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Managed Aquifer Recharge: A Case Study of Its Impact on Groundwater Recharge in Guelph, Ontario

Zohaib Khaliq[1], Roheel Multani[1], Hajrah Nosheen[2]
[1]University of Guelph, 50 Stone Rd E, Guelph, Ontario, Canada N1G 2W1
[2]Department of Civil Engineering, Institute of Southern Punjab, Multan, Punjab, Pakistan

Abstract. Water is vital, but population increase and climate change have caused water scarcity issues. Managed Aquifer Recharge (MAR) can help replenish the aquifers in various ways. The study evaluates a few types of MARs and their impact in the city of Guelph, Ontario, Canada, using MODFLOW. Guelph mainly relies on fractured dolostone aquifers to fulfill its population's water needs, and a future rise in water demand could cause a water shortage. A MODFLOW model comprising three 10 m layers to represent the 30 m deep Guelph Formation aquifer. Hydraulic conductivities due to sand dominance are given 35, 20, and 10 m/day values from top to bottom layers, respectively. Recharge rate and boundary conditions are defined based on the site data analysis. The steady-state model shows that the highest head values are in the North region of the study area, and the lowest is in the middle region. A drought scenario was developed by decreasing recharge and increasing pumping rate for three years, resulting in an average 4m head drop. MAR was implemented for the next three years using an infiltration basin, and five injection wells resulted in a 5 m rise in the head only in the areas where MAR systems were installed. Furthermore, the spread of contamination into most of the domains occurred in three-year MAR activity areas due to various contamination sources. Overall, MAR demonstrated the potential to increase the water table and contamination vulnerability. With proper management, MAR could assist in long-term groundwater sustainability.

Keywords: Aquifer properties; Groundwater Recharge; Injection wells; Managed Aquifer Recharge (MAR); Recharge.

Email address: zohaib.khaliq76@gmail.com,

1. Introduction

Groundwater is a crucial source for the world's population, accounting for almost 30% of the total population that relies on it for drinking. It is a major source of potable water around the globe, with most people drinking water probably derived from this resource (Kath & Dyer, 2017). This source has a big impact on engineering, environmental management, urbanization, and rural development. Roughly 2.5 billion people living in remote areas lacking centralized water supplies depend on aquifer supplies as an indispensable lifeline. Population growth and climate change make it necessary to integrate better groundwater management into environmental water policy (Kath & Dyer, 2017). Groundwater, increasing urbanization, rural development, sustainability of resources, and control of pollution, when taken as a whole, these studies demonstrate how vital groundwater is to a number of human endeavors and how crucial good management is. (Foster, 2001). On the other hand, the negative impacts of both human activity and climate change resulting in water supply drying out and pollution. It is imperative to concentrate on groundwater research and policymaking, and more data and research-informed policies should be made available.

Although there are occasional localized water shortages, particularly in the prairie provinces of Saskatchewan, Alberta, and Manitoba, Canada is a water-rich country.

There is groundwater scarcity in these places, which is exacerbated by the melting of glaciers and increasing rates of economic and population growth (Percy, 2004). Therefore, it is essential that groundwater resources in Canada are properly understood and managed to ensure the sustainability and availability of groundwater resources for future generations. (DELETEE) Due to the melting of glaciers, increasing rates of economic and population growth, and other factors, the situation of water shortage in these areas has gotten worse (Percy, 2004). To make sure that groundwater resources will be around for future generations, it is very important that groundwater resources in Canada are better known and managed.

Guelph has been supplying its water needs from groundwater since 1879. Guelph's municipal supply is made up of 25 producing wells, four of which are now closed because of problems with the quality of the water. The present-day groundwater supply capacity is over 83,000 m^3/d. (DELETE)The water supply of Guelph is groundwater. This water supply constitutes a significant source of water in Guelph, Ontario, for all its residents. There have been numerous studies into the effect of urban, industrial, and agricultural activities on the quality of this water by several authors over time. These activities will result in mixed surface and shallow groundwater flows thus disturbing the natural flow system. Highlights more reasons for the sustainability of groundwater resource development, especially in sedimentary bedrock aquifers. (DELETE) Knowledge management for groundwater is shown through a comprehensive system in Guelph. Unique consideration of the impact of the old river valleys in the formation of the karstic aquifer and its bearing upon the groundwater of the Guelph area. In addition, the pumping of production wells and the dewatering operations for the management of a mining quarry in Guelph, Ontario, Canada, have been proven to have a high effect on the quality of the city's bedrock aquifer as well as the flow system (Nunes et al., 2021). This results in pollution concerns with respect to long-term water quality reduction and proper groundwater resource control. When completing the necessary investigations for the Water Supply Master Plan Update, it has been determined that there is enough groundwater to meet the proposed growth expectations at present. However, it should be noted that the local groundwater source is finite; therefore, extracting more groundwater to meet the growing population and economic demands could lead to water shortage. In summary, although the current supply is adequate to meet the demands of Guelph, vigilant oversite and prudent allocation are imperative to ward off impending scarcity (City of Guelph 2013).

Various investigations on the spatial estimation of groundwater recharge in southern Ontario, including Guelph, used a precipitation runoff modeling system (Khader, 2017). The traditional approach to water budgeting in this context has been observed to be outdated. This shows how complex interactions between groundwater pumping, recharge, and water quality of Guelph require more studies. To deal with such issues, this study recommends moving to another direction known as Managed Aquifer Recharge (MAR). MAR is a fundamental means for controlling underground and surface waters and provides numerous advantages for society. It includes artificial recharge systems that are deliberately used to refill groundwater. Aquifers can be replaced and restored when too much has been allocated to them, or they become saline to protect aquifer-dependent environments and improve urban and rural water supplies, minimizing evapotranspiration. This is highly relevant during the sustainable management of groundwater sources to increase groundwater capacity (DELET) and knowledge. Modeling is also essential when evaluating MAR systems because it helps optimize fluid flow schemes such as gas, oil, or water. The practice is more effective if realized through check dams and improves groundwater quality, quantity, and community livelihood (Renganayaki & Elango, 2013). MAR may deliver water-supply resilience over groundwater abstraction and climate variations. Many studies have proved that MAR is one of the best sustainable solutions for sustainable water management. In summary, MAR is an integral part of mitigating water shortages and conserving groundwater systems in the long term.

Managed Aquifer Recharge (MAR) has been shown to be effective in increasing groundwater recharge and raising the groundwater table, as demonstrated by the example of Linqing City, China. (Li et al., 2021). It is an essential tool for integrated water resources management that can restore over-allocated or brackish aquifers, enhance the quality of urban and rural water supplies, and benefit ecosystems that depend on groundwater. (Dillon, 2005). MAR is a low-cost, eco-friendly treatment technique for recycled water that has the potential to significantly reduce the energy required for water distribution. (Dillon, 2005). In the Middle East and North Africa, MAR is a crucial strategy for reducing the consequences of climate change and groundwater depletion. It can improve groundwater quality and lessen resource stress. (Sherif et al., 2023).

Numerous studies have emphasized how important modeling is to MAR system evaluation and optimization (Ringleb et al., 2016). An established groundwater flow modeling program called MODFLOW will be used for the Managed Aquifer Recharge (MAR) project in a specific hydro geo setting in Guelph, Ontario, Canada. In order to comprehend how MAR activities, including injection wells and infiltration basins, could aid in recharging aquifers and storing subsurface water in Guelph, Ontario, Canada. This study examines these activities. The goal is to assess the MAR practice's effectiveness and suitability for the hydrogeology environment in the focus zone. This work uses MODFLOW, a flexible modeling approach that has been shown to be reliable, to investigate the details of groundwater flow and recharge under various MAR operating circumstances. The study aims to simulate possible groundwater contamination scenarios in a detailed manner and finally make recommendations regarding the efficiency of MAR approaches that offer lasting benefits in aquifer replenishment and the long-term sustainability of water resources.

