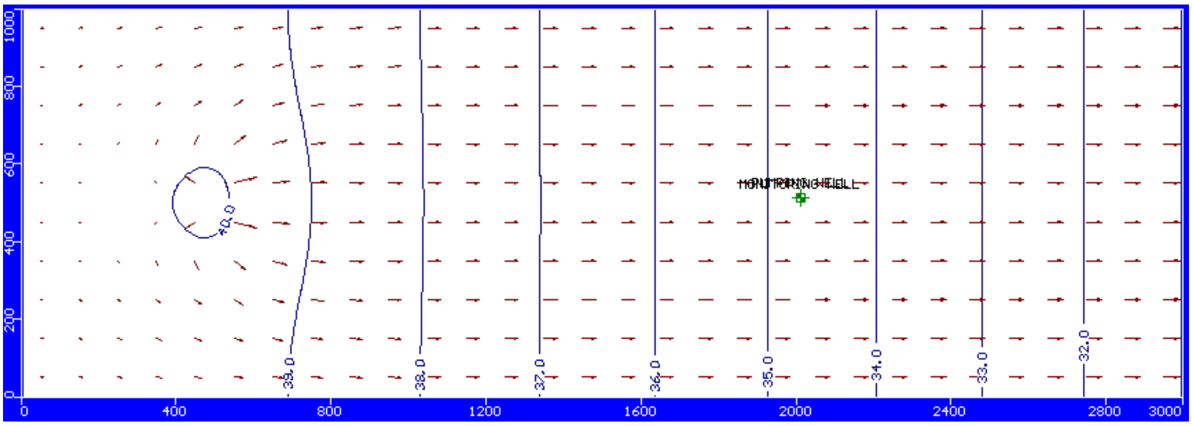


Figure 3-6 Equipotential lines and velocity arrows for the model with a 2:1 infiltration ratio after 210 days.

Comparing the two figures above reveals notable differences, in the simulated model with a basin, after the initial 210-day infiltration period, there is a discernible alteration in the equipotential lines compared to the model without a basin. Specifically, the equipotential line at 40 meters has shaped around the basin area, indicating an elevation in the water table within the aquifer. This suggests that the presence of the basin has contributed to raising the water table, which potentially it is expected to compensate for some of the volume of water abstracted from the well.

Additionally, results after 7300 days are depicted in Figure 3-7Figure 3-8, representing the completion of the production well's last cycle of abstraction when the infiltration basin is inactive. The figures depict the equipotential lines of the hydraulic head, along with the direction and magnitude of groundwater flow represented by velocity arrows.

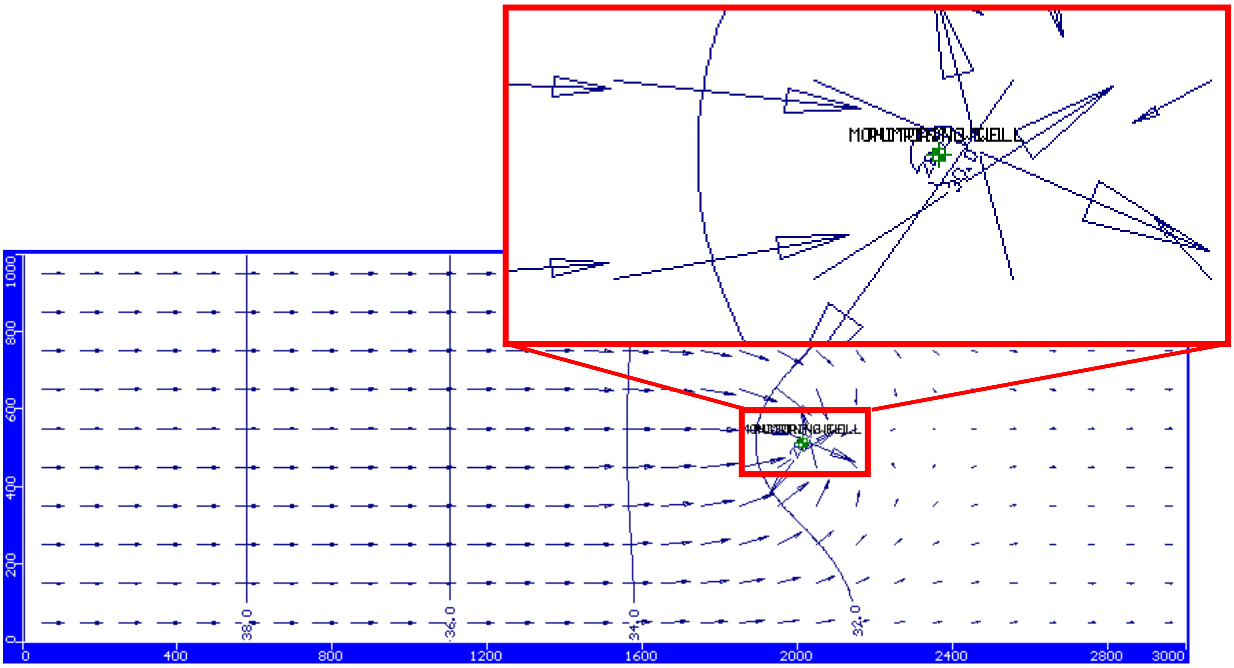


Figure 3-7 Equipotential lines and velocity arrows for the base model after 7300 days.

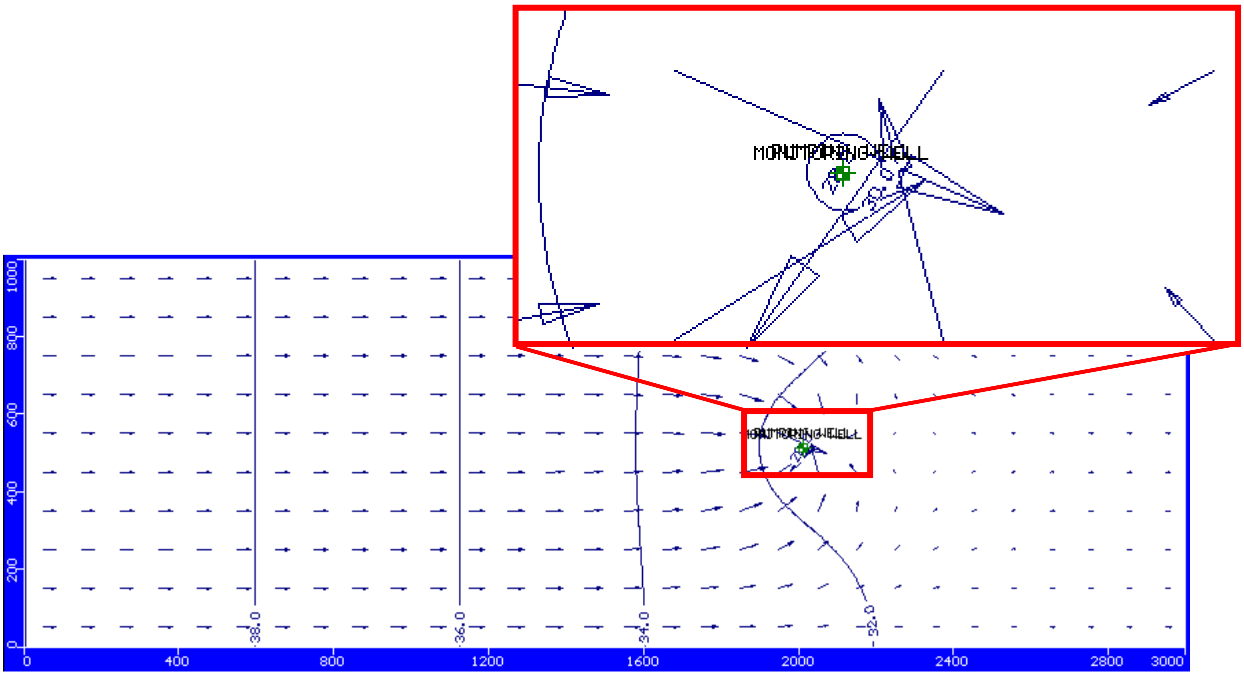


Figure 3-8 Equipotential lines and velocity arrows for the model with a 2:1 infiltration ratio after 7300 days.

Upon reviewing Figure 3-7Figure 3-8, the discernible impact of infiltration on the equipotential lines around the well may not be pronounced, yet it is observable that the head equipotential line of 30 meters around the production well in the model with the basin is wider. Examining the final hydraulic head values reported in Table 3-1, the increase in the hydraulic head for the models with infiltration rates of 1:1 (model number 2) and 2:1 (model number 3) with respect to the base model is 0.17 m and 0.34 m, respectively. As previously noted, for evaluating the influence of different variables on production operations and the final recorded hydraulic head in the well, maintaining the 2:1 infiltration rate was chosen for its higher gain, ensuring more evident changes.

3.1.2 Effect of Change in The Shape of The Basin

As previously mentioned, the shape of the infiltration basin, while maintaining the same basin area, has been altered in two ways: one with increased elongation in the transversal direction to the flow, and the second adopting the shape of an arc. The figures below depict plots of hydraulic heads versus time over a 20-year simulation period for the two models with the modified shapes of the infiltration basins.

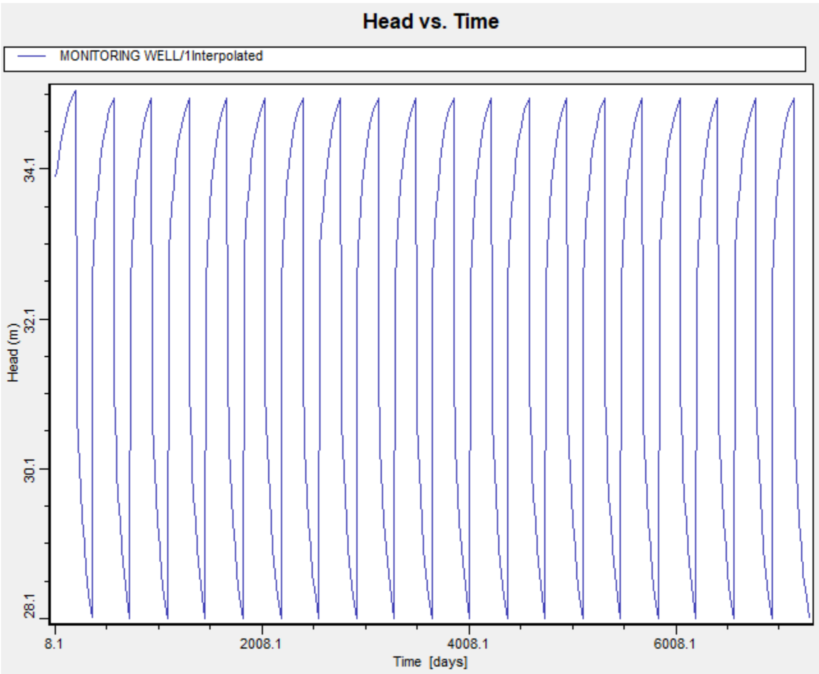


Figure 3-9 Hydraulic head vs time for the model with altered basin shape—increased length in the transversal direction to the flow.

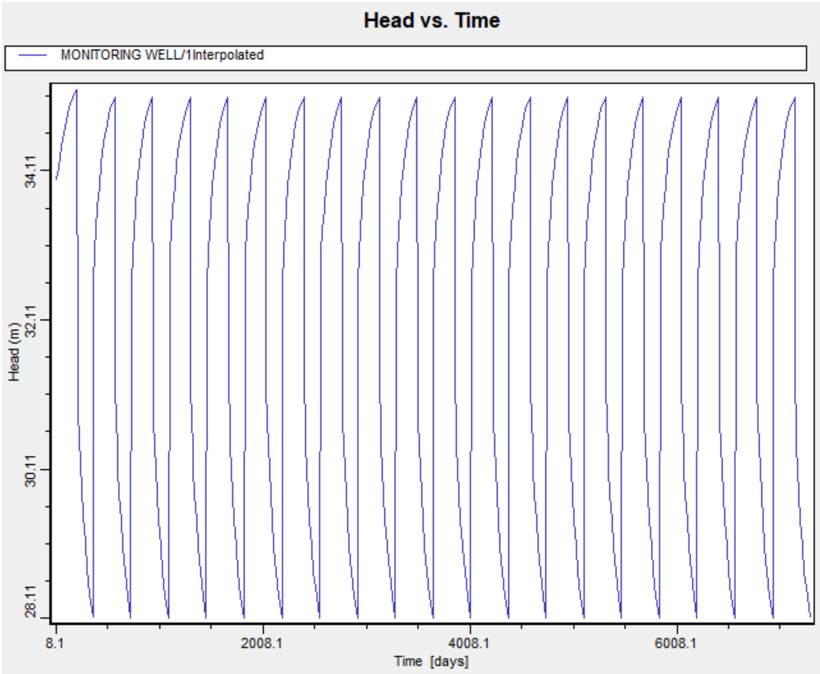


Figure 3-10 Hydraulic head vs time for the model with altered basin shape—like an arc.

Models number 4 and 5 share the same area in terms of square meters as model number 3, with the only difference being in their shape. The investigation aims to determine if the change in shape has noticeably change and more importantly has improved the hydraulic head, in order to assess whether shape is a significant variable in this context. As indicated in Table 3-1, the final hydraulic head for models number 4 and 5 is 28.096 and 28.111 meters, respectively, showing a minimal increase of approximately 0.015 meters compared to the final head of model 3.

Based on these reported results, it can be inferred that, given the constant area, the change in shape does not significantly improve or strongly influence the final hydraulic head. Consequently, shaping the basin differently may not be a worthwhile practice for enhancing the system's performance. However, the positive aspect is that, since shape is not a decisive factor, one can configure the basin based on land availability while maintaining a specified area for the system.

3.1.3 Effect of Change in The Dimensions of The Basin

In the context of varying the size of the basin, four different dimensions were considered, including: 300x200 m^2, 50x100 m^2, 40x60 m^2, and lastly, 20x30 m^2. The graphs below illustrate the hydraulic head versus time for each of these configurations, highlighting how changes in size impact the production well's head over a 20-year period of seasonal abstraction.

