Assessing Groundwater Recovery Scenarios for Opencast Mining Using Numerical Modelling

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SUMMARY

A generic groundwater flow model is developed using the code MODFLOW (McDonald & Harbaugh 1988) in order to evaluate dewatering and groundwater recovery scenarios based on the Hope Downs-1 North mine site, Pilbara, Western Australia. Substantial lowering of the groundwater table is required for open-cut mine operations below the water table in the region to enable dry pit mining. If water management is not carried out carefully during dewatering activities, biodiversity, groundwater-dependent ecosystem, communities, wildlife in the region may become affected. With the cessation of mining, the water level around the dewatered mine pit will begin to rise. However, mine pits may become groundwater sinks, especially in areas such as the Pilbara, where the loss of water by evaporation is greater than the gain through rainfall. If recovery occurs, it may take several years until the groundwater reaches pre-mining groundwater levels, given the climatic conditions in the Pilbara. It is therefore critical for mine closure, to obtain reliable predictions of mine water recovery. This research examines 100-year groundwater recovery predictions through model scenarios based on a groundwater flow model, which mimics the overall geological and climatic conditions encountered in the Pilbara. Scenarios encompass the prediction of water level recoveries under different evapotranspiration and recharge regimes. Furthermore, backfilling of the pit and Managed Aquifer Recharge (MAR) are examined as two important water management strategies of mine sites. The backfilling scenarios prevented water loss in the pit lake due to evaporation. However, they were not able to speed up long-term water level recovery. Installation of 16 injection wells for MAR applications, saw roughly 29.5% of the water taken by dewatering returned to the pit. This resulted in a slightly faster recovery times, however, the impact remained minor.

DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Signed: Caglar Bozan

Date: 01/06/2021

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1. INTRODUCTION

1.1. Background

The mining industry plays a crucial role in Australia's economic development, as it does in many countries around the world (Mudd 2004). Beginning with the discovery of gold in the states of Victoria and New South Wales in the 1850s, and later discoveries of other ores around Australia, Australia has become a leading country in the mining industry (Maponga & Maxwell 2000). It is among the top 5 countries in the world in 16 different commodities producing mainly gold, bauxite, iron ore, nickel and coal (Britt et al. 2020).

Although the prime importance in mining areas is the determination of mineral deposits and the extraction of these resources, the same importance must be given to groundwater studies in order to sustain mining activities successfully. With the development of mining technologies, open-cut mining has been developing rapidly in the world in recent years. It is estimated that there are 1800 open-cut pits of varying size and depth in Western Australia alone, one of the major centres of mining for Australia. About 150 of these existing mine voids are operated under the water table (Johnson & Wright 2003). In the Pilbara region of Western Australia, a region rich in iron ore, almost all major iron ore mines are open cut (Geoscience Australia 2021). This coincides with numerous ecosystems in the area, including mangroves, grasslands and wetlands, and endemic species of flora and fauna, all of which are closely related to groundwater (Environmental Protection Authority 2014)

In order to extract an economically valuable commodity, it is necessary to conduct dewatering studies to reduce the water level in areas where the groundwater level is high (Kumar et al. 2009). In other words, as soon as the water table reaches a level lower than the depth of the mine site, the mine site begins to be operated (Ardejani et al. 2007). The decrease in groundwater level with dewatering depends on the size of the mine site and the volume of pumping. Groundwater levels rise again after operations in mine sites are terminated and dewatering activities cease. Thus, pit lakes, which are the most important heritage, are formed with the rise of the water level in the mine excavation areas (Reed & Singh 1986).

Pit lakes are created in the mine void with the increase of the water level, unless the open-cut mining operations that take place below the water table are backfilled, (Reed & Singh 1986). Pit lakes can act as groundwater sinks because the evaporation rate in the Pilbara area is higher than rainfall, and consequently, the water level of the pit lakes will remain below the pre-mining level. Thus, the local groundwater flow system and any dependent ecosystems may be affected in the long term. The water quality within pit lakes can also be affected by the high evaporation rates, with some pit lakes becoming saline over time. Other water quality concerns are the generation of low-pH waters if sulfidic material is present within the pit area. (Johnson & Wright 2003).

Groundwater recovery at mine sites depends on multiple site-specific factors. The width and depth of the mine site are particularly important for groundwater recovery. This is because the larger the mine site, the more water must be abstracted during the dewatering activities in order to maintain dry mine conditions. As a result, the bigger the mine void, the greater the amount of water will be required for re-filling. Furthermore, the region's climatic and hydrogeological conditions are further significant factors influencing groundwater recovery (Reed & Singh 1986).