2. Literature Review

2.1. Managed Aquifer Recharged

A technique used in groundwater engineering popularly referred to as Managed Aquifer Recharge, i.e., intentional storage of hydraulics in aquifers for future recovery or environmental benefits (Zhang et al., 2020). The notion of MAR stems from early cultures and goes deep into history. An example is the development of the Karez system in China. The term “managed aquifer recharge” Gale and Dillon coined MAR for the first time in 2005. It is seen as a solution to a water crisis that arises primarily in drought-prone areas. MAR approaches are used to help increase the natural storage of aquifers for a better temporal balance between supply and demand for water (Hartog & Stuyfzand, 2017). This process happens when one deliberately injects water from different sources like a river, storm, rain, desalinated seawater, treated wastes, and even from another aquifer into the soil zone or porous strata for re-use. One of MAR’s goals includes supporting higher water needs, improving water quality, and preventing water evaporation, algae growth, and atmospheric deposition of pollutants during underground storage (Hartog & Stuyfzand, 2017).

Many applications, including, for instance, adjusting hydrological regimes and reservoirs, environmental protection, and improving water quality, have proved the efficacy of MAR schemes. To illustrate, MAR has been applied with regard to time, quantity, and direction of water movement, altering water resources and significantly contributing to agricultural and municipal water supply (Sprenger et al., 2017). An example of a successful MAR project is eight operational MAR sites in Berlin, Germany, generating over 135 million m^3/a and accounting for 67% of the city's total water supply. The 1960s saw the Central Valley of the United States increase, resulting in the creation of spreading basins. (Scanlon et al., 2016). Additionally, MAR has been linked to preserved ecosystems that rely on groundwater as a safeguard against seawater intrusion and land subsidence. (Sprenger et al., 2017).

The importance of MAR stems from its capacity to manage water resources in a sustainable and dependable manner in the face of increasing population growth, fluctuating water supplies, rapid urbanization, and the effects of climate change (Zhang et al., 2020). Hartog and Stuyfzand (2017) cite the reduction of temporal disparities, improvement of water quality, and defense against evaporation losses as the benefits of MAR. They also serve as alternatives to surface water storage, which has a number of drawbacks.

Concerns over water scarcity have been addressed by MAR with promise, therefore, in the future, we might observe higher use (Zhang et al., 2020). Understanding hydrogeology, legal frameworks, water quality management, monitoring procedures, and maintenance needs is essential to ensuring the planning and successful execution of MAR tactics. Techniques for artificial intelligence and data analytics should also be included (Dillon, 2005).

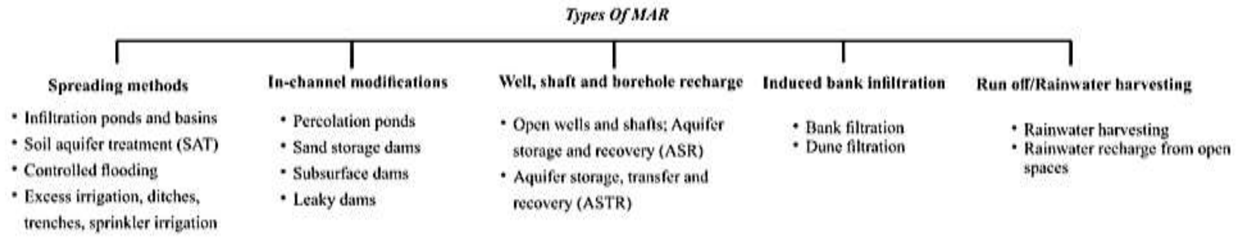


Figure 1. Various types of MAR Approaches

2.2. Managed Aquifer Recharged

2.2.1. Types of MAR

Managed Aquifer Recharge (MAR), a deliberate procedure aimed at replenishing aquifers and enhancing groundwater storage, encompasses a variety of techniques. Owing to the diversity of MAR, several strategies appropriate for specific hydrogeological conditions and water management objectives can be applied. MAR methods, such as spreading techniques, in-channel alterations, and recharge via wells, shafts, and boreholes, are adapted to local hydrology, hydrogeology, and other parameters. Multiple aquifers are used for storage and treatment with recovery for a variety of purposes (Zhang et al., 2020). MAR techniques include a variety of tactics, each with specific advantages and uses, including recharge ponds, injection wells, infiltration basins, and others. These methods are crucial for ensuring sustainable water management practices, boosting groundwater supplies, and decreasing water scarcity. Understanding the types of MAR techniques and their applications is necessary to address water resource challenges in a variety of geographic locales and hydrogeological situations (see Figure 1 for an overview of MAR types and subtypes).

2.2.2. Spreading Methods

Spreading techniques are cost-effective methods commonly used in Managed Aquifer Recharge (MAR) to replenish aquifers with surface water. Controlled flooding, excessive irrigation, infiltration ponds, and soil aquifer treatment (SAT) are a few of these methods. Rainfall or stormwater is held in infiltration ponds, which are often excavated or surrounded by banks with the goal of allowing it to percolate through permeable soils and into aquifers. Periodically, SAT systems infiltrate the water from these ponds, mostly helping open aquifers that are near the surface. This method works well with aquifers composed of sandstone, alluvium, and occasionally carbonate minerals (Zhang et al., 2020).

2.2.3. In-Channel Modifications

In-channel changes involve altering rivers, streams, or canals to store water and boost vertical recharge in aquifers. The dam is the main instrument utilized in these modifications. It can be in the shape of recharge releases, subsurface dams (such as leaky dams), sand storage dams, percolation ponds, and more. By retaining and storing water runoff, especially during flooding, these modifications enhance water retention and storage in the modified channels. By effectively regulating surface water discharge, these methods greatly enhance aquifer recharge (Zhang et al., 2020).

2.2.4. Well, Shaft and Borehole Recharge

In regions with deep aquifers, a few popular recharge techniques are open wells, aquifer storage and recovery (ASR), and aquifer storage, transport, and recovery (ASTR). Injection techniques, which involve open wells and shafts and are commonly utilized in these areas, are used to recharge shallow phreatic aquifers. Spreading practices may lead to well dryness from overexploitation and declining water tables in regions with low permeability surface layers. ASR involves storing water underground by injecting and collecting water from the same well, but ASTR, an enhanced ASR, also involves injecting and recovering water from other wells. Because of its prolonged residence times, ASTR is particularly useful for enhancing the quality of water that has been preserved (Pyne, 2017). These techniques are effective for deep aquifers with impermeable upper layers (Pyne, 2017).

2.2.5. Induced Bank Infiltration

An indirect technique for replenishing groundwater is induced bank infiltration, which includes dune and bank filtration. By drawing groundwater from a well next to a river or lake, a process known as "bank filtration," surface water penetration into the aquifer is encouraged, and the quality of the recovered water is enhanced. Dune filtering functions similarly to bank filtration according to a similar premise. A journey lasting more than a month is required to guarantee surface water treatment through underground natural processes (Maliva et al., 2012).

2.2.6. Rainwater Harvesting

Rainfall is directed to a deep hole in this Managed Aquifer Recharge system so that it can percolate and be used for other purposes. This effective technique helps rainfall naturally filter into aquifers, which helps replenish water in the hydrological cycle, especially in metropolitan areas (Kim et al., 2007). This method works well where runoff may be captured and used for valuable reasons. Figure 2 provides illustrations of several technologies.