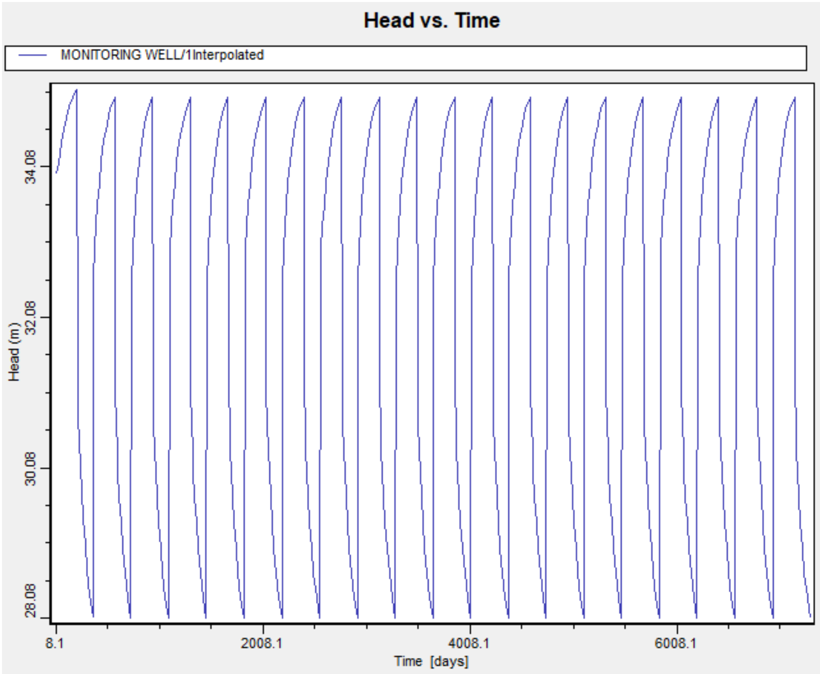


Figure 3-11 Hydraulic head vs time for the model with basin dimension of 300x200 m².

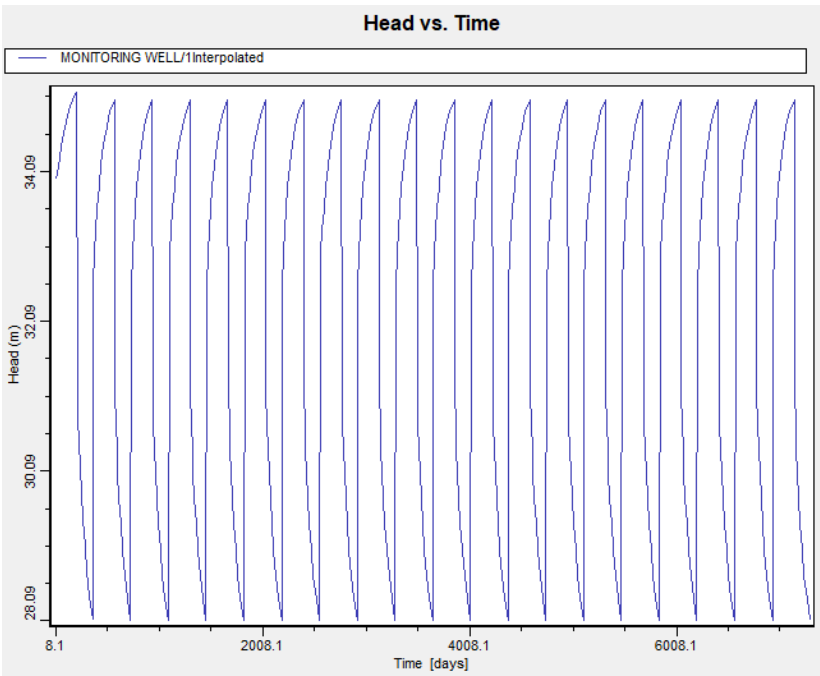


Figure 3-12 Hydraulic head vs time for the model with basin dimension of 50x100 m².

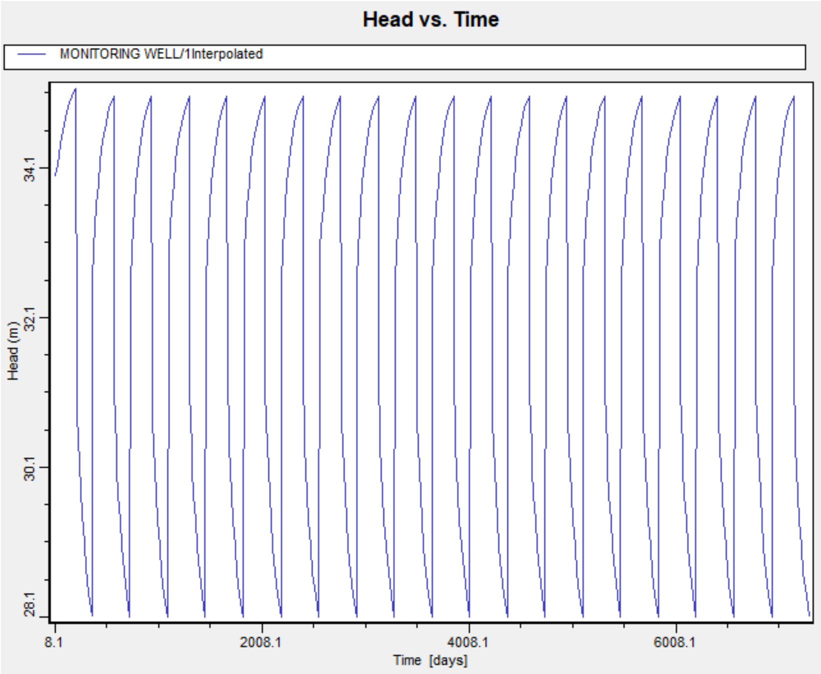


Figure 3-13 Hydraulic head vs time for the model with basin dimension of 40x60 m^2.

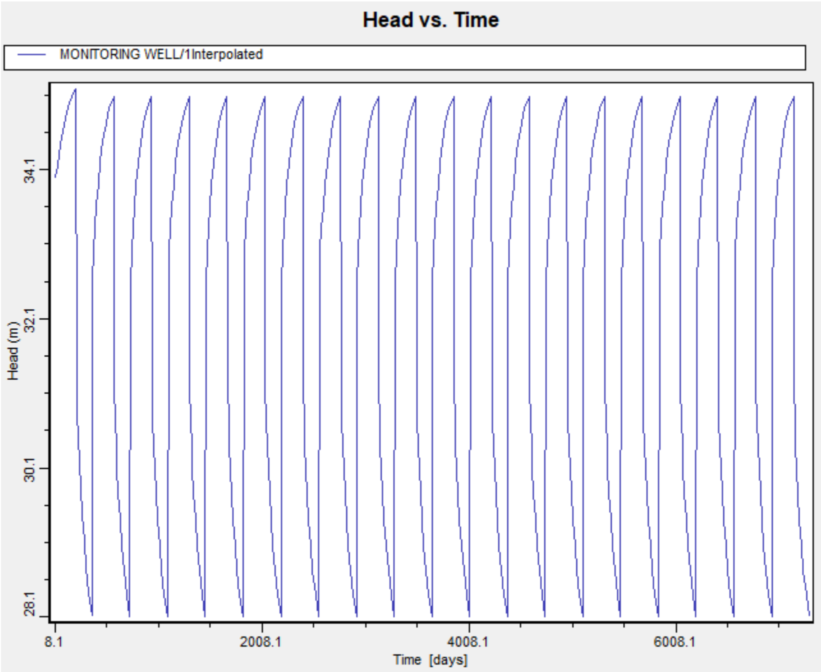


Figure 3-14 Hydraulic head vs time for the model with basin dimension of 20x30 m^2.

Based on the findings presented in Table 3-1, altering the area of the basin while maintaining the front of the basin in the same location does not yield a significant change in the final hydraulic head at the well. However, it's noteworthy that with an increase in area, there is a marginal negative impact on the gain in hydraulic head. Conversely, reducing the area, as observed in model 9 with dimensions of 20x30m, results in an improvement of almost 0.03m in hydraulic head gain compared to model 3. While this improvement may not be substantial, it holds significance. This outcome is crucial, because by decreasing the basin area, not only we are considering important aspects such as land use in the design of an infiltration basin, but we are also enhancing the final hydraulic head rather than diminishing it.

An additional consideration arises when decreasing the basin area while maintaining the same volume of infiltrated water for all models. This leads to an increase in the infiltration rate over the reduced basin area. In this context, the potential for groundwater mounding becomes pivotal, as excessively high mounding could impede further water infiltration, causing water to flow on the surface once it surpasses the aquifer thickness.

To assess the adequacy of the optimum model (model number 9), a monitoring well was introduced at the basin to record the water level and the hydraulic heads. The figure below depicts the equipotential lines of the hydraulic heads after the initial 210-day infiltration period, where the most significant water level increase happens before initiation of the well production. According to the data obtained from the monitoring well, the maximum water level reaches a height of 42.8 meters, which is below the thickness of the model (50 meters). This indicates that the area of 20x30m, as applied in model number 9, can be safely considered for the defined configuration without exceeding the aquifer thickness limitation.

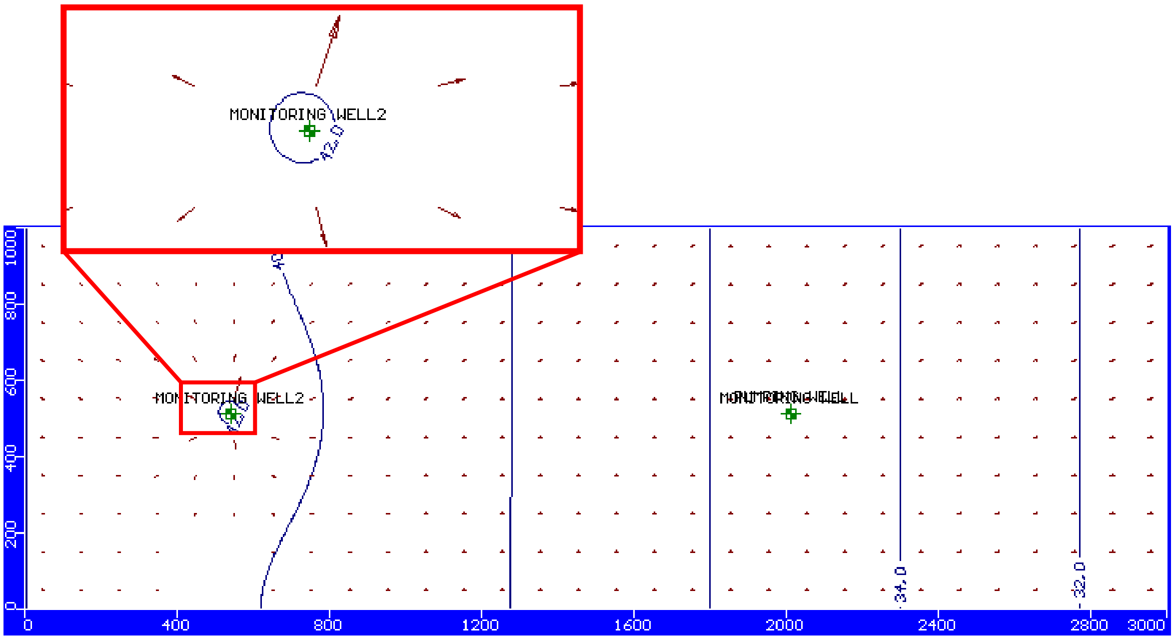


Figure 3-15 Hydraulic head equipotential lines map for model number 9 after first infiltration period (at 210 days).

Given that the model number 9 has produced the most satisfactory results in terms of the final hydraulic head at the well while maintaining the minimum occupied area, the upcoming section which delves into examining the influence of the relative distance between the basin and the well, employs the basin with dimensions of 20x30 meter square for simulation.

3.1.4 Effect of Change in The Relative Distance of The Basin and The Well

In this section, we delve into the examination of the relative distance between the well and the infiltration basin, aiming to discern the correlation between this distance and the ultimate drawdown in the well. The reference basin was initially positioned at 550 meters from upstream of the model along the x direction, while the well was situated at 2012.5 meters, resulting in a 1462.5-meter distance between the basin and the well.

To explore the impact of distance, various configurations were simulated and the basin was systematically relocated, first by increasing the distance by 200 (model n.11) and 400 (model n.10) meters beyond the reference distance (with the relative distance of 1662.5 and 1862.5 meters, respectively). Subsequently, the basin was progressively brought closer to the abstraction well in increments of 200 (model n.12), 400 (model n.13), 600 (model n.14), 800 (model n.15), 1000 (model n.16), 1200 (model n.17), and 1400 (model n.18) meters with the relative distance of 1262.5, 1062.5, 862.5, 662.5, 462.5, 262.5 and 62.5, respectively for each mentioned simulated realization. This analysis enables us to gain insights into how variations in the relative distance between the basin and the well influence the final hydraulic head in the well over the course of the simulation.

To minimize the number of figures and keep it concise, a selection of hydraulic head vs. time plots for specific realizations has been provided here.

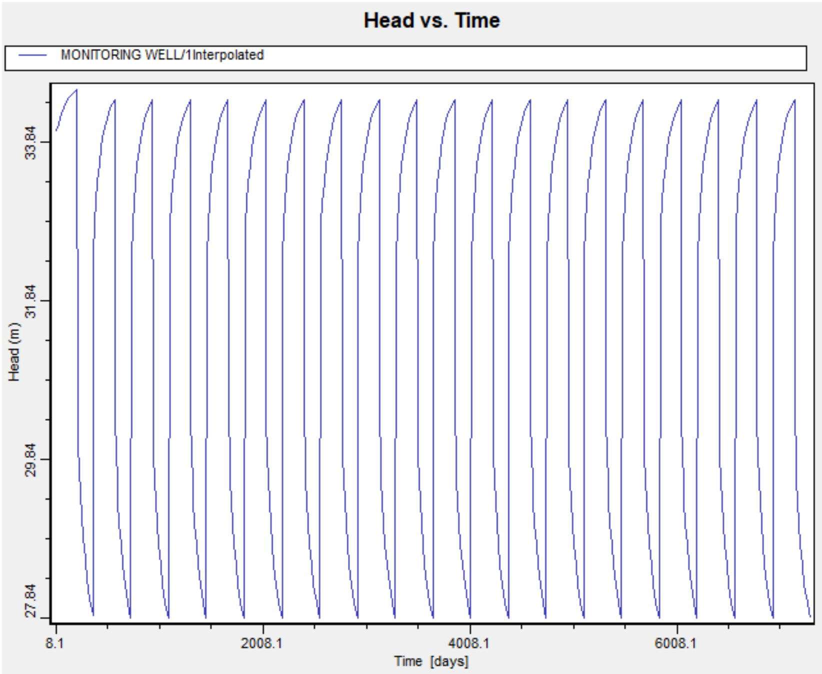


Figure 3-16 Hydraulic head vs time for the model n.10, positioned 400 meters farther from the well than the reference distance.