The thorough study of hydrological, hydrogeological, geological and meteorological data at mine sites is required for predicting recovery of groundwater level. Based on these studies, simulations of mine recovery scenarios can be undertaken. These are critical in assessing the extent of the post-mining groundwater recovery problem that could be confronted in the long term and its potential consequences.

1.2. Problem Statement

The Pilbara region in north west Australia has experienced important hydrological changes due to mining activities. Dewatering operations around the mine sites significantly reduce the water level in the region. With decreasing water levels, groundwater-related ecosystems and local communities have been affected in some areas (McCullough & Lund 2006). It is therefore desirable, that with the cessation of mining, groundwater levels are brought back to pre-mining levels to guarantee the sustainability of the regional water resources. Water level in pit lakes, especially in dry and arid areas such as the Pilbara, may require many years until pre-mining levels are attained.

This study examines how long it would take for the post-mining water level to rise to the pre-mining level by developing a generic model for the Hope Downs 1 North mine pit in the Pilbara Region. The impact on groundwater recovery is explored for various water management strategies.

Groundwater quality effects of pit lakes and downstream regions are not explored and are outside of the scope of this thesis.

1.3. Research Objectives

Possible closure plans of open-cut iron ore mines in the Pilbara region directly affect the regional hydrological/hydrogeological conditions. If the mine is backfilled groundwater recovery may be able to be sped up depending on the backfill material. Furthermore, in terms of plant water use, percolation and direct evaporation, the vegetation cover over the backfilling area inevitably influences the groundwater dynamics. Without backfilling, due to extreme evaporation in the Pilbara, the groundwater level may never reach pre-mining levels without management interventions. One such intervention could be the use of Managed Aquifer Recharge (MAR). This would allow groundwater pumped out during dewatering to be returned to the aquifer instead of this water being pumped into surface water features and lost through evaporation. In this case, the effective distance of injection wells to the mine site is critical to avoid impact during dewatering through water flowback into the pit, but to allow benefits during recovery.

The main objective of this study is to predict how many years and to what level the groundwater will rise under different management scenario. The model scenarios are thereby based on the Hope Downs-1 North open-cut mine field located in Pilbara region.

The specific aims of the study are to;

I. examine groundwater recovery level using different hydrological parameter such as recharge, rainfall, evapotranspiration.
II. observe how backfilling and revegetation affect the groundwater recovery.
III. evaluate the groundwater level recovery under managed aquifer recharge (MAR) scenarios.

1.4. Organization and Structure of the thesis

The thesis is divided into six major chapters:

- **Chapter 1: Introduction**

This chapter focuses on the economic contribution of mining activities in Australia, their environmental effects, the significance of mine closure plans, and groundwater recovery studies in pit lakes. This chapter further outlines the thesis's main objectives, problem statement, and structure.

- **Chapter 2: Literature Review**

This chapter highlights seven significant research topics and links to related literature. These topics include opencast mining methodologies, hydrogeological and geological characteristics, dewatering activities, post-mining groundwater recovery, mine void types, managed aquifer recharge (MAR), and mine sites in the Pilbara region.

- **Chapter 3: Description of Study Area**

This chapter explains the climatic, meteorological, geological and hydrogeological characteristics of the Hope Downs 1 North mine site, which is the basis of the thesis, and its surroundings.

- **Groundwater Flow Model**

This chapter describes the PMWIN groundwater flow model software that was used in the research, as well as how the model is set up step by step. Following that, the model parameters, steady recharge analysis, and main groundwater recovery scenarios are presented. Finally, the accuracy of the generic model is tested by comparing it to Theis solution.

- **Result and Discussion**

This chapter contains the scenarios prepared for the mine pit in the generic model, as well as a comparison of these scenarios. In these analyses, groundwater recovery level, backfilling studies, effect of different evapotranspiration rates and MAR applications are evaluated according to different model scenarios.

- **Conclusion and Recommendation**

This last chapter reiterates the works from all previous chapters and summarizes the research subject, main findings and outcomes. It also makes some recommendations for the future studies.