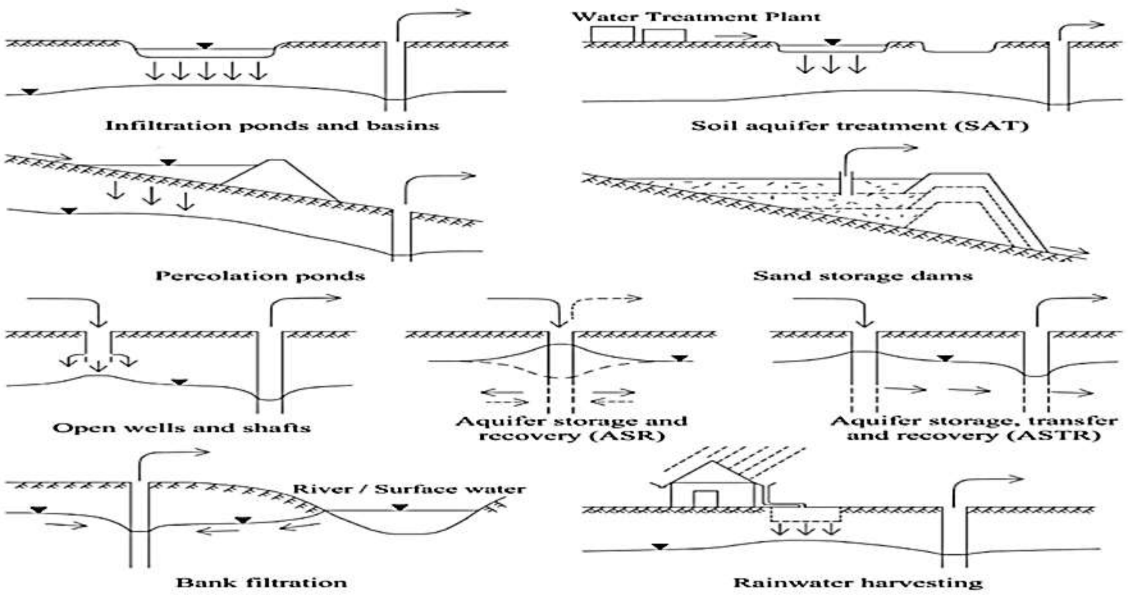


Figure 2. Schematic Diagram of various types of MAR (Zhang 2020)

2.2.7. Effectiveness of MAR

The efficacy of Managed Aquifer Recharge (MAR) systems is determined by their ability to increase groundwater reserves and aquifers in a sustainable manner. MAR has shown to be highly effective in preventing groundwater depletion, particularly in regions with limited water resources. By purposefully introducing surface water or treated wastewater into aquifers using a variety of techniques like infiltration basins, injection wells, or recharge ponds, MAR seeks to improve aquifer storage. Its effectiveness stems from its ability to restore over-used aquifers and adjust to different hydrogeological conditions.

Furthermore, MAR contributes to the quality of recharged groundwater by allowing water to naturally filter pollutants as it percolates through soil layers. The effectiveness of MAR approaches, however, can be impacted by hydrogeological characteristics, recharge rates, recharge water quality, and ongoing maintenance to prevent issues like obstruction. Success stories from MAR projects, including the utilization of eight operational MAR sites in Berlin, Germany, which produce about 135 million m^3/year of water, attest to the projects' value in addressing water scarcity and meeting water demand (Sprenger et al., 2017).

Furthermore, MAR has been utilized to protect ecosystems and the environment, proving its usefulness in maintaining ecosystems and natural resources. Examples of this include safeguarding ecosystems that rely on groundwater, reducing land subsidence, and preventing saltwater intrusion (Sprenger et al., 2017).

MAR is a crucial tool for managing water resources sustainably since it has shown promise in improving water security and has the potential to be utilized more extensively (Zhang et al., 2020). Overall, when applied with respect to site-specific conditions and augmented by appropriate management techniques, MAR is a useful and effective tool for ensuring sustainable groundwater management and resolving concerns with water resources.

2.2.8. Boundary Condition

For groundwater modeling to accurately predict flow and transport processes, boundary conditions are necessary. It describes the connections between the modeled aquifer and its surroundings. It is essential to take into account local water flow variations, human activities, and environmental factors while projecting boundary conditions. The aquifer's internal water flow is determined by these characteristics. Boundary conditions fall into two main categories: the specified flux boundary and the declared head boundary. The head boundary, which specifies the hydraulic head or pressure at certain points along the model's border, reflects the interaction of the aquifer with external water bodies or hydraulic structures. On the other hand, the specified flow border specifies how water enters and exits the aquifer domain and depicts features like recharge or discharge zones. These boundary conditions need to be clearly described in order for a groundwater flow pattern model to replicate real-world hydrological processes and respond appropriately to evolving external influences. Transient boundary conditions that account for changes over time, such as seasonal variations or human-caused modifications, further enhance the accuracy and reliability of groundwater models. Different boundary conditions are used in groundwater modeling to mimic how the aquifer system interacts with its surroundings. The primary categories are as follows:

- Specified Head border: This boundary condition establishes the hydraulic head or pressure at specific points along the model's border. It depicts situations in which the aquifer interacts with bodies of surface water, such as lakes, rivers, or seas, or in which hydraulic constructions, such as wells or pumps impact groundwater levels.
- Specified Flux Boundary: Unlike the specified head boundary, this condition defines the water flow rate into or out of the aquifer. It depicts discharge zones-where groundwater empties into rivers or drains-or recharge zones-where water seeps into the aquifer.
- No-flow border: This setting presumes no flow over the model border, signifying impermeable walls or regions with minimal or restricted groundwater movement, including geological obstacles or shallow permeability zones.
- Constant Head Boundary: Similar to the specified head boundary, this condition maintains a constant hydraulic head or pressure at the boundary nodes throughout the simulation, reflecting steady or unchanging hydraulic conditions.
- Flux Controlled Boundary: This condition uses given flux values to control the flow rate at the boundary nodes. It refers to circumstances in which the flow rate into or out of the aquifer is known and regulated; it is frequently utilized in conjunction with artificial recharge systems or wells.
- General Head Boundary: This boundary condition enables more complicated representations of boundary behavior by including both head and flux components in certain zones. It applies a combination of defined head and specified flux conditions.

In order to effectively simulate groundwater flow and behavior inside a model and capture the many interactions between the aquifer and its surroundings in various hydrogeological situations, each of these boundary conditions is essential.

3. Study Area

3.1. The City of Guelph

This includes the City of Guelph and the nearby townships of Puslinch and Guelph-Eramosa, making up a 180 km^2 coverage area in southwest Ontario. Guelph is located in Ontario, a province of Canada. The population of Guelph was around 131,794, according to Statistics Canada. It is around 28 kilometers east of Waterloo and 100 kilometers west of Toronto. It is the city itself, covering an area of around 87 km^2. By 2031, the number could surpass 175,000, according to demographic estimates (Matrix Solutions Ltd., 2017). The city lies at the junction of the Speed and Eramosa rivers, tributaries of the Grand River – southern Ontario’s most enormous watershed covering 6800 km^2, mainly urbanized around agricultural areas. Although it lies directly next to the Great Lakes with abundant surface water, Guelph stands wholly and solely upon drawn groundwater extracted from the underlying dolostone aquifers. As per (Singer 2003), these aquifers have a reputation for having a natural good water quality.