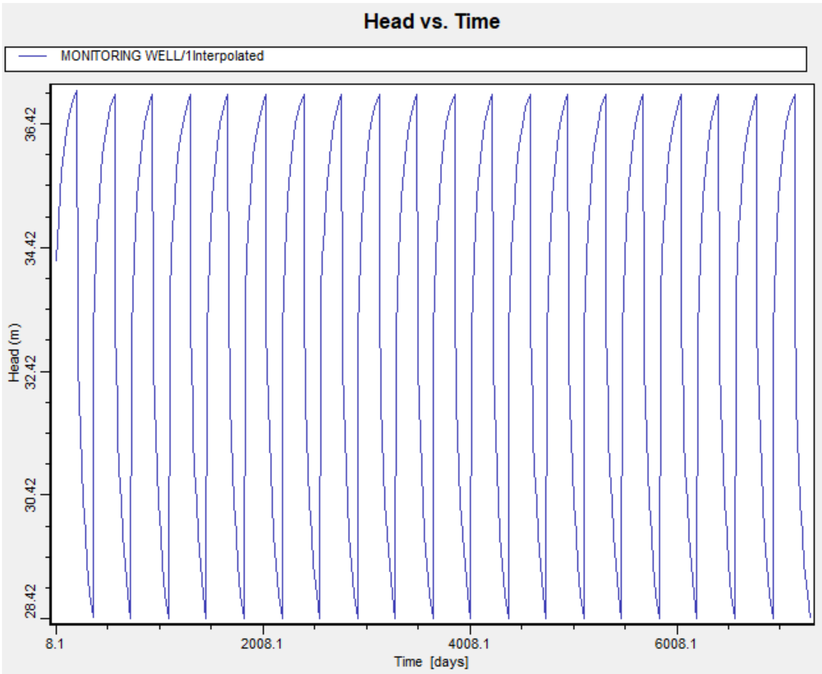


Figure 3-17 Hydraulic head vs time for the model n.16, positioned 1000 meters closer to the well than the reference distance.

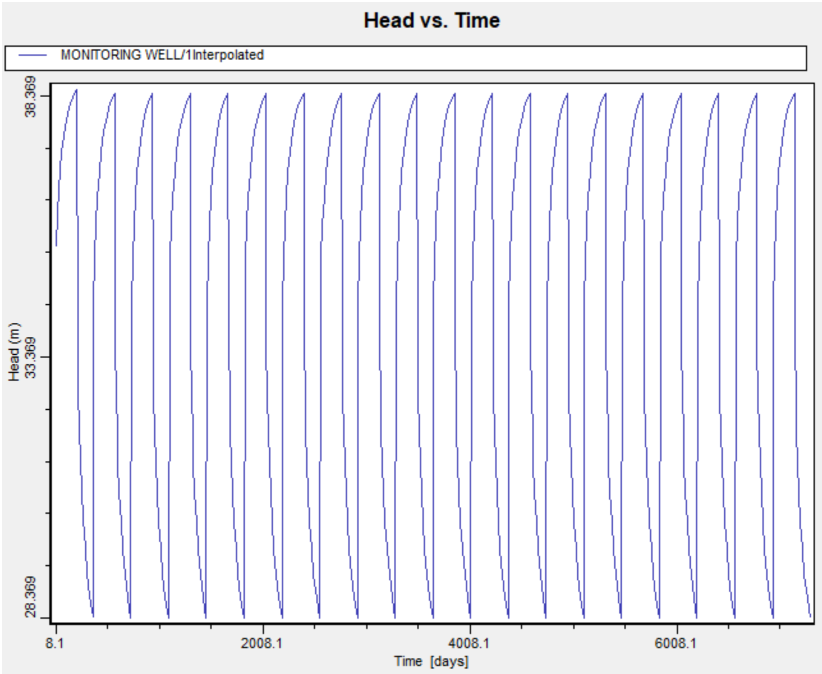


Figure 3-18 Hydraulic head vs time for the model n.18, positioned 1400 meters closer to the well than the reference distance.

The examination of altering the distance between the basin and the well aimed to assess the extent and magnitude of the impact on the hydraulic head gain at the production well. The results indicate that as the basin relocates farther away, the increase in hydraulic head becomes less pronounced, whereas moving the basin closer to the well results in a more significant gain. Figure 3-19Figure 3-20 depict the final hydraulic head at the abstraction well and the hydraulic head gain compared to the base model over time, respectively.

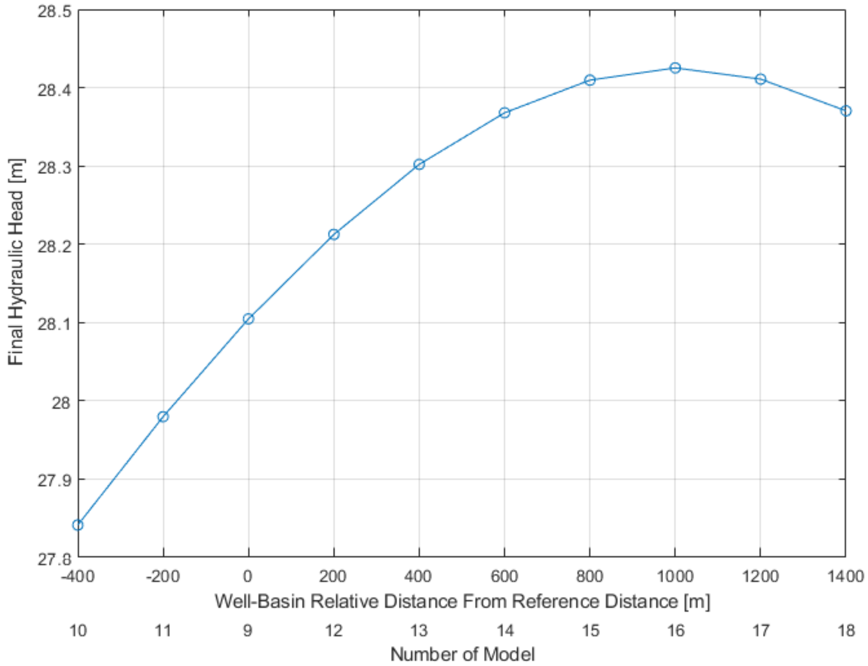


Figure 3-19 Effect of change in relative distance of basin-well on final hydraulic head.

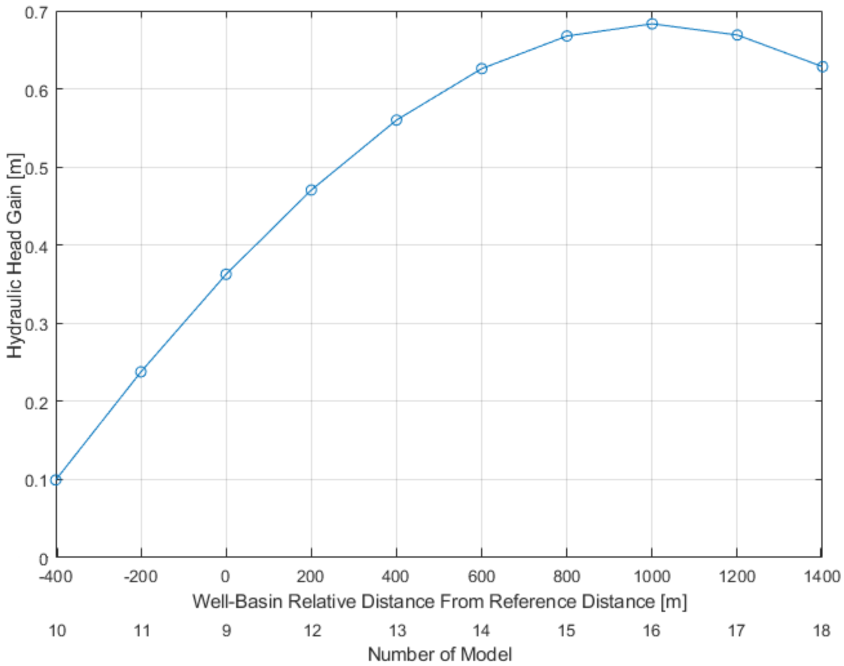


Figure 3-20 Effect of change in relative distance of basin-well on hydraulic head gain.

The presented figures offer valuable insights, highlighting two notable observations. Firstly, it is evident that there exists a critical threshold regarding the proximity of the basin to the well. Beyond a specific distance, the gain in hydraulic head not only diminishes but takes on a negative trend. This implies the existence of an optimal distance for the well-defined system configuration, beyond which the hydraulic head gain is counterproductive.

Secondly, the figures underscore the asymmetric impact of adjusting the distance from the well. The influence of increasing the distance is more substantial compared to decreasing it. This disparity is discernible in the plot's slope, which initiates with a steep incline when the basin is distanced from the well. However, as the basin is brought closer, this increase in hydraulic head becomes progressively less significant. This nuanced understanding of the distance's impact on hydraulic head dynamics is pivotal for optimizing the system's performance.

3.2 Model Outcomes with Low Hydraulic Conductivity

In this section, the predefined scenarios are replicated, this time with a reduced hydraulic conductivity of 0.0005 m/s, which is half of the reference hydraulic conductivity value (refer to Table 2-1). Similar to the previous analysis, the sensitivity analysis in the model encompasses variables such as area, shape, rate, and the distance of the basin from the well, each meticulously detailed in Table 3-2. This comprehensive set of parameters is crucial for evaluating how variations in these factors influence the dynamics of the simulation. The table not only includes the inputs data to the MODFLOW but also presents the simulation results, including the initial head, final head, and drawdown in the abstraction well. These simulation outcomes provide valuable information regarding the expected gain or increase in the final hydraulic head at the well over the 20-year simulation period.

In this section, the objective is to explore the impact of a decreased hydraulic conductivity on the hydraulic head at the well under various scenarios of defining a basin in the model. This exploration aims to unveil how such adjustments influence the overall performance and the outcomes of the simulation.

Table 3-2 Model scenarios' input variables and simulation results of the scenario with low hydraulic conductivity, over a period of 20 years.

	Base model	Introducing the basin		Change in the shape of the basin		Change in the area of the basin				Change in the relative distance of the basin and the well								
N. of model	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Description	(No basin)	1:1 infiltration rate	2:1 infiltration rate	Alongated transversal to flow	With shape of an arc	Increase in area	Decrease in area	Decrease in area	Decrease in area	Basin farther from well by 400 m	Basin farther from well by 200 m	Basin closer to well by 200 m	Basin closer to well by 400 m	Basin closer to well by 600 m	Basin closer to well by 800 m	Basin closer to well by 1000 m	Basin closer to well by 1200 m	Basin closer to well by 1400 m
Distance of basin and well (m)	1462.5	1462.5	1462.5	1462.5	1462.5	1462.5	1462.5	1462.5	1462.5	1862.5	1662.5	1262.5	1062.5	862.5	662.5	462.5	262.5	62.5
Basin rate (mm/y)	-	116383	232766	232766	232766	77588	931064	1939716	7758870	7758870	7758870	7758870	7758870	7758870	7758870	7758870	7758870	7758870
Basin area (m^2)	-	100x200 =20000	100x200 =20000	50x400 =20000	50x400 =20000	200x300 =60000	50x100 =5000	40x60 =2400	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600
Initial head (m)	33.470	34.188	34.893	34.966	35.047	34.894	34.966	34.982	35.010	33.857	34.429	35.607	36.225	36.868	37.546	38.293	39.232	41.177
Final head (m)	18.074	19.472	20.607	20.704	20.808	20.605	20.702	20.727	20.763	18.900	19.923	21.455	22.006	22.411	22.676	22.794	22.754	22.550
Draw down (m)	15.396	14.716	14.286	14.262	14.239	14.289	14.264	14.255	14.247	14.957	14.506	14.152	14.219	14.457	14.870	15.499	16.478	18.627
Final head difference from base model (m)	-	1.39844	2.53329	2.63015	2.73422	2.53108	2.62804	2.65254	2.689193	0.826633	1.848960	3.381860	3.932056	4.337095	4.602905	4.720304	4.680315	4.475961

3.2.1 Effect of Introducing The Basin

Similarly to previous analyses, two models with different infiltration rates for introducing the basin were simulated, each featuring a basin with a ratio of volume infiltrated to volume abstracted of 1 and 2, respectively. The figures provided below visually depict the time-dependent plot of hydraulic heads. These plots are derived from the data recorded by a monitoring well strategically placed at the well location, over a 20-year simulation period. The first figure represent the model serves as the base, representing no infiltration, while the second figure demonstrates the model with a basin of 2:1 infiltration ratio.

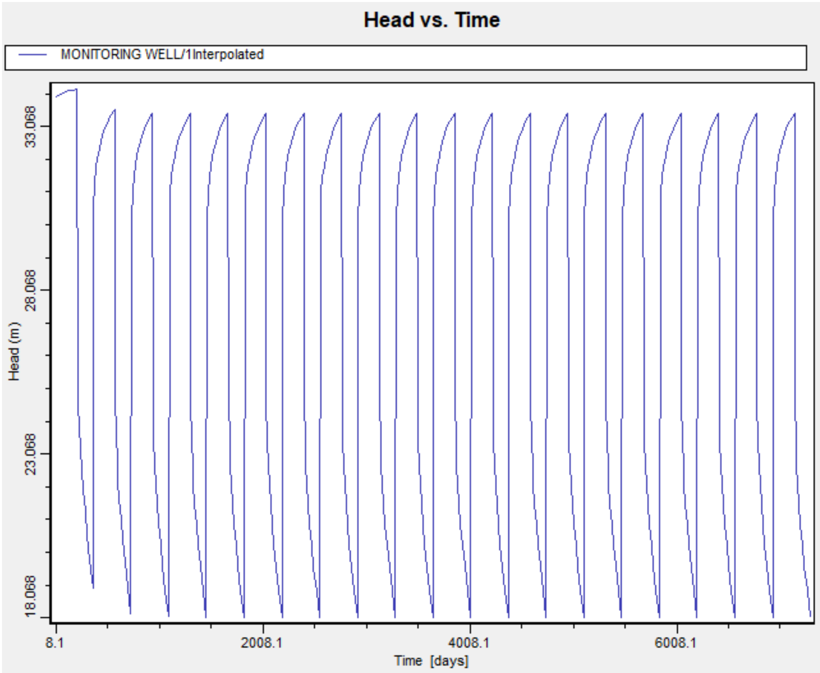


Figure 3-21 Hydraulic head vs time for base model (no basin) with low hydraulic conductivity.