2. LITERATURE REVIEW

2.1. Opencast Mining Methodologies

The opencast mining includes effective removal of soil cover and interburden materials to reach economically valuable mineral ore. Opencast pit activities commence with excavation operations (Zhao et al. 2017). The pit is then gradually expanded and deepened. Excavation work continues until the pit area reaches the required size, and waste rock or spoil material is dumped out of the pit area (Mackie 2009).

2.2. Hydrogeological Characterization

It is necessary to understand the groundwater system at a below-water open-cut mine site in order to plan dewatering operations as well as plan for closure management.

The first step of the hydrogeological characterization studies is to determine the boundaries of the groundwater system or area of influence of mining activities within the mine site. Data on topography, climate and meteorology characteristics, soil classification, land use, vegetation cover and population characteristics of the settlements, as well as the geological, hydrological, hydrogeological and hydrogeochemical characteristics of the basin are needed.

Once dewatering commences, pumping will cause a drawdown around the well initially, and over time, the effected region expands and forms a cone of depression around the mine site. Each depression cone varies in size and shape depending on the pumping rate, pumping time, aquifer type, and aquifer parameters. For confined aquifers with low transmissivity a small and compact, deep drawdown cone develops, while aquifers with high transmissivity form shallow, wide-ranging cones (Figure 2-1). Transmissivity has thereby a greater impact on drawdown than storativity (Freeze & Cherry 1979). In unconfined aquifers storativity is equal to the specific yield. Water is drained from the porous media during dewatering and the cone of depression expands more slowly than in the case of confined aquifers.

Figure has been removed due to copyright restriction.

Figure 2-1 Comparison of different cone of depressions according to different storage parameters
Source: Freeze and Cherry (1979)

In addition to the hydrogeological data, climate and meteorological data need to be compiled. Based on this data, numerical groundwater flow models are commonly used to evaluate dewatering and recovery operations at each mine site.

2.3. Geological Characterization

Geological conditions should be evaluated in depth in the mine regions where hydrogeological research can be undertaken. It is therefore important to establish which units, distributions and recharge areas have aquifer characteristics in the basin. In addition, the determination of structural elements that make secondary porosity, the classification of fault zones and their degree of permeability, the density of joints and fractures, the general directions and depths at which they are active are critical for the understanding of the hydrogeological system.

2.4. Dewatering Activities

Dewatering removes groundwater from the mine pit area with the aid of pumping wells in order to keep the mine base dry and hence to maintain mining operations (Johnson & Wright 2003). As dewatering operations typically entail a high volume of groundwater pumping, they affect the water balance of mine sites and its surrounding region and require the off-site discharge of groundwater.

According to Morton and Mekerk (1993) and Read and Beale (2013), there are five different dewatering methods that are commonly carried out;

- **Dewatering Wells**

Depending on the mine site and the volume of water, many pumping wells are operated in open pit mining activities. During dewatering, these pumping wells are typically located outside the mine pit and create a cone of depression. As a result of the use of a different number of dewatering wells, different cone of depression will create an interference effect, causing the water level to drop rapidly.

- **Drain Holes**

Drains commonly constructed horizontally and angled considering gravity are used for lateral dewatering of mine sites.

- **Dewatering Tunnels and Galleries**

In conditions where the topography is suitable, tunnels dug under the mine sites are used to drain the area. Different pumping systems, however, are needed for groundwater that cannot be drained naturally.

- **Seepage Faces**

Controlling groundwater flowing into mine is one of the most difficult issues for open cut mines developed in fractured rock systems. The designed seepage faces eliminate groundwater flow, which varies depending on the width of the fractures, and therefore dry mining conditions are preserved.

- **Sumps and Water Collection Systems**

The sump systems constructed at lower levels than the mine pits are designed to capture potential surface water and residual groundwater flows in the mine void and remove them through pumping.

Although the dewatering methods employed in mining research varied, the amount of water removed depends on the size of the mine site. The following paragraphs provide detailed information on the dewatering activities of some mining operations.

Dewatering volumes can be large. For instance, the Roy Hill 1 Iron Ore Stage 1 is located 110 kilometres north of Newman, in the foothills of the Chichester Range. It is expected to mine 600 million tonnes of bedded Marra Mamba iron ore over a period of 10-15 years (Environmental Protection Authority 2009). The groundwater level in the region is 35 m below ground, and the depth of the planned open cut mine is 100 m, so the water level needs to be reduced by about 70 m. In order to maintain dry mine conditions, 20.46 megalitres (ML) of groundwater per day should be extracted for 10 years.

The RioTinto mine Yandicoogina is roughly 85 kilometres