Figure 3. Location of Guelph, Ontario

Guelph handled 16.9 billion liters of water in total in 2016. That amounts to an average of 46.3 million liters daily, with a peak of 56.5 million liters on June 23. The variations in such figures are caused by the weather, such as draughts or water lost through ice or cracks in the lines. A well-crafted groundwater management plan is essential to guaranteeing the sustainable use of the groundwater resources that are accessible. This strategy should involve, among other things, gaining a deeper comprehension of the factors influencing water quality and the amount of time groundwater remains in the system.

The city's average daily water use decreased between 2006 and 2015 due to concerted community initiatives to save water. The difference between the amount of water generated and used during this time was typically 8000 cubic meters per day (City of Guelph, 2015). However, in 2013, things started to change as the daily water usage increased.

3.2. Physiography and Topography of Guelph

The site is located in the Guelph Drumlin Field, identified by a group of expansive, oval-shaped hills called drumlins that line up from northwest to southeast (Chapman & Putman, 1984). The region is mostly on top of a drumlin and is made up of calcareous, rocky till that comes from dolostone formations. On average, the composition of the till is 50% sand, 35% silt, and 15% clay (Chapman & Putman, 1984). These drumlins originate in valleys next to sand and gravel terraced spillway channels that contain Grand River tributaries such as the northeastern Torrance Creek Swamp (Chapman & Putman, 1984). In addition, eskers, or gravel ridges, run over the till plain in a general direction parallel to the drumlins. Much of the Site is located in the Torrance Creek Sub watershed, which is distinguished by hummocky terrain, flat spillway channels that are spaced throughout the drumlin fields, and a topography that slopes southwest towards Gordon Street and northeast towards Torrance Creek Swamp (Chapman & Putman, 1984). The site's altitudes vary from lows around Gordon Street (337 m AMSL) to peaks near Valley Road (344.5 m AMSL) (Chapman & Putman, 1984).

3.3. Hydrography of Guelph

As shown in earlier modeling work (Solutions, 2017), the hydrogeological framework of the Guelph region identifies many aquitard and aquifer systems. These comprise the subsequent discrete units: Aquifer Upper Sand and Gravel: The main constituents of this unconfined aquifer are outwash sand and gravel deposits. The vertical hydraulic conductivity is one-tenth (0.1) to an order (1.0) of magnitude lower than the horizontal hydraulic conductivity, with the horizontal hydraulic conductivity ranging from 7.0 x 10-4 m/s to 6.0 x 10-6 m/s (Solutions, 2017). Lower Till Aquitard: Composed of glacial till that is densely sandy to silty and occasionally has irregular lenses of coarse sand and gravel interbedded. The hydraulic conductivity of the aquitard is horizontal and ranges from 1.0 x 10-4 m/s to 2.0 x 10-9 m/s. The vertical hydraulic conductivity is half (0.5) to one order (1.0) of magnitude lower than the horizontal hydraulic conductivity (Solutions, 2017).

3.4. Contact Zone Aquifer

This unit comprises unconsolidated, coarse granular deposits that are directly on top and hydraulically related to the higher bedrock that has been worn and broken. Usually, it creates a narrow aquifer two meters above and below the bedrock surface or about four meters thick. It shows 1.0 x 10-4 m/s to 1.0 x 10-5 m/s for horizontal hydraulic conductivity and half (0.5) to an order (1.0) of magnitude lower vertical hydraulic conductivity than horizontal hydraulic conductivity (Solutions, 2017). Bedrock Aquifer: The Guelph Formation's medium-to-thick bedded fossiliferous dolostone defines this aquifer. The vertical hydraulic conductivity is one-tenth (0.1) to an order (1.0) of magnitude lower than the horizontal hydraulic conductivity, with the horizontal hydraulic conductivity ranging from 8.0 x 10-3 m/s to 7.0 x 10-9 m/s (Solutions, 2017).

According to Solution's calibrated steady-state groundwater flow model, groundwater flow interpretations show regional migration northwestward and ultimately discharge to the Speed River. Locally, however, analyses point to northeast and eastward flow close to the Site, which may be affected by pumping from the Carter and Burke Municipal Production Wells (Solutions, 2017). Furthermore, GRIN mapping shows 100–200 mm/year yearly recharge rates and downward vertical hydraulic gradients across the site (GRCA, 2019).

3.5. Precipitation in Guelph

Precipitation and temperature data are regularly gathered at the University of Guelph meteorological station. These data are crucial for determining the area's monthly precipitation to potential evaporation ratios. Understanding the water balance and how it affects the surrounding ecosystem depends on this information. Precipitation levels in Guelph from 2016 to 2019 showed inconsistent trends throughout monitoring sites. While Arkell Well 15 reported a slightly higher average of around 792 mm annually, the City Hall station recorded an average of about 661 mm annually in precipitation. The FM Woods station recorded 755 mm on average every year. However, the rainfall at the Clair Rd station was consistently more excellent, averaging around 1001 mm per year. With an estimated citywide average rainfall of about 802 mm per year throughout various monitoring stations over this period, these differences reflect varied rainfall patterns across Guelph (City of Guelph, 2022).

3.6. Future Management Strategies

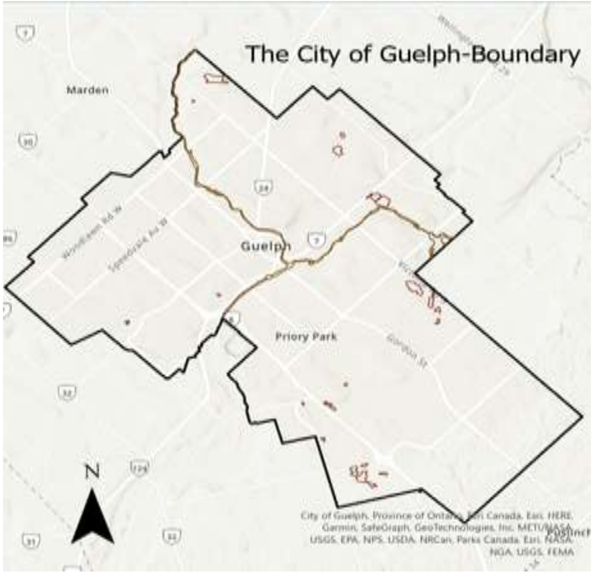
To maximize the area's water resources, the City of Guelph has proactively put several groundwater recharge management techniques into place. One crucial component is using collectors' surplus flows during seasons of high seasonal demand to fulfill customer requests and support groundwater system recovery. The Aquifer Storage and Recovery (ASR) techniques, including injecting excess water into aquifers during times of abundance and extracting it as needed, are essential to these tactics. This all-encompassing strategy covers several aspects, such as the development of additional wells inside and outside the city limits, the optimization of current municipal sources, and the execution of water conservation programs. Models at the Guelph Innovation District Lands have demonstrated encouraging results, with ASR systems running at 60% of the intended extraction rates. This form of operation maximizes the potential of the ASR system while ensuring the long-term viability of the current municipal wells. Total potential additional system capacity from the Arkell ASR: 1,170 m3/day, subject to additional optimization evaluation). Further optimization and evaluation of injection/extraction strategies and artificial recharge systems are anticipated to significantly bolster additional system capacity, potentially enhancing sustainable water resource management in the region (City of Guelph, 2022).

4. Methods

4.1. Data Collection

4.1.1. Study Area

The city of Guelph, Ontario, was taken as a study area and can be seen in Figure 4. The x and y coordinates for this region fall within NAD 1983 UTM Zone 17N, and all the data extraction and model input were done in reference to this system.