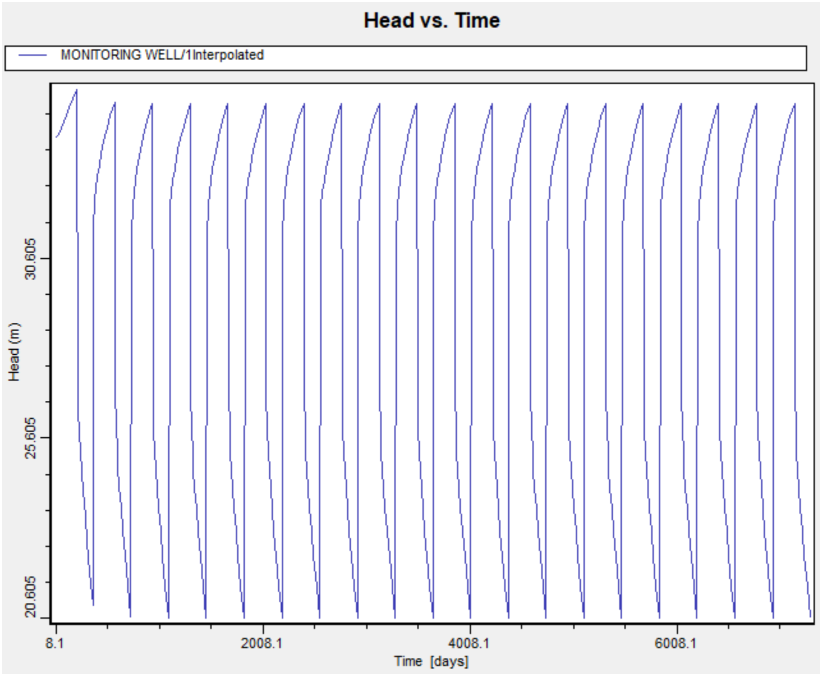


Figure 3-22 Hydraulic head vs time for the model with 2:1 infiltration ratio and low hydraulic conductivity.

Figure 3-23Figure 3-24 illustrate the simulation outcomes following the initial cycle of water infiltration into the model, specifically at 210 days. These figures visually represent the head equipotential lines and the velocity arrows, providing insights into both the direction and magnitude of the flow. Upon comparing Figure 3-6Figure 3-24, it becomes evident that in the scenario of reduced hydraulic conductivity, there is a more pronounced rise in water levels around the basin at the conclusion of the initial infiltration cycle.

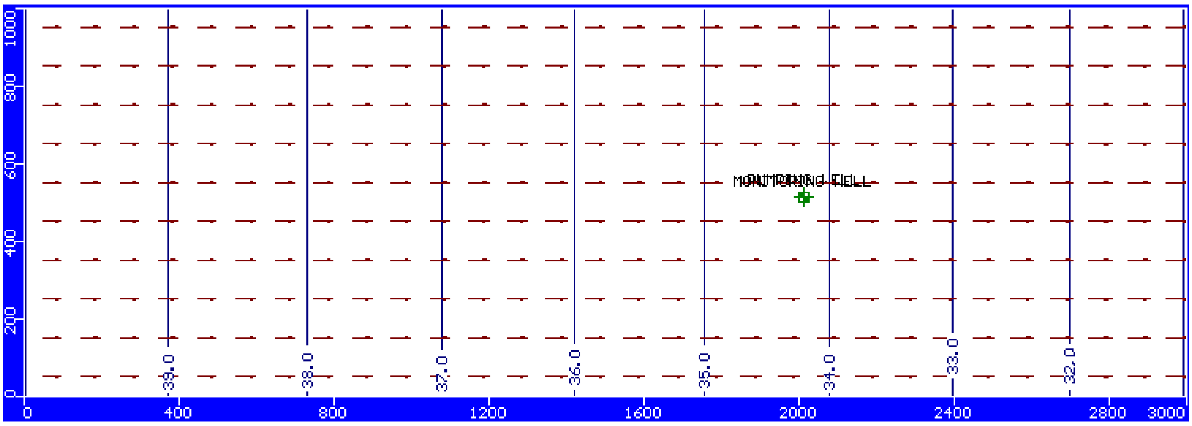


Figure 3-23 Equipotential lines and velocity arrows for the base model with low hydraulic conductivity after 210 days.

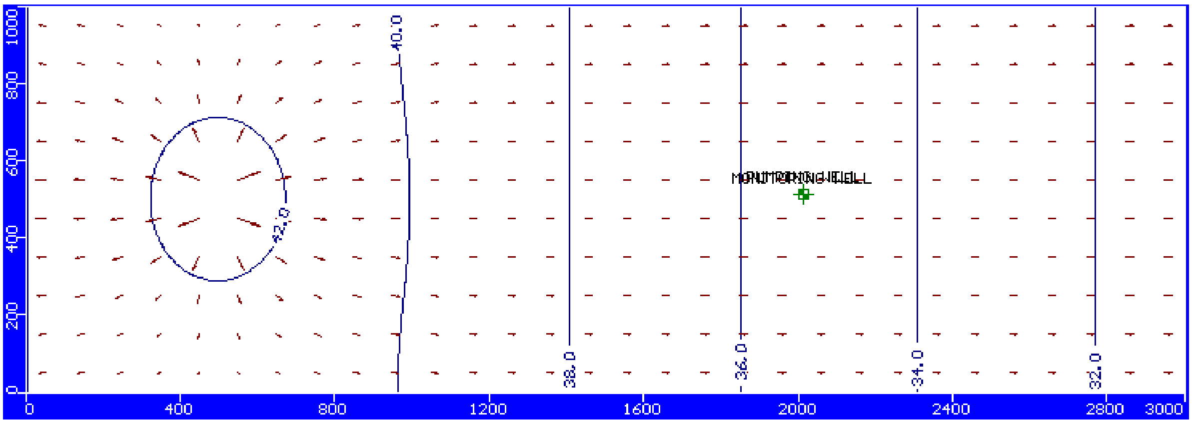


Figure 3-24 Equipotential lines and velocity arrows for the model with a 2:1 infiltration ratio and low hydraulic conductivity after 210 days.

Figure 3-25Figure 3-26 portray the simulation outcomes after 7300 days, equivalent to a 20-year duration. These figures symbolize the conclusion of the production well's final cycle of abstraction. The visualizations present equipotential lines of hydraulic head and the magnitude and directional flow of groundwater through velocity arrows.

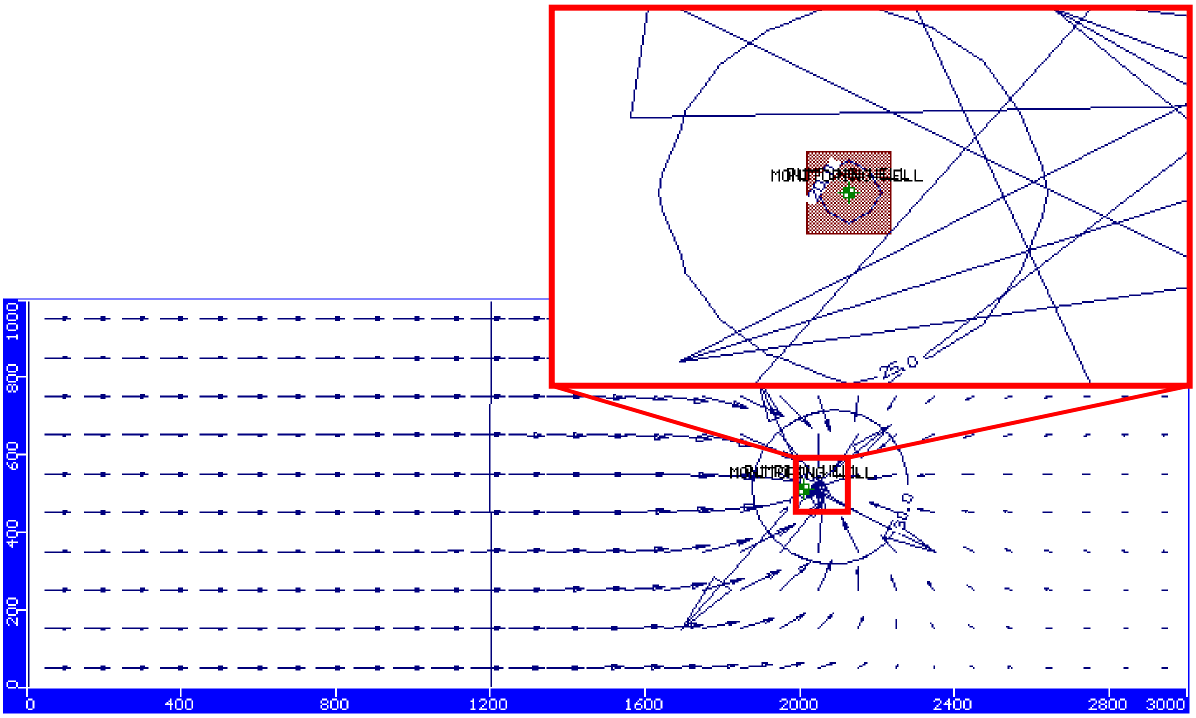


Figure 3-25 Equipotential lines and velocity arrows for the base model with low hydraulic conductivity after 7300 days.

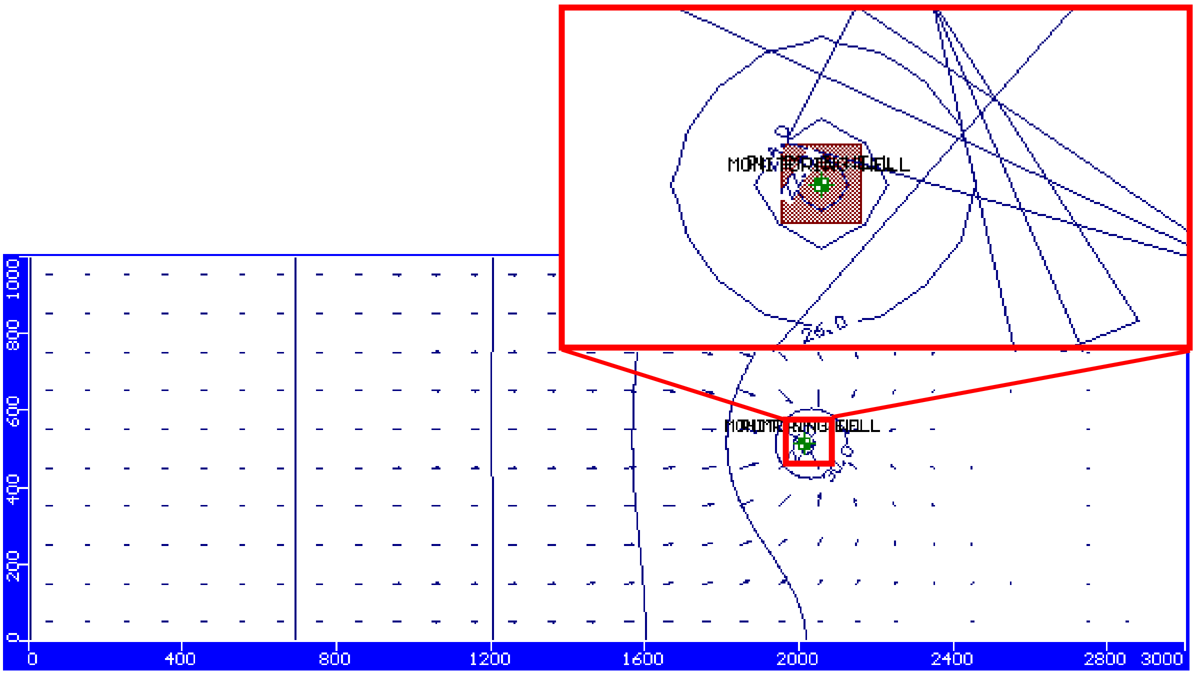
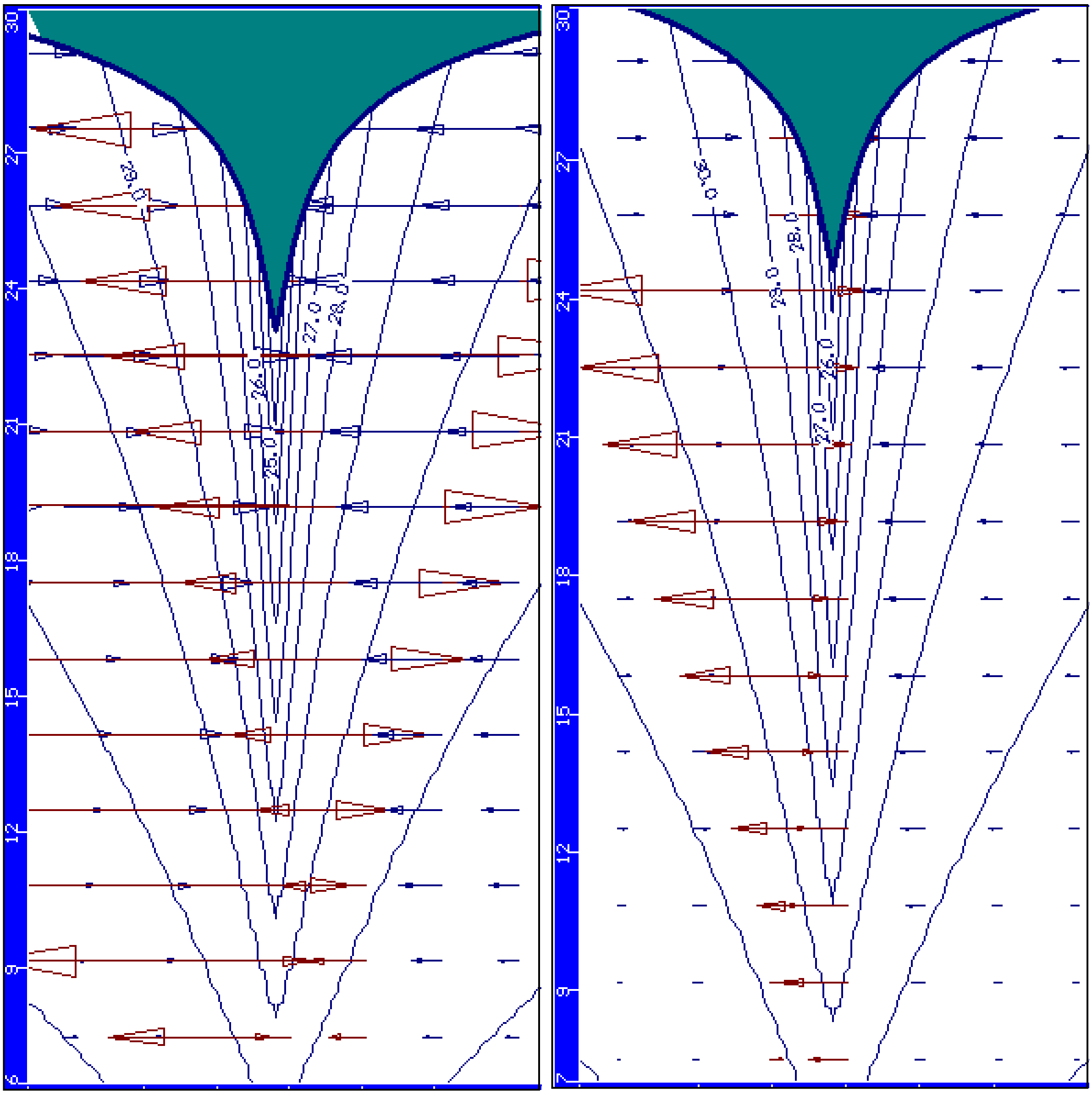


Figure 3-26 Equipotential lines and velocity arrows for the model with a 2:1 infiltration ratio and low hydraulic conductivity after 7300 days.