City of Guelph, Province of Ontario, Esri Canada, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, USDA, NRCan, Parks Canada, Esri, NASA, NGA, USGS, FEMA

Figure 4. Study Area - The city of Guelph

This area depends mainly on fractured dolostone aquifers for its water supply needs, which mainly contain horizontal bedding plane parallel fractures (Maldaner et al., 2019). Allen et al. (2017) studied the hydraulic properties of this formation using bore logging techniques and hydraulic tests. They discussed how the presence of many fractured patterns in this aquifer makes it an important water supply source.

According to a technical memorandum by Banks (2016), bedrock aquifer is the primary water source for domestic and municipal supply. Although the Guelph and Gasport formations were considered one hydrological unit due to their similar hydraulic properties, the Eramosa Formation overlays the Gasport Formation. It acts as an aquitard; therefore, Guelph and Gasport Formations are considered two different aquifers. Most pumping wells in the west of the study area use their water from the Guelph Formation, which is around 30 m thick, and the east side relies on a 30-35 m thick Gasport formation aquifer.

According to Kaczmarek (2020), borehole details upper .76 m consists of very loose, dark brown silty organic topsoil, the next 2.34 m consists of sand and silt, and the next 6.58 contains Silt and Sand till. Further 5 m into the ground is dense, medium to coarse sand. In addition, Banks (2016), based on an estimate from the meteorological stations in Guelph data from 1981 to 2010, stated that the overall annual precipitation is 925 mm, and the average yearly evapotranspiration is 555 mm. After evapotranspiration out of 370 mm, the annual run-off is found to be 190mm; therefore, the groundwater recharge is 180 mm. For this project, Guelph formation was considered, given that its thickness varies across the city of Guelph. However, a constant thickness of 30 m was considered, and the aquifer was divided into three layers of equal thickness, 10 m each. Based on the (Records, 2023) data analysis at various locations in the city of Guelph for boreholes above 30 m deep, it was found that different boreholes vary in geological formation. However, most boreholes contained coarse, medium, and fine sand with a mixture of gravel and stones. For the modeling, the 35, 20, and 10 meter/day hydraulic conductivities for the top, middle, and bottom layers were taken, respectively.

4.1.2. Surface Area

To create three layers and an initial head as an input in the model, Digital Model Elevation (DEM) was developed based on contour details (Geodatahub, 2020). The data was converted to a raster file and masked to the boundary of the study area. Future the input file for MODFLOW flex for creating the top surface of a thousand points, their respective X and Y coordinates and elevations were calculated. This file created respective middle and bottom layers by decreasing their elevation levels by 10 m and 20 m, respectively, from the top surface. A 3D view of the model's top surface can be seen in Figure 5.

4.1.3. Initial Heads

Initial heads play a vital role in accurately estimating water movement and hydraulic heads throughout the model (Al-Taliby et al., 2017). The initial head values data set was set using the Ontario well data source. Records (2023) were input and clipped for the study area, which contained 3,844 wells. The data was further classified using the select by attribute tool and applying two conditions: head value must be greater than 0, and well completion date should be post 2000. After applying this filter, 301 data points were exported into a new feature layer, and from there, X and coordinates and their respective head levels from the sea level were calculated so that the initial head surface could be created in MODFLOW FLEX.

4.1.4. Boundary Conditions

Bizhanimanzar et al. (2019) highlighted the importance of accurately defining the dynamic boundary conditions to properly estimate groundwater systems' behavior. There are three type boundary conditions; type-1 is the constant head boundary condition represented by the exterior or interior model domains where head values are known and remain constant. Type-2 boundary conditions are represented by known flux across the model boundary or specific locations, such as abstraction and recharge. Type-3 boundary condition is where both the head and flux are known, such as flow from a stream into an aquifer. No-flow boundary conditions are used when no water exchange or flow occurs; this boundary condition represents an impermeable barrier.

In this model, a water course data set was incorporated to find the type-1 BC where areas of constant heads in the city of Guelph region were found, and based on their locations, nine pond polygons were extracted from the ArcGIS for incorporating the MODFLOW Flex model. In addition, Records (2023) was filtered to only wells with some head value; based on this analysis, constant head boundaries were assigned to each side based on average head values at each boundary. Furthermore, for type-3 BC, a speedy river moving within the city of Guelph boundary was also extracted for further groundwater modeling analysis. The annual groundwater recharge will be utilized as a type-2 BC.

4.1.5. Observation Wells

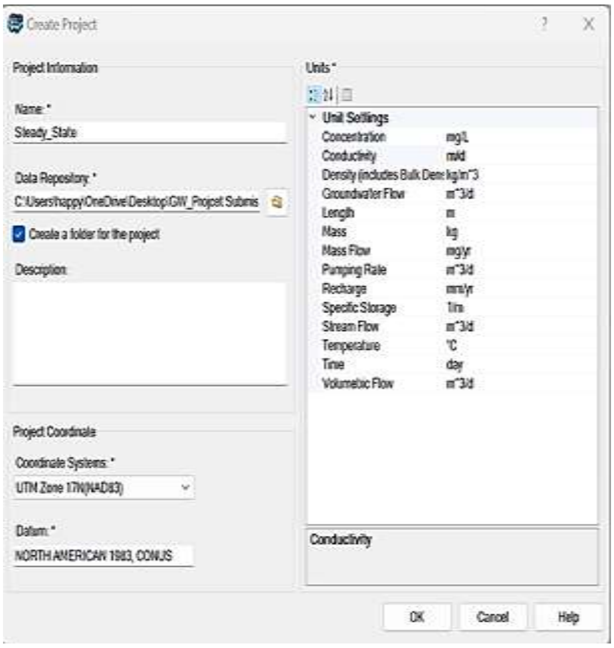
Observation wells play a vital role in calibrating and validating the groundwater model. These wells provide the actual head values at specific domain locations, and the correlation between the observed and model-calculated head values gives an idea about the accuracy and reliability of the groundwater flow model (Bailey et al., 2016). In order to validate the city of Guelph groundwater model, (Records, 2023) was filtered for wells with head values greater than zero and well completion date after 2020, and a total of 66 wells were extracted for model validation. The X and Y coordinates are their respective head values, and all the required information was updated to check the calculated heads against the observed head values.

4.1.6. Pumping Wells

According to (Guelph, 2021), Guelph has 21 operational groundwater wells that serve as drinking water sources. Shallow aquifer wells are Arkell 1, and a shallow water collector is known as the Glen Collector system. This is located in Arkell Spring Grounds in Puslinch and comprises a series of perforated pipes that collect water during April and November. Interestingly, the MAR is applied in the city of Guelph, and the collected water is transferred to an artificially engineered infiltration pond where the water soaks and replenishes the groundwater resource. The total yearly pumping from Arkell 1 is 58647 m^3 (Guelph, 2021). In this project, five pumping wells are assumed to be pumped from the shallow aquifer, and the pumping rate was set to 250 m^3/day.

4.2. Groundwater Modeling

The first step during the city of Guelph groundwater modeling is to select the coordinate system, and for this study area, NAD 1983 UTM Zone 17N was selected, as can be seen in Figures 5. After that, the start date was set to the first day of 2020, as during the data collection, only observation and pumping data starting from this date were selected.



Project Information

Name: * Steady_State

Data Repository: * C:\Users\happy\OneDrive\Desktop\GW_Project Submis

☑ Create a folder for the project

Description:

Project Coordinate

Coordinate Systems: * UTM Zone 17N(NAD83)

Datum: * NORTH AMERICAN 1983, CONUS

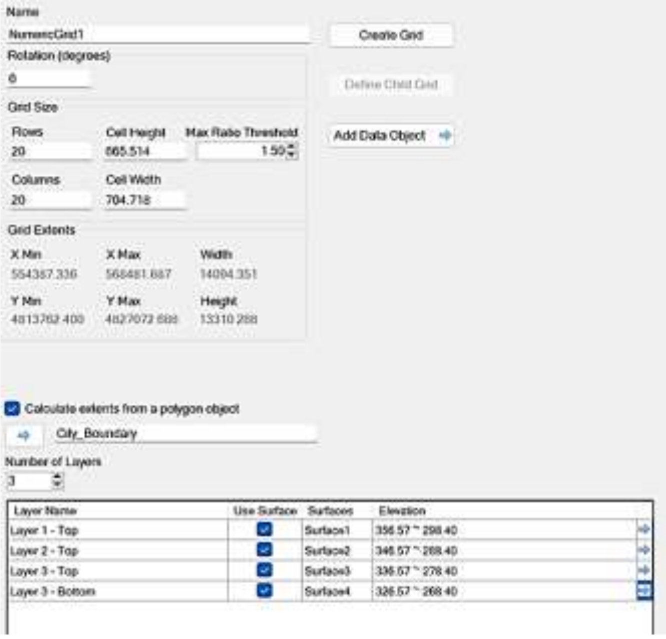
Units *

Unit Settings	
Concentration	mg/L
Conductivity	m/d
Density (includes Bulk Dens	kg/m^3
Groundwater Flow	m^3/d
Length	m
Mass	kg
Mass Flow	mg/yr
Pumping Rate	m^3/d
Recharge	mm/yr
Specific Storage	1/m
Stream Flow	m^3/d
Temperature	°C
Time	day
Volumetric Flow	m^3/d

Conductivity

Figure 5. Selection of Units and Coordinate System

The grid was created by importing the city of Guelph polygon and dividing the grid into 50 columns and 50 rows, and three layers were created by making four surfaces, as seen in Figure 6. The extent of the domain was taken from the city of Guelph Polygon, and the surface was created based on the imported data from ArcGIS.



Name: NumericGrid1

Rotation (degrees): 0

Grid Size

Rows: 20
Cell Height: 665.514
Max Ratio Threshold: 1.50
Columns: 20
Cell Width: 704.718

Grid Extents

X Min: 554387.336
X Max: 568481.687
Width: 14094.351
Y Min: 4813762.400
Y Max: 4827072.688
Height: 13310.288

☑ Calculate extents from a polygon object

City_Boundary

Number of Layers: 3

Layer Name	Use Surface	Surfaces	Elevation
Layer 1 - Top	☑	Surface1	356.57 ~ 298.40
Layer 2 - Top	☑	Surface2	346.57 ~ 288.40
Layer 3 - Top	☑	Surface3	336.57 ~ 278.40
Layer 3 - Bottom	☑	Surface4	326.57 ~ 268.40

Figure 6. Creating Grid

After creating the grid, all the surfaces based on the given Digital Elevation Model (DEM) were created; the 3D DEM for the third surface can be seen in Figures 7. The elevation of the highest point for this surface is 335.11m, and the lowest point is in the middle of the domain from where the speedy river flows and its elevation is 279.5 m.

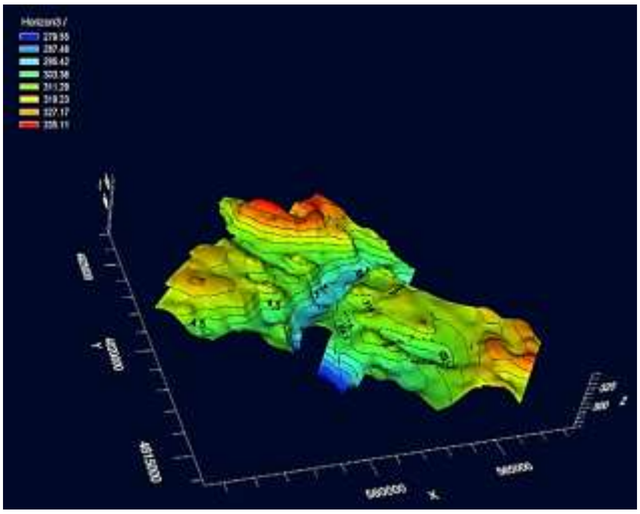


Figure 7. DEM for the third Surface

After creating the surfaces and grid, the hydraulic conductivity for each layer was defined by creating three hydraulic conductivity zones of 35, 20, and 10 m/d, respectively. The 3-D zones for all three hydraulic conductivity zones can be seen in Figure 8. For the model's simplicity, zonal hydraulic conductivities are kept constant, and schematic diagrams of their respective colors also illustrate the same.

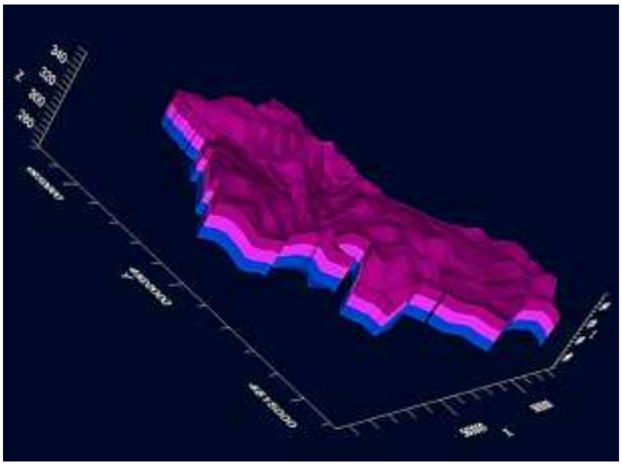


Figure 8. Hydraulic Conductivity Zones

The initial head data, created in Arc-GIS, is imported as a point source, and based on that, the surface was created and used to define the initial head values, as seen in Figure 9. As can be seen, the head values change within the study domain and are calculated from the well data dated after 2020. The initial head values range from 287.58 to 347.64.

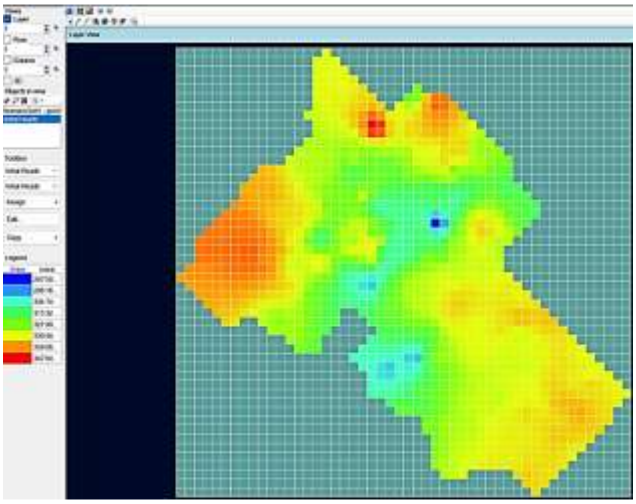


Figure 9. Initial Head Values

River BC, which is type-3 BC, was added by importing the polylines extracted from ArcGis, adding rivers using data objects, and defining their stage, bed, and thickness values. The constant head values for all eight ponds were assigned using the constant head boundary conditions. In addition, Records (2023) were analyzed to find the constant head boundary conditions at the corners of the city of Guelph. The analysis was done in Arc-Gis, and an average of the well data at each boundary was extracted and assigned in the model. The last type-2 boundary condition in the recharge of 180 mm/year was applied to the whole region. All the assigned boundary conditions can be seen in Figures 10.