The figures above, representing the results after a 20-year simulation period, highlight a noticeable difference in equipotential lines around the well. In the base model, the change in equipotential lines is abrupt, attributed to the system's concerted effort to maintain a constant production rate despite the low hydraulic conductivity. Conversely, Model Number 3, featuring an infiltration rate of 2:1, exhibits a more gradual shift in equipotential lines and the water table. This is attributed to a portion of the water satisfying the production rate of 100 liters/s originating from the recharged water of the basin. With lower hydraulic conductivity, the alterations in water level and hydraulic head become more pronounced. Figure 3-27 (a) and (b) illustrate a zoomed-in view of the y-z cross-sectional plane in the vicinity of the production well, highlighting more vividly the differences between models 1 and 3 in terms of the changes in the water level and head equipotential lines after 20 years of simulation. As indicated by the figures, the drawdown is more pronounced in the base model. Furthermore, upon examining the velocity vectors in this model, their larger size indicates a higher magnitude of flow in the vicinity of the well, necessary to meet the same abstraction rate.



(a) (b)

Figure 3-27 Cross sectional view of production well after 7300 days at (a) base model (n.1); (b) model with 2:1 infiltration rate (n.3).

Comparing the drawdown in the current scenario (with a hydraulic conductivity of 0.0005 m/s) and the one with moderate hydraulic conductivity of 0.001 m/s, where the values measure approximately 6 and 15, respectively, reveals that the drawdown is more than two times greater in the present scenario (refer to Table 3-1Table 3-2). This phenomenon arises from the decrease in hydraulic conductivity; whether we are infiltrating water or extracting it, the change in water level becomes more pronounced. This results in a higher disparity between the initial and final hydraulic head, consequently leading to an increased drawdown.

3.2.2 Effect of Change in The Shape of The Basin

We have observed that when dealing with moderate hydraulic conductivity, the shape of the basin does not play a decisive role in this study. However, as the hydraulic conductivity decreases, the changes in simulation results become more significant. This is attributed to the system exerting additional effort to meet the production rate, as the ease of water flow and the provision of the requested abstracted water become more challenging. Consequently, we have revisited the investigation into the impact of the basin's shape on the system's performance. The rationale behind this is to explore whether, as hydraulic conductivity decreases, the effect of the basin's shape becomes significant enough to be considered a decisive factor in designing the MAR project and the infiltration basin or not.

Models number 4 and 5, while sharing the same area in square meters as model number 3, differ only in their shape. Therefore, we aim to compare the final hydraulic head recorded in the production well for these three models to discern the impact of the basin's shape. According to the data presented in Table 3-2, the final hydraulic head for models number 4 and 5 is reported as 20.704 and 20.808 meters, respectively. This represents a minimal increase of approximately 1 to 2 centimeters compared to the final head of model 3, recorded as 20.607 m. As a result, it can be concluded that, even when the hydraulic conductivity is low, given a constant area, the change in shape does not significantly enhance or strongly influence the final hydraulic head. Consequently, altering the shape of the basin may not be a particularly beneficial or a worthwhile practice for improving the system's performance. However, as mentioned before, the positive aspect is that, since changing the shape does not influence the results significantly, one can adjust the shape of the basin based on land availability while maintaining a specified area in terms of square meters for the designed system.

3.2.3 Effect of Change in The Dimensions of The Basin

In the context of altering the size of the basin, simulations have been reconducted for four predefined distinct areas: 300x200 m², 50x100 m², 40x60 m², and finally, 20x30 m². Diminishing the basin area while maintaining a constant volume of infiltrated water for all models, introduces the phenomenon of groundwater mounding and the rise of water level.

In this specific scenario, the hydraulic conductivity has been decreased. Hydraulic conductivity serves as a measure of how easily water can traverse a porous medium, such as an aquifer. A lower hydraulic conductivity signifies reduced permeability and diminished ability of the aquifer to transmit water efficiently.

When water is introduced into an aquifer with low hydraulic conductivity, it encounters greater resistance to flow through the subsurface. Consequently, the water tends to accumulate within the aquifer, resulting in a more substantial increase in water level compared to an aquifer with higher hydraulic conductivity. Conversely, in a highly conductive aquifer, water can traverse the subsurface more effortlessly, leading to a less pronounced rise in water level due to more efficient dispersion within the porous medium. This principle holds significance in various hydrogeological applications, notably in groundwater recharge. Understanding the hydraulic properties of the aquifer becomes crucial for effective management of water resources and environmental protection. By comprehending how hydraulic conductivity influences water flow and level changes, one can make informed decisions in applications ranging from groundwater recharge strategies to broader environmental conservation efforts.

In this scenario, with the reduced hydraulic conductivity, the impact of the rise in groundwater becomes more pronounced. To ascertain whether this groundwater mounding surpasses the limit of the aquifer thickness, a monitoring well has been strategically introduced at the center of the infiltration basin. Figure 3-28 depicts the hydraulic head equipotential lines of the model after 210 days, representing the most significant rise in water level during the 20-year simulation. Additionally, Figure 3-29 illustrates the model's cross-section at the y-z plane coordinate, offering insights into the groundwater mounding at the end of the 210-day period before production from the well commences.

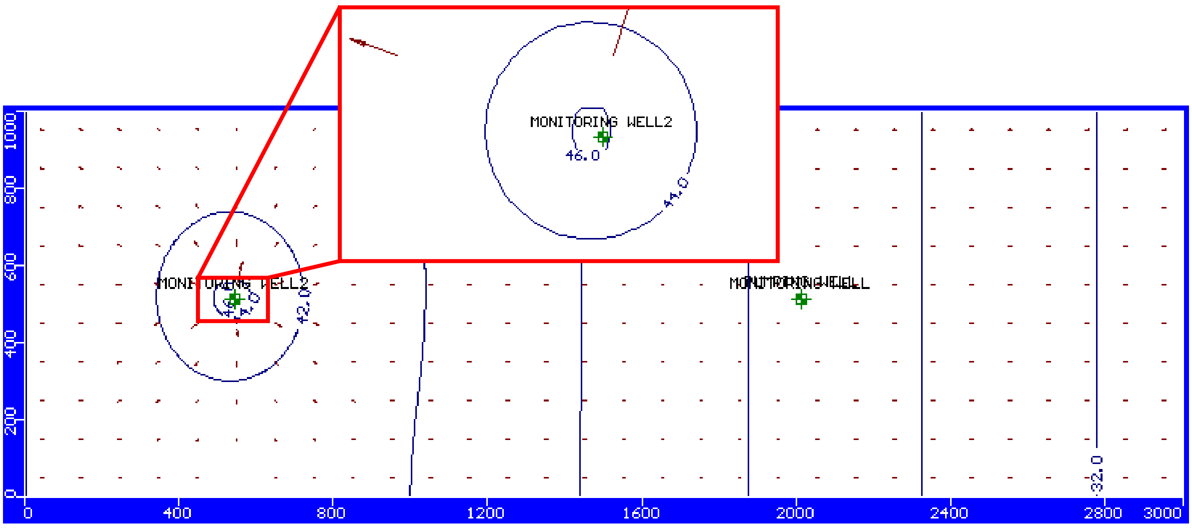


Figure 3-28 Hydraulic head equipotential lines map for model number 9 at 210 days with low hydraulic conductivity.

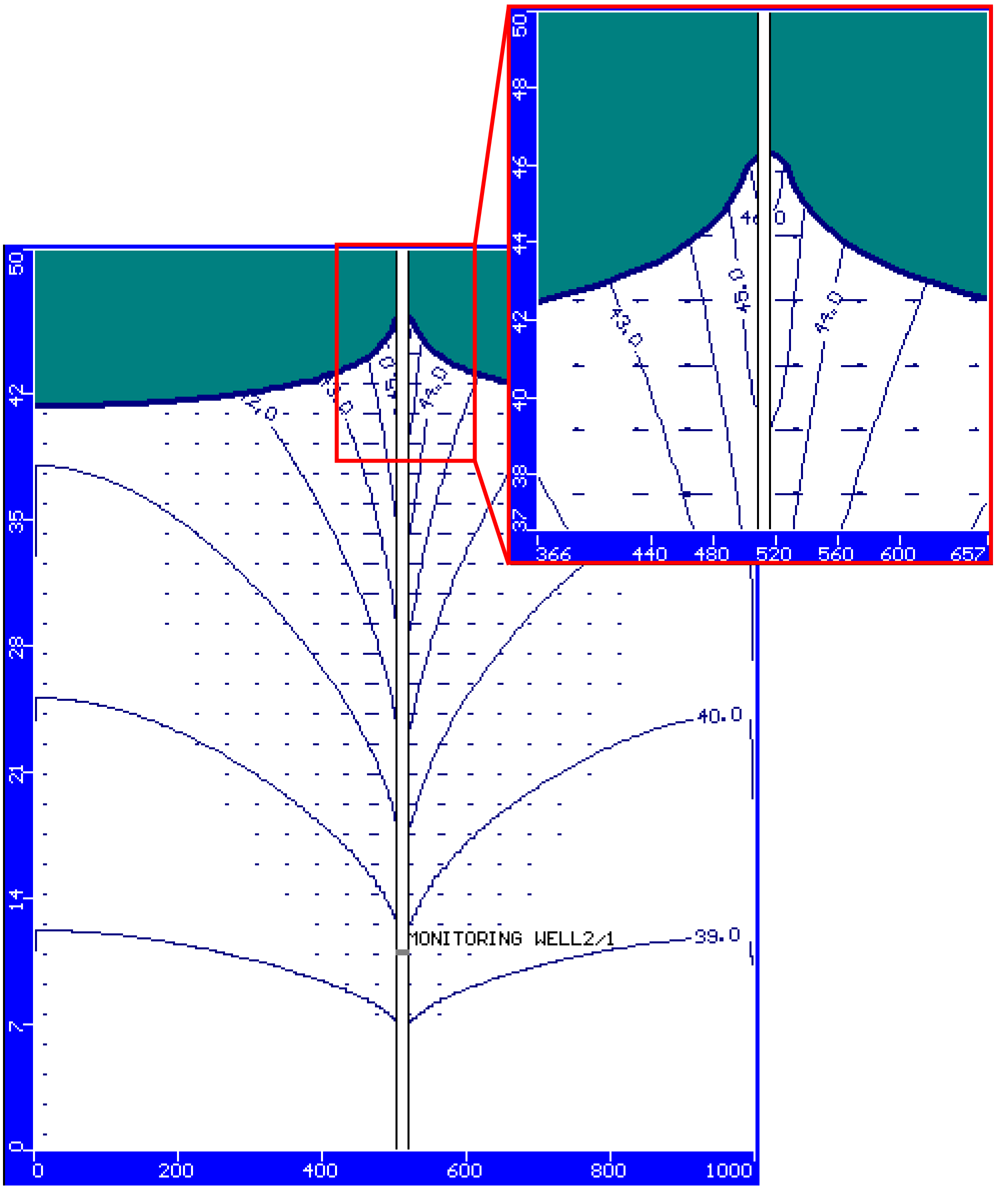


Figure 3-29 Cross-sectional view of monitoring well after 210 days in the model with low hydraulic conductivity.

The aquifer reaches its highest water level of 46.3 meters at the conclusion of the initial infiltration period. This outcome assures us that the proposed basin dimensions and the applied infiltration rate can be confidently adopted without encountering any issues. When we compare the results across models number 6, 7, 8, and 9 with model number 3, it becomes evident that model number 9 outperforms others in terms of system performance and the final hydraulic head at the well. Besides its efficiency in utilizing the least possible area, model number 9 adheres to the concept of land use in defining a basin.

Given these mentioned advantages, model number 9 has been selected to further investigate the remaining sensitivity analysis in the MODFLOW. This choice is based on the model's ability to deliver satisfactory performance, optimal land use, and favorable final hydraulic head at the well, making it a suitable candidate for a comprehensive analysis of system dynamics.

3.2.4 Effect of Change in The Relative Distance of The Basin and The Well

In this section, we explore how a combined variation in hydraulic conductivity and the relative distance between the well and the infiltration basin impacts the final hydraulic head. Our objective is to ascertain whether a decrease in hydraulic conductivity alters the optimal distance between the well and the basin, resulting in the maximum gain in hydraulic head, signifying the most substantial increase in the production well's hydraulic head.

As in previous analyses, the reference basin was initially situated 1462.5 meters away from the well. This distance was subsequently adjusted in both directions, with simulated distances of 1862.5 meters and 1625.5 meters, representing increases in distance of 400 meters and 200 meters, respectively. Subsequently, this distance was systematically reduced by 200, 400, 600, 800, 1000, 1200, and 1400 meters with respect to the reference distance. The final model in this series reached a distance of 62.5 meters from the well.

Considering the concept of water mounding, it is crucial to assess whether these changes in basin location pose any issues. After reviewing data recorded in the basin's monitoring well, it was determined that the model numbered 13, situated 400 meters closer to the well, exhibited the maximum level rise. However, this value remained below the aquifer thickness. The cross-sectional area under the basin, as depicted in the figure below, confirms the safety of this model configuration. The model with the highest rise in water level is positioned far enough from both upstream (40 meters) and downstream (31 meters) boundaries, minimizing their impact on its hydraulic head rise.

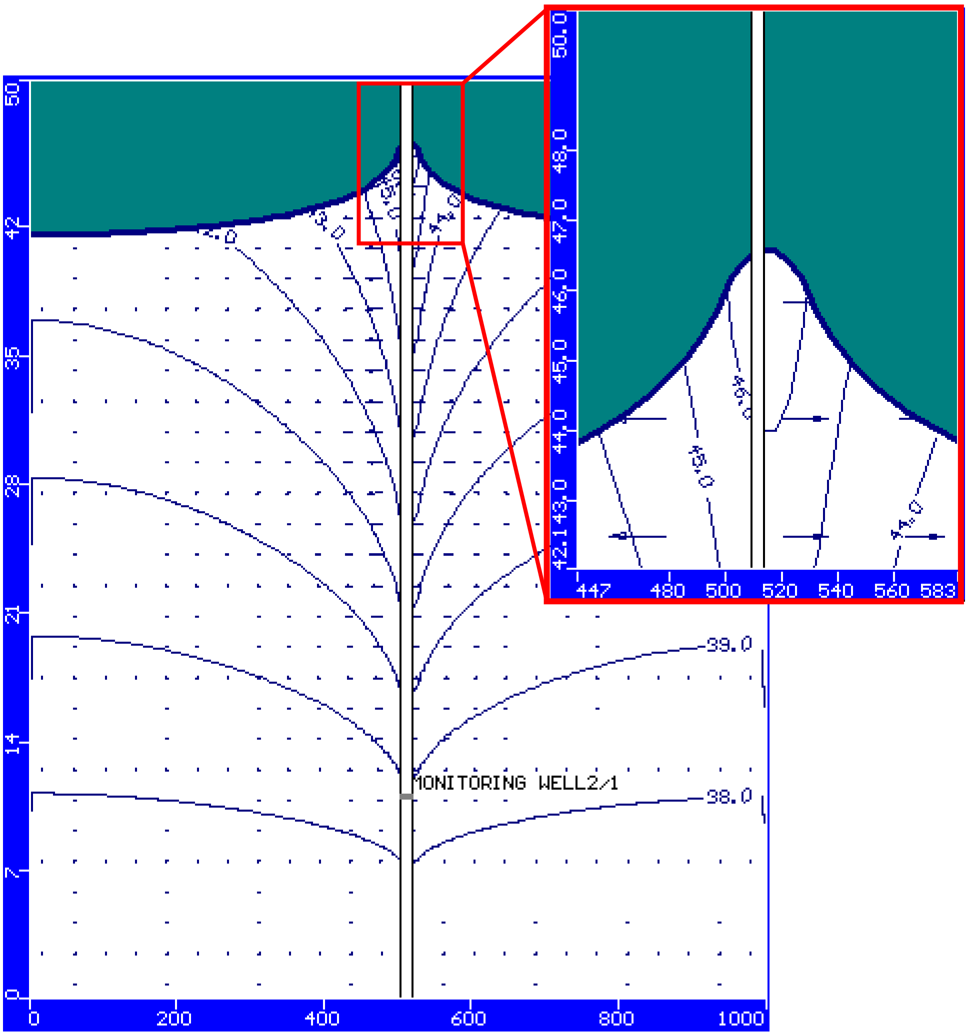


Figure 3-30 Cross-sectional view of monitoring well placed at basin for model n.13.

The analysis of changing the distance between the basin and the well under reduced hydraulic conductivity aimed to evaluate the impact of these changes on the hydraulic head gain at the production well. The findings reveal that as the basin moves farther away, the increase in hydraulic head compared to the model with no basin becomes less significant. Conversely, moving the basin closer to the well leads to a more substantial gain, up to a certain distance from the well. Figure 3-31Figure 3-32 illustrate the final hydraulic head at the abstraction well and the hydraulic head gain compared to the base model over time, respectively.

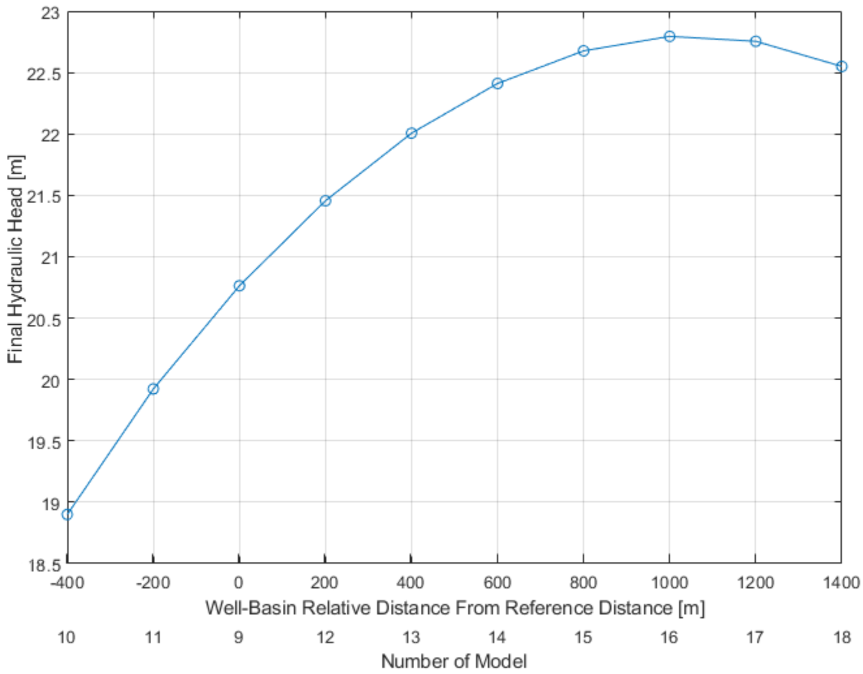


Figure 3-31 Impact of changing basin-well distance on final hydraulic head in scenario with low hydraulic conductivity.

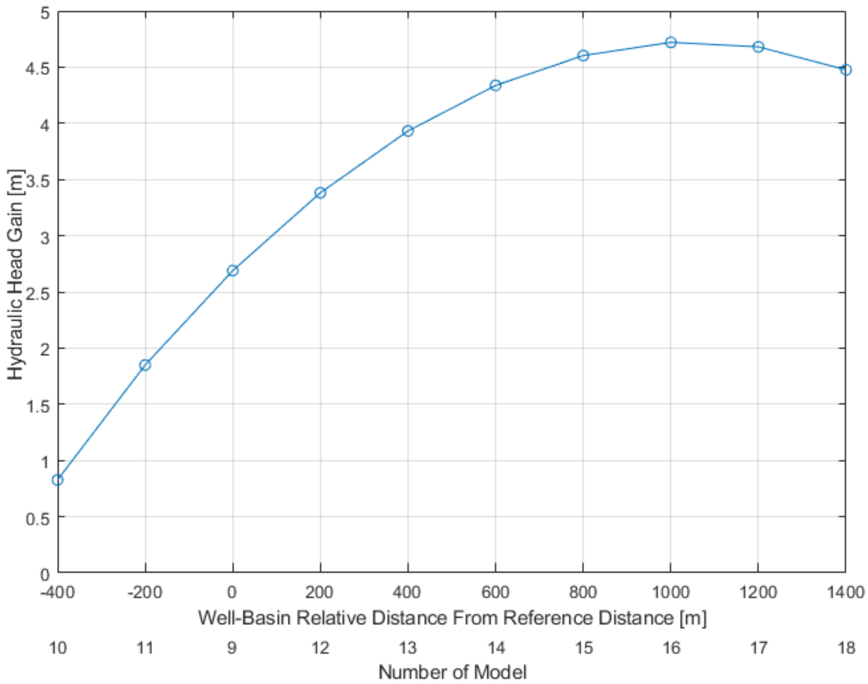


Figure 3-32 Impact of changing basin-well distance on hydraulic head gain in scenario with low hydraulic conductivity.

The data presented in the figures provides valuable insights into the relationship between the proximity of the basin to the well and the resulting hydraulic head. Two critical observations stand out. First and foremost, there exists a crucial threshold concerning the distance of the basin from the well. Once this specific distance is surpassed, the increase in final hydraulic head diminishes, indicating the presence of an optimal distance for an efficient system configuration. The figure distinctly illustrates that among the models, model n.16, with a basin distance of 462.5 from the well, represents the optimal configuration, being 1000 meters closer to the well than the reference basin. Secondly, the figures underscore an intriguing phenomenon as the basin approaches the well. As the distance between the basin and the well varies, there is an initial increase in hydraulic head up to a certain distance, but this is accompanied by a decrease in the slope of the graph. Initially, the slope is steep, indicating that if the basin is moved farther from the well, the change in the final hydraulic head is more significant. For instance, when the basin is relocated by 400 meters farther than the reference distance from the well, the change in the final hydraulic head is the same as the case where the same basin is shifted by the same distance (400 meters) closer to the well. The change is more evident when the basin is moved farther. Consequently, the reduction in hydraulic head (hydraulic head loss) due to distancing the basin from the well is more significant than the increase (hydraulic head gain) achieved by bringing it closer to the well.

3.3 Model Outcomes with High Hydraulic Conductivity

In this section, we have repeated some of the predefined scenarios with an increase in hydraulic conductivity to 0.002 m/s. An increase in hydraulic conductivity influences groundwater flow in various ways. Firstly, higher hydraulic conductivity allows water to disperse over a larger area, impacting the lateral extent of groundwater flow and the distribution range of recharge water within the aquifer. Secondly, increased hydraulic conductivity has a limited water storage impact, leading to quick drainage. In aquifers with high hydraulic conductivity, water tends to drain rapidly, preventing significant buildup and notable changes in hydraulic head.

Given the fact that in aquifers with high hydraulic conductivity, well production and basin recharge do not significantly affect the water elevation and hydraulic head in the well, and also considering the findings from previous investigations where the shape of the basin had negligible effects on the system's performance, this section avoids reevaluating the effect of shape of the basin on the simulation’s results. Additionally, regarding evaluationg the effects of the changes of the basin’s dimension on the final hydraulic head, the investigation focuses only on scenarios with increased area to 200x300 square meters and decreased area to 20x30 square meters. This aims to validate whether the conclusions drawn in previous sections remain applicable when altering the basin's dimensions.

For the sake of comparability, the number of models and scenarios has been kept consistent with the previous sections, even though some scenarios will not be repeated in this section.

The sensitivity analysis in the model involves key variables including area, rate, and the distance of the basin from the well. Table 3-3 compiles data serving as input to the MODFLOW software, presenting simulation results such as the initial and final hydraulic head in the production well from the last cycle of production period at the conclusion of the 20 years, along with the drawdown in the well and the hydraulic head gain of each simulated scenario with respect to the model with no basin. These simulation outcomes offer valuable insights particularly for a system with high hydraulic conductivity into the anticipated improvement or increment in the final hydraulic head at the well throughout the 20-year simulation period.

Table 3-3 Model scenarios' input variables and simulation results of the scenario with high hydraulic conductivity, over a period of 20 years.

	Base model	Introducing the basin		Change in the area of the basin		Change in the relative distance of the basin and the well								
N. of model	1	2	3	6	9	10	11	12	13	14	15	16	17	18
Description	(No basin)	1:1 infiltration rate	2:1 infiltration rate	Increase in area	Decrease in area	Basin farther from well by 400 m	Basin farther from well by 200 m	Basin closer to well by 200 m	Basin closer to well by 400 m	Basin closer to well by 600 m	Basin closer to well by 800 m	Basin closer to well by 1000 m	Basin closer to well by 1200 m	Basin closer to well by 1400 m
Distance of basin and well (m)	1462.5	1462.5	1462.5	1462.5	1462.5	1862.5	1662.5	1262.5	1062.5	862.5	662.5	462.5	262.5	62.5
Basin rate (mm/y)	-	116383	232766	77588	7758870	7758870	7758870	7758870	7758870	7758870	7758870	7758870	7758870	7758870
Basin area (m^2)	-	100x200 =20000	100x200 =20000	200x300 =60000	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600	20x30 =600
Initial head (m)	34.311	34.550	34.788	34.788	34.827	34.441	34.634	35.018	35.209	35.401	35.595	35.801	36.055	36.598
Final head (m)	31.146	31.165	31.184	31.184	31.187	31.156	31.172	31.200	31.211	31.218	31.224	31.225	31.223	31.218
Draw down (m)	3.165	3.385	3.604	3.604	3.640	3.285	3.462	3.818	3.998	4.183	4.371	4.576	4.832	5.380
Final head difference from base model (m)	-	0.01945	0.03878	0.03880	0.041473	0.011152	0.026618	0.054691	0.065328	0.072961	0.078271	0.079216	0.077909	0.072746

3.3.1 Effect of Introducing The Basin

As previously explained, in aquifers characterized by high hydraulic conductivity, the impact of both production and injection processes is minimal. This phenomenon becomes evident when examining the graphical representation of hydraulic head plotted versus time throughout the 20-year cycle of infiltration and production. Figure 3-33Figure 3-34 effectively illustrate the limited influence that the infiltration basin exerts on aquifers with elevated hydraulic conductivity levels.