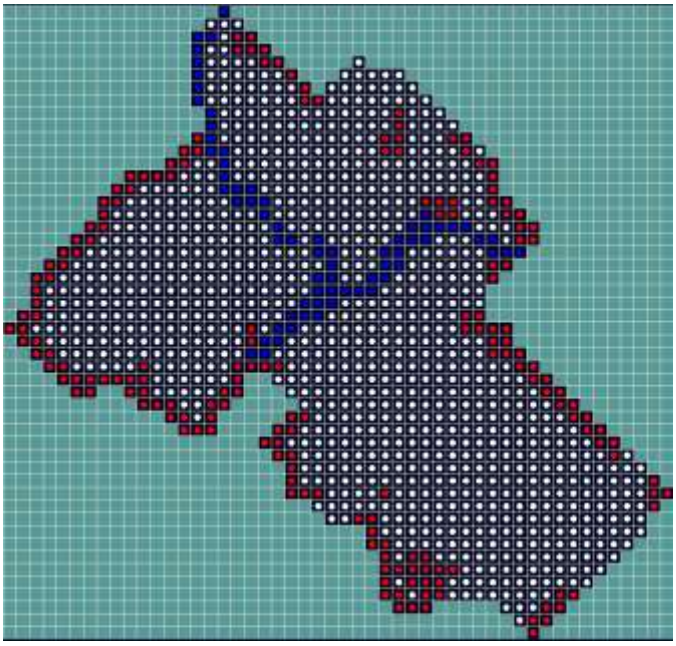


Figure 10. Assigned Boundary Conditions

5. Results and Discussions

The model was run for a steady state for a total duration of 1095 days, as seen in Figure 11. According to the results, a significant study area is dry for the first layer, which is 10 m deep. The highest head value, 338 m, is in the North-South region of the city of Guelph. At the same time, the lowest head values are in the middle of the study area where the speedy river is passing.

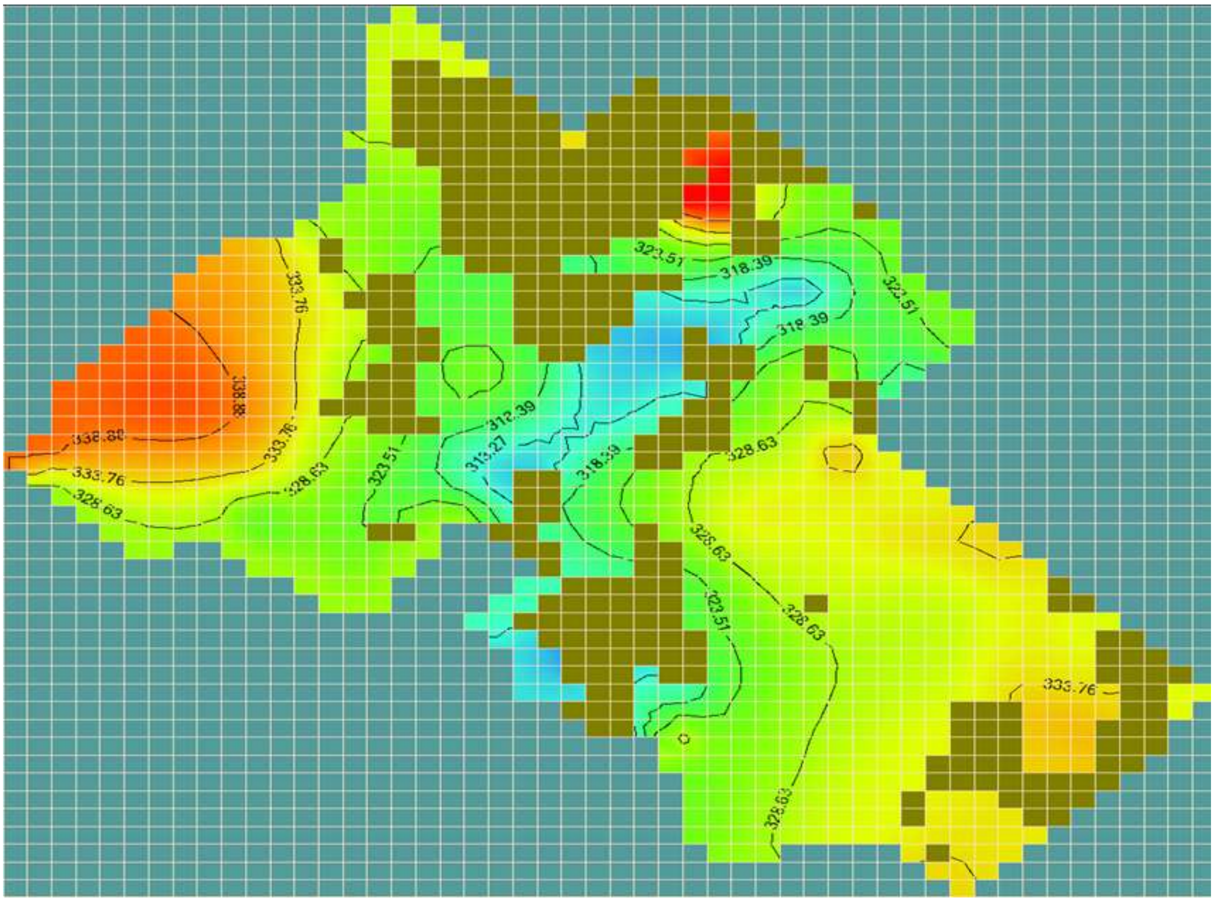


Figure 11. Assigned Boundary Conditions

On the other hand, layer 3 data have only two dry cells, and the highest head values are in the northeast corner of the study domain, as can be seen in Figure 12. In addition, the head values in the middle are below 325m, and the extremes of the study domain have head values above 330m.

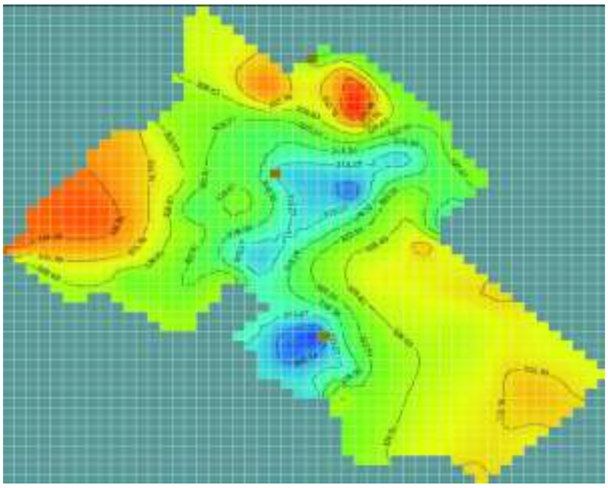


Figure 12. Head Values Layer-3

Observation well data was imported into the model before running the PEST analysis. After running the single analysis, the chart of calculated and observed values was analyzed, and their statistical results are given in Figure 13. According to normalized statistics, the root mean square value is 5.63, and the residual mean is 1.16. The PEST analysis was performed several times; however, the run always failed. Further analysis was done with homogenous hydraulic conductivity values assigned at the start.

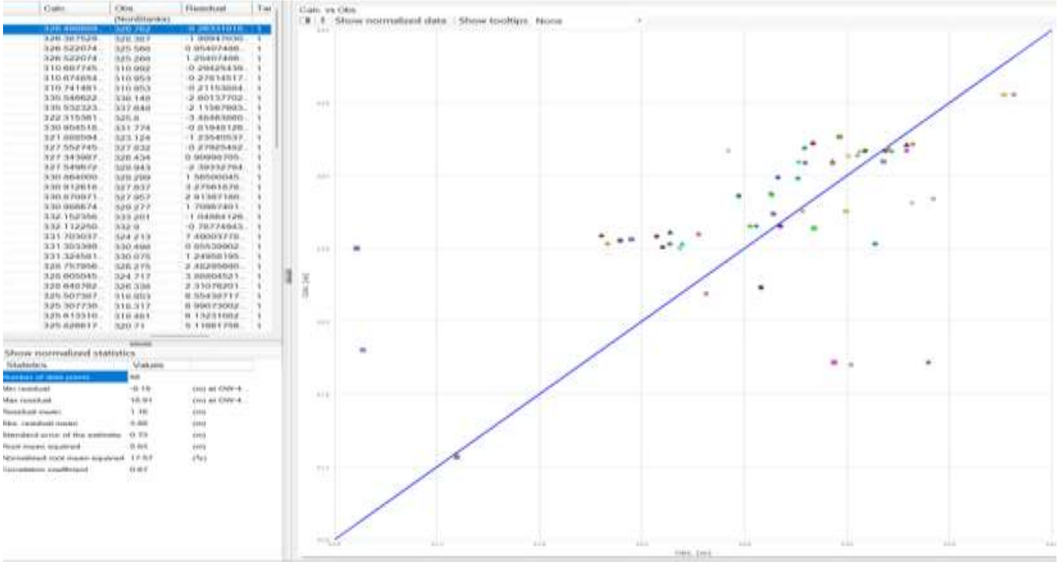


Figure 13. Calculated vs Observed Statistical Analysis

Drought was introduced into the model by decreasing the recharge value for three years. The recharge value was decreased from 180 mm/year to 20 mm/year, and the model was run based on the head values of the previous run. For a three-year analysis, five pumping wells are installed at various locations in the city, pumping at the rate of -250 m3/day. This aims to highlight the impact of drought and continuous consumption on the existing head values. According to this analysis, average head values decreased by around 4 m in the study domain (Fig. 14).

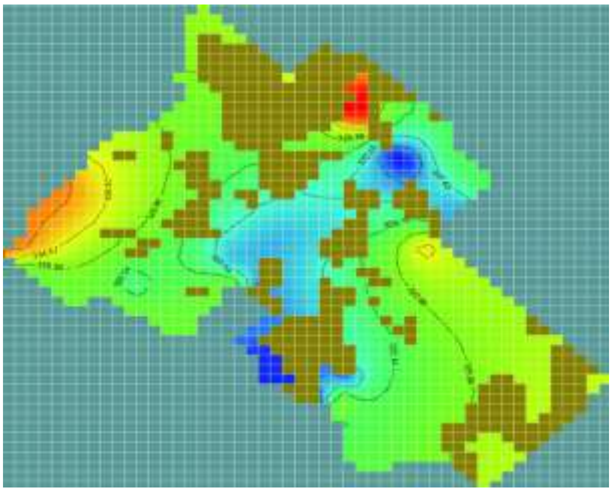


Figure 14. Impact of drought and Pumping

Managed Aquifer Recharge (MAR) was applied for this study area using five injection wells injected at 600 m3/day for the next three years. In addition, an infiltration pond was also used to infiltrate water into the aquifer at a rate of 1500 mm/year. The head values obtained after running the 3-year drought run were used as initial head values for this run. The improvement in the head values after three years of MAR activities can be seen in Figure 15. The improvement in heads only occurred in the southern part of the study area where the injection wells and the infiltration pond are located, and around 5m head improvement can be seen by comparing Figs. 15 and 16.

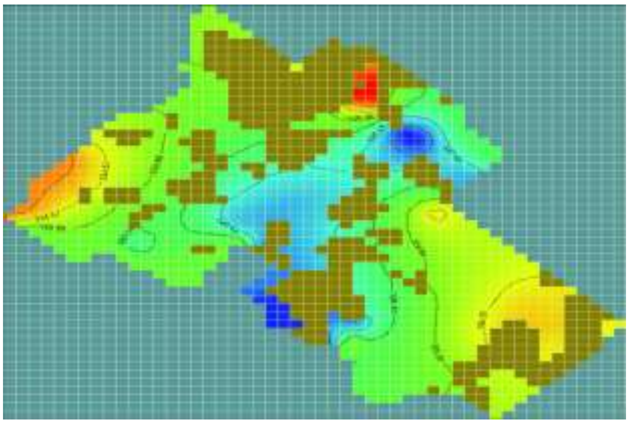


Figure 15. Assessment of MAR impact

In order to assess the transportation of contamination through infiltration ponds and injection wells, the same model was run after activating the transport in the defined modeling objective. For the retardation method, the linear isotherm option was selected. All the injection wells and the infiltration pond were assumed to contain 1000 mg/L initial concentration of contamination. The model was run for transport engines using MT3DMS and checked for a three-year analysis. The contamination levels at the end of three years can be seen in Figure 16.

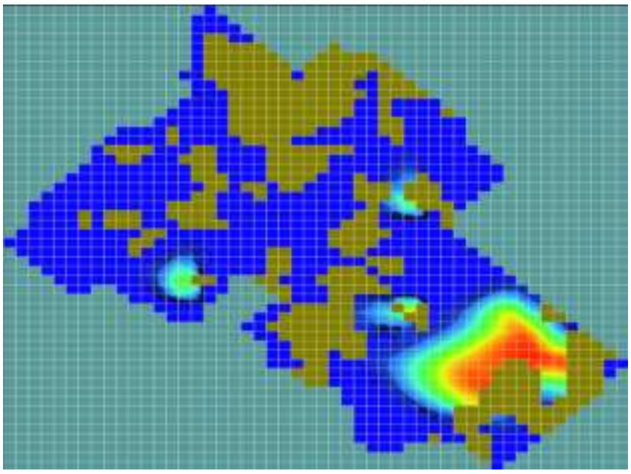


Figure 16. Contamination Transport in the Study Area

5.1. Limitations

As the data collection needs resources and time, the model run was made based on numerous assumptions enlisted below due to time and resource constraints.

- The geology for the city of Guelph is complex, as an analysis of data from various boreholes suggested. In this model, homogeneous layers with homogeneous conductivity values of 35, 20, and 15 m/d are assumed.
- Five pumping wells at -250 m3/day were considered; however, three pumping wells are extracting water at higher rates from the shallow aquifer.
- The stage and bed details, such as their width, depth, thickness, and conductance, are assumed.
- Constant head values for all the ponds are 2m above their respective DEMs.
- Constant head values at the corners of the study area are based on the average of wellhead data over 80 years.
- Injection wells and infiltration pond flow rates are assumed, and actual values can only depend on the availability of water source.

Extensive data collection will be required to create an accurate groundwater modeling profile for Guelph.

5.2. Conclusions and Recommendations

In conclusion, this study provides a feasibility assessment for using MAR to provide a sustainable water supply for the city of Guelph to cater to its future water demand. The MODFLOW model was developed based on three 10 m layers of varying hydraulic conductivities that simulated the groundwater flow for the shallow aquifer. The scenarios of drought and continuous pumping along with MAR through injection wells and infiltration ponds demonstrated the decrease and increase in the water table. Specifically, a 4 m drop was observed during three years of drought and pumping. On the other hand, a 5 m gain was observed when MAR through injection wells and infiltration ponds was applied for the same period. However, the simulation highlighted the vulnerability of the aquifer to contamination spread, particularly during MAR activities. Specifically, a 1000 mg/L initial concentration of contamination spread significantly across the aquifer over three years.

It is recommended that numerous injection wells and other types of MAR systems should be installed to maximize the recharge efficiency. In addition, contamination intrusion into the aquifer through MAR is a significant concern, and proper water quality monitoring and protection against contamination injection is required.

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