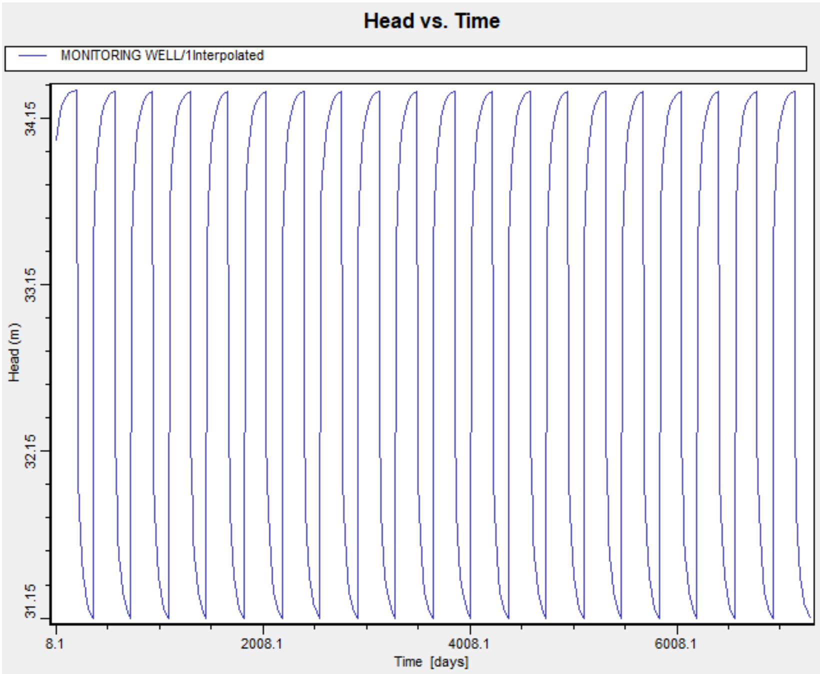


Figure 3-33 Hydraulic head vs time for base model (no basin) with high hydraulic conductivity.

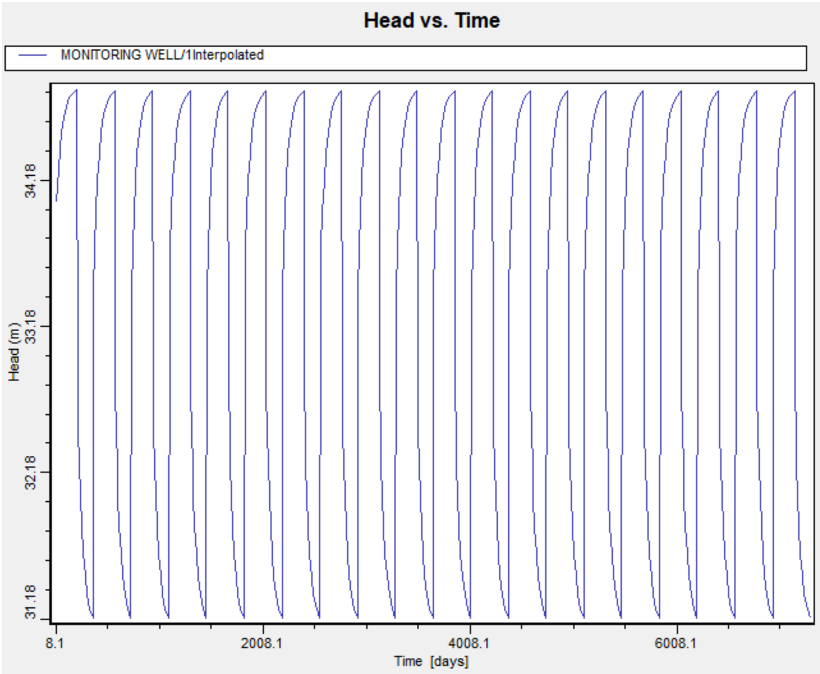
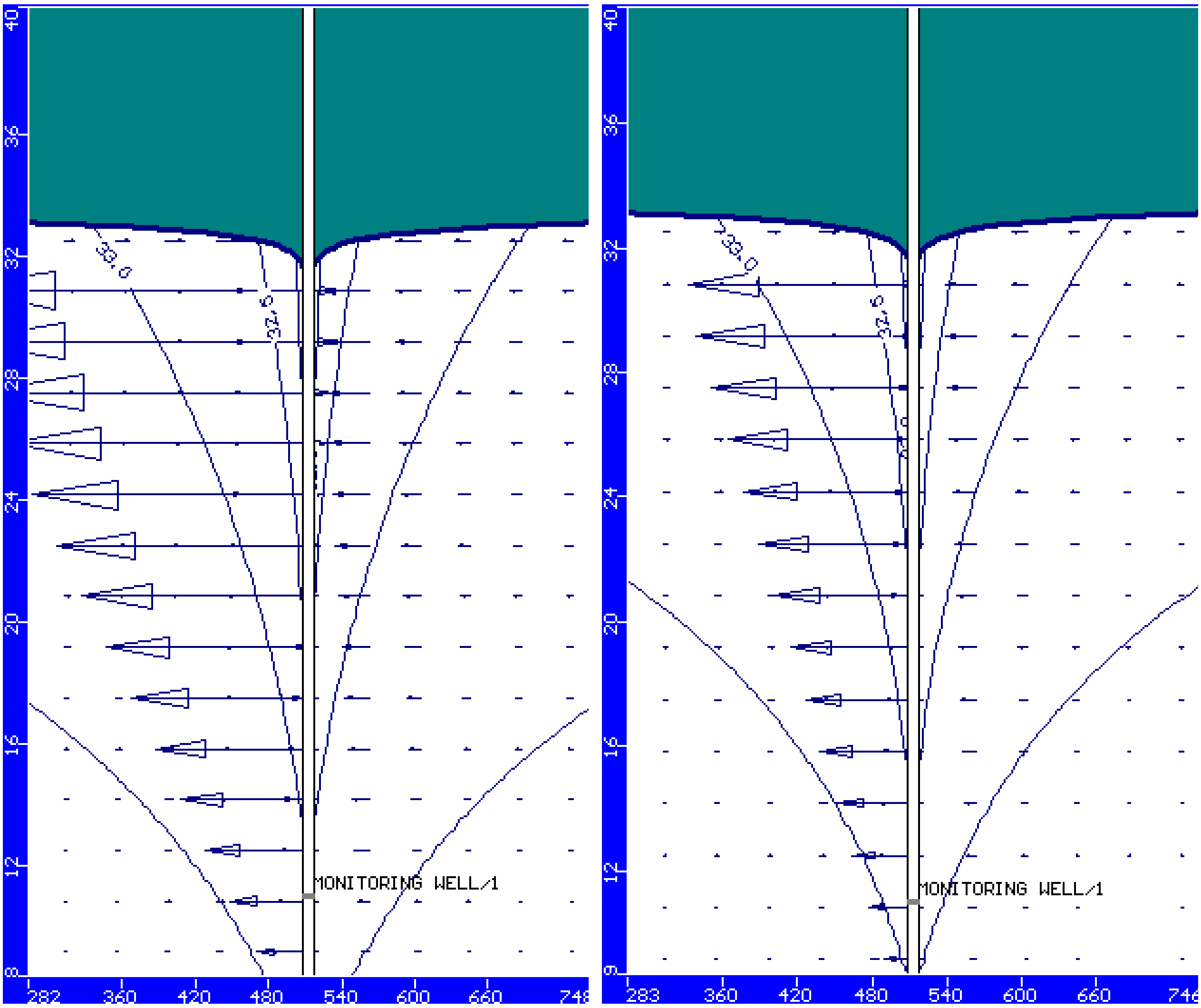


Figure 3-34 Hydraulic head vs time for model with 2:1 infiltration ratio and high hydraulic conductivity.

From the provided figures, it can be asserted that the drawdown measures approximately 3 meters for both the base model and the model with a 2:1 infiltration ratio. The range within which the hydraulic head undergoes changes is nearly identical for both models, though with a slight difference. This observation aligns with the output results documented in Table 3-3, where the final hydraulic head for Model 1 and Model 3 is recorded as 31.146 and 31.184, respectively. Consequently, the estimated gain in hydraulic head following the introduction of an infiltration basin with double volume of the infiltrated water with respect to the produced volume, is approximately 0.04 meters.

To further examine the spatial distribution of equipotential lines and velocity vectors around the production well, a zoomed-in view of the y-z cross-sectional area of the production well is presented here. As depicted in Figure 3-35 (a) and (b), the base model exhibits a more pronounced row of velocity vectors around the well. However, the overall impact of the infiltration basin in this model is not readily discernible. As previously mentioned, in aquifers with high hydraulic conductivity, the storage capacity is minimal. Consequently, the water injected underground, instead of being produced by the well, tends to escape farther downstream, diminishing the conspicuous effects of the infiltration basin on the overall system dynamics.



(a) (b)

Figure 3-35 Cross sectional view of production well after 7300 days at (a) base model (n.1); (b) model with 2:1 infiltration rate (n.3).

In aquifers with high hydraulic conductivity, water injected underground, for example, through the process of artificial recharge or infiltration from a basin, tends to move rapidly through the aquifer. Instead of being retained within the aquifer for an extended period, the water quickly travels downstream. This rapid movement minimizes the water's residence time in the aquifer, and it may not be captured by the production well before reaching farther downstream.

The statement is highlighting that in such aquifers, the injected water does not contribute significantly to the water available for extraction by the production well. Instead, it quickly moves through the aquifer and escapes downstream, diminishing the noticeable effects of the infiltration basin on the overall behavior of the groundwater system.

3.3.2 Effect of Change in The Dimensions of The Basin

In this exploration focused on the basin's area, the baseline configuration starts with a reference basin dimension of 100x200 m^2. The primary objective is to investigate the implications of altering the basin's area, leading to the consideration of two specific scenarios. In the first instance (model n.6), the basin's area is intentionally increased, stretching out to 200x300 m^2. Conversely, the second scenario (model n.9) involves a deliberate reduction in the basin's dimensions, shrinking down to 20x30 m^2.

It is crucial to note that, in both scenarios, the front of the basin is consistently positioned at the same location, maintaining an equal distance from the abstraction well. This deliberate standardization eliminates the variable of distance in this specific examination. Therefore, the focus remains squarely on the impact of altering the basin's area while keeping the distance unchanged. The significance of this detail lies in isolating the effect of area variation, contributing valuable insights to the understanding of system dynamics under such specified conditions.

The investigation into the basin's area delves into two critical factors, each holding significance in optimizing the overall system performance. The first consideration revolves around the potential increase in the final hydraulic head, a factor that based on which fundamentally influences the choice of the optimal area for designing the system. Secondly, the examination brings into focus the importance of land use. A smaller basin area is not only conducive to efficient land utilization but also aligns with the goal of preserving valuable land resources.

Analyzing the results detailed in Table 3-3, the reported gain in hydraulic head for scenarios featuring basin areas of 200x300 m^2 and 20x30 m^2 stands at 0.0388 and 0.0414 meters, respectively. Model number 9, despite having an area 100 times smaller than model number 6, which is significant for land use considerations, it also exhibits better performance in the simulation results. Although the numerical discrepancy between the hydraulic head gains in two mentioned models is marginal, it still holds the importance that a basin with a smaller area exhibits a slightly superior performance in elevating the hydraulic head at the well. This finding holds profound implications, suggesting that choosing a basin with a smaller area proves to be a smart choice, not only in terms of optimizing land utilization but also in achieving improved water levels at the end of the last cycle of water production. This understanding underscores the intricate interplay between basin dimensions, land use considerations, and their collective impact on the overall effectiveness of the system.

3.3.3 Effect of Change in The Relative Distance of The Basin and The Well

In this section, we aim to investigate the variation in hydraulic head at the end of the simulation by altering the distance from the well to the basin where water is being recharged to compensate for the water level loss due to production. Given the high hydraulic conductivity in this scenario, concerns about the recharged water surpassing the aquifer thickness are alleviated. Nevertheless, it is valuable to explore the distance from the well at which the basin will induce the maximum rise in water level in the aquifer and determine whether this distance aligns with scenarios featuring different hydraulic conductivity.

Upon comparing the maximum hydraulic head achieved in the underlying aquifer, it was observed that the highest water elevation in the aquifer occurred for model n.10, where the basin is situated 1862.5 meters away from the well or, in other words, has been moved farther upstream by 400 meters compared to the reference distance of the basin-well in model n.9. The accompanying figure provides a zoomed-in view of the cross-sectional plane just below the basin, illustrating that the water is significantly distant from reaching the surface.

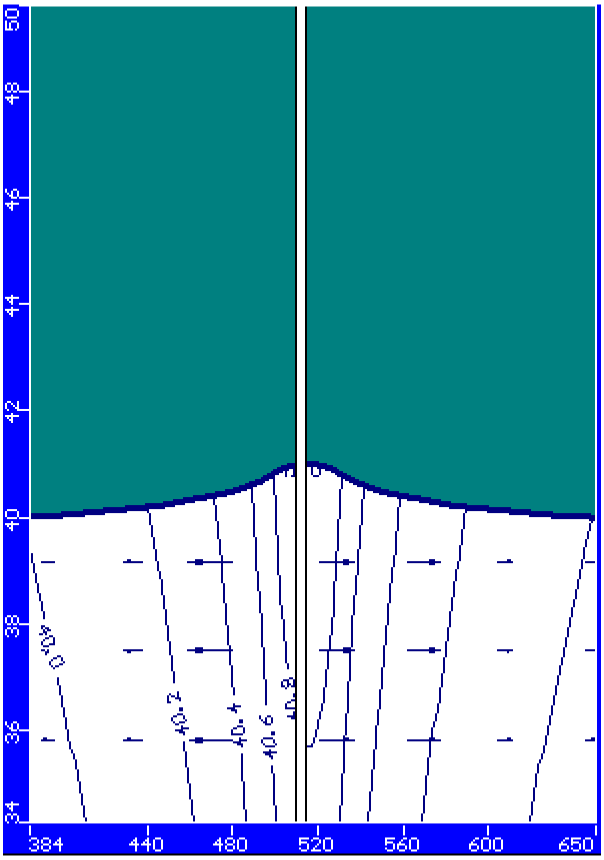


Figure 3-36 Cross-sectional view of monitoring well placed at basin for model n.10 with high hydraulic conductivity.

The examination of varying the distance between the basin and the well, coupled with an increase in hydraulic conductivity, sought to assess the impact of these combined variations on hydraulic head gain at the production well. The results demonstrate that increasing the distance of the basin with respect to the reference distance (of model n.9) leads to a diminishing increase in hydraulic head. Conversely, bringing the basin closer to the well results in a more substantial gain, reaching a maximum at a certain distance from the well, following by a decline at the end. Figure 3-37Figure 3-38 depict the final hydraulic head at the abstraction well and the hydraulic head gain compared to the base model over time, respectively.

The data presented in the figures offers valuable insights into the correlation between the proximity of the basin to the well and the resulting hydraulic head. The graph's anticline-like shape indicates that bringing the basin too close to the well has limitations, and beyond a certain threshold, the gain decreases. Model n.16, with a basin distance of 462.5 meters from the well, emerges as the optimal configuration, being 1000 meters closer to the well than the reference basin. Bringing the basin even closer to the well has an opposite effect. Another notable observation from the figures is the initial sharp slope of the graph. When the basin is farther upstream, even a small change in distance contributes to a relatively significant alteration in hydraulic head gain. As the basin approaches the well, the influence of change in the distance becomes less pronounced.

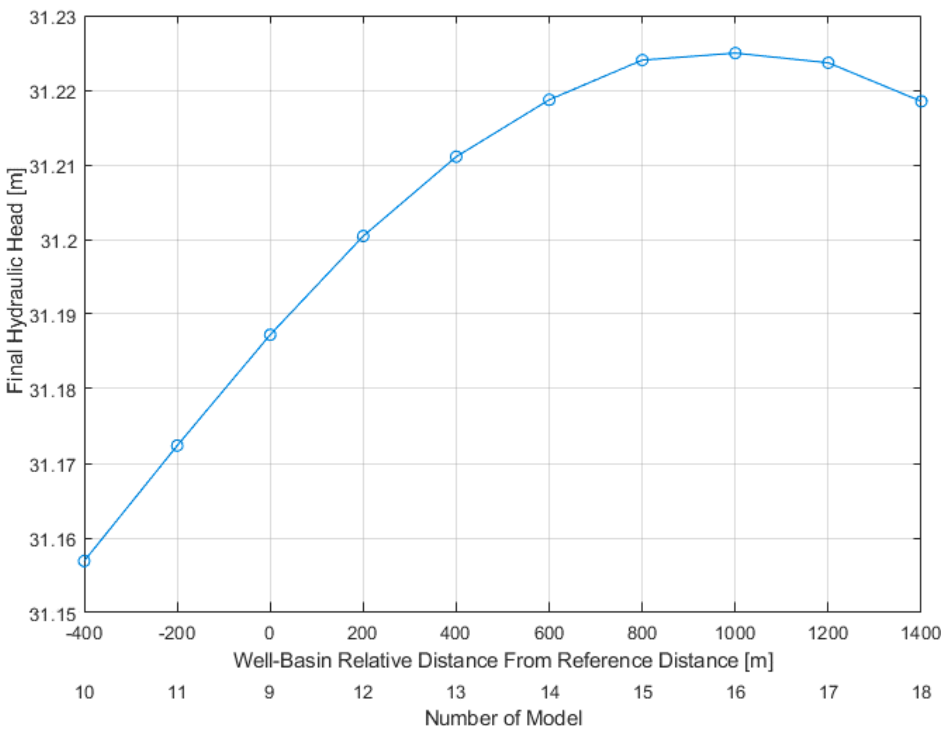


Figure 3-37 Impact of changing basin-well distance on final hydraulic head in scenario with high hydraulic conductivity.

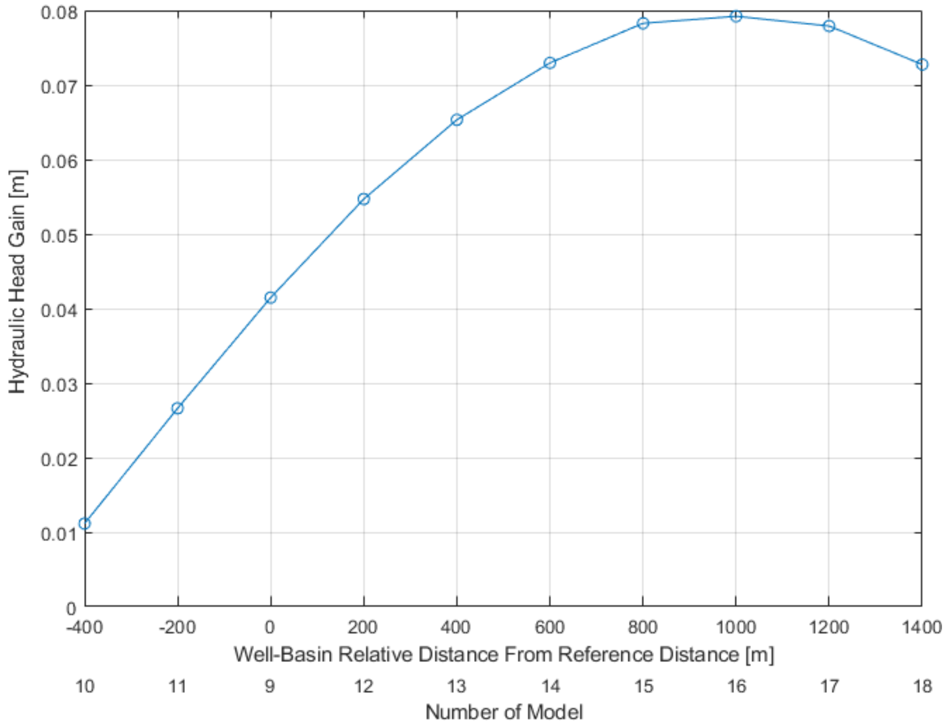


Figure 3-38 Impact of changing basin-well distance on hydraulic head gain in scenario with high hydraulic conductivity.

3.4 Hydraulic Head Gain and Its Effect on Increasing The Abstraction Rate

The primary objective of this study is to explore the changes in final hydraulic head of an abstraction well under influence of different scenarios. The specific goals are as follows:

- Evaluate MAR Method Performance: Assess the effectiveness and efficiency of the Managed Aquifer Recharge (MAR) method under investigation. This method involved off-seasonal aquifer recharge through an infiltration basin positioned at a specific distance from the well.
- Quantify Variable Influence: Examine the degree of impact each variable had on the system's performance and final hydraulic head. The variables considered included variations in the hydraulic conductivity value, the presence of the infiltration basin and changes in its recharge rate, as well as modifications to the well-basin configuration such as alterations in shape, area, and distance.
- Optimize Abstraction Rate with Basin Influence: Determine, in the event of an increase in the hydraulic head of the production well due to the presence of the basin, the extent to which the abstraction rate in the well can be elevated. The aim was to leverage the raised water level achieved by introducing the basin as a means to apply a higher

production rate in the well while maintaining the same final hydraulic head as a scenario without a basin.

In particular, the introduction of the basin served the purpose of elevating the water level in the well. The gained hydraulic head was intended to be utilized as a factor enabling an increase in the abstraction rate from the well. This strategy aimed to achieve a higher production rate while ensuring that the final hydraulic head matched the scenario without a basin.

Therefore, in this phase of the study, our focus is on determining the increased production rates for optimal scenarios associated with various hydraulic conductivity values obtained in our simulations. The objective is to quantify the potential increase in production rate influenced by specific hydraulic conductivity conditions.

To achieve this, we have selected the model with the highest gain in final hydraulic head from the 18 different scenarios simulated for various hydraulic conductivity values. Identifying optimal scenarios for each hydraulic conductivity value allows us to compare and pinpoint the most effective configurations leading to a gain in hydraulic head in the production well. Subsequently, our analysis extends to calculating the extent by which we can augment the production rate while maintaining the desired final hydraulic head.

Model n.16 exhibited the maximum gain in hydraulic head among all scenarios considered for different hydraulic conductivity values. The table below presents the characteristics of this model in each scenario, along with the increased production rate, determined through a process of trial and error, while ensuring the final water level at the well matches that of the model without a basin, which serves as the target hydraulic head, as presented in the table.

Table 3-4 Computation of increased production rate for various hydraulic conductivity scenarios.

N. of model	Hydraulic conductivity of system	Final hydraulic head	Target hydraulic head	Hydraulic head gain	Initial production rate		Increased production rate	
	(m/s)	(m)	(m)	(m)	l/s	m^3/d	l/s	m^3/d
16	0.0005	22.794	18.074	4.72	100	8640	117.7	10170
	0.001	28.425	27.742	0.683			109.4	9450
	0.002	31.225	31.145	0.080			102.4	8850

As indicated in Table 3-4, the abstraction rate in the well can be enhanced by 1530, 810, and 210 m3/d for scenarios with low, moderate, and high hydraulic conductivity, respectively. Consequently, we deduce that the introduction of a basin in a partially low-conductive aquifer can lead to a more substantial gain, ordered by an increase in the daily production rate.

However, it is essential to note that in aquifers characterized by low hydraulic conductivity, exceeding a certain threshold in production rate can lead to system failure. This is attributed to the aquifer's limited capacity to provide the requested rate at the well. Therefore, careful consideration is warranted to ensure that the production rate remains within the sustainable limits of the aquifer, preventing potential adverse consequences on system performance.

This analysis will shed light on the benefits and feasibility of utilizing the basin-induced gain in hydraulic head to enhance groundwater abstraction rates in an environmentally sustainable manner. This computation is crucial as it provides practical insights into the potential benefits of introducing infiltration basins, especially in the context of managing aquifer recharge and groundwater abstraction. The results will contribute to the understanding of how variations in hydraulic conductivity, coupled with the presence of a basin, can be leveraged to optimize groundwater extraction rates in a sustainable and controlled manner. This optimization aligns with the overarching goal of enhancing water resource management practices based on the unique hydrogeological conditions encountered in the study area.

3.5 Comparing Model Outcomes under Varied Hydraulic Conductivity Conditions

Upon comparing the outcomes derived from the simulations as presented in Table 3-1Table 3-2Table 3-3, several noteworthy conclusions emerge:

1. **Optimal Distance Insensitivity to Hydraulic Conductivity:** Alterations in hydraulic conductivity do not influence the optimal distance between the basin and the well. This implies a consistent relationship between these two elements, indicating that the configuration's optimality remains unaltered despite changes in hydraulic conductivity.
2. **Enhanced Basin Efficiency in Low Conductive Aquifers:** The study reveals that the introduction of a basin in a low-conductive aquifer results in the highest efficiency. This underscores the efficacy of infiltration basins in enhancing groundwater conditions, particularly in aquifers characterized by lower inherent conductivity.
3. **Factors Influencing Groundwater Mounding Location:** The location of the highest groundwater mounding is intricately influenced by factors such as the hydraulic conductivity of the system, constant boundary conditions, recharge rate of the basin, and resulting changes in water level along the basin. This interplay culminates in a rise in hydraulic head. In scenarios where the rise is substantial, the basin induces the greatest groundwater mounding at a location maintaining a reasonable distance from both

upstream and downstream boundaries. Conversely, when the rise is less pronounced, optimal basin placement is closer to the upstream boundary, exhibiting a higher constant hydraulic head, resulting in the highest groundwater mounding.

4. **Insignificant Role of Basin Shape in Final Hydraulic Head:** The shape of the basin has minimal impact on the final hydraulic head at the production well. This finding offers practical benefits, allowing basin configuration based on land availability without concerns that it might adversely affect system behavior.
5. **Effects on Initial and Final Hydraulic Head of The Well with Basin Introduction:** The introduction of an infiltration basin into the system influences both the initial and final hydraulic head of the well during its last production cycle. This is particularly evident in the last 155-day of production period, spanning from day 7145 to 7300 in the 20th year of simulation. The increase in initial and final hydraulic head varies across different hydraulic conductivity scenarios. For moderate and low hydraulic conductivity, the drawdown after basin introduction increases compared to the model with no basin. However, in the low hydraulic conductivity scenario, although both initial and final head increase, the drawdown is less than the base model due to a lower rate of increase in initial head compared to the rate of increasing the final head.
6. **Precision Required for Low Hydraulic Conductivity Aquifers:** In aquifers with low hydraulic conductivity, precision is crucial when introducing a basin with a small area while maintaining a high infiltration rate. This is particularly significant as groundwater mounding poses the most significant limitation in such porous mediums.
7. **Benefits of Reducing Basin Area for Sustainable Land Use:** The reduction of the basin's area proved beneficial for improving the final hydraulic head while aligning with the concept of sustainable land use. Emphasizing the reduction of the basin's footprint represented a thoughtful response to the intricate interplay of hydrological considerations and broader ecological landscapes, aligning the study's objectives with sustainable land management practices.

These insights contribute to a comprehensive understanding of the complex interactions within the aquifer system, guiding decisions in aquifer management and sustainable groundwater resource utilization.

4 Conclusions

The thesis provides simulation results depicting the impact of a seasonal infiltration basin on a production well, aimed at supplying water for an agricultural field under various scenarios. These scenarios encompass changes in the model's hydraulic conductivity, the basin's infiltration rate, basin's shape, area, and the relative distance between the basin and the well. A variety of simulations conducted utilizing MODFLOW 2011 have yielded a multitude of noteworthy insights and revelations.

The findings underscore the significant influence of both the volume of infiltrated water and the relative distance between the well and basin on the performance of the production well. Notably, the shape of the basin exhibited minimal impact on the outcomes, demonstrating its adaptable nature and allowing configuration of the infiltration basin based on land availability without adversely affecting system's behavior. Similarly, when infiltrating the same volume of water, the basin's area showed negligible effects on the results, albeit with a slight rise in water levels as the area decreased. Owing to this observation, minimizing the basin's area remains crucial for land use considerations, aligning with sustainable practices and emphasizing the need for thoughtful basin configuration.

Furthermore, the study unveiled the optimal distance between the basin and well remains insensitive to changes in hydraulic conductivity, demonstrating a consistent relationship between these elements. This stability in configuration optimality persists despite variations in hydraulic conductivity. Additionally, the location of the highest groundwater mounding was shown to be a complex interplay influenced by various factors, including hydraulic conductivity, boundary conditions, and recharge rate. These insights underscore the multifaceted nature of groundwater dynamics and the importance of considering diverse factors in aquifer management.

Lastly, the investigation demonstrates that implementing a basin within a low-conductive aquifer yields the highest efficiency, particularly in enhancing the production rate at the well. This emphasizes the positive impact of infiltration basins in enhancing groundwater conditions, especially in challenging hydrogeological settings.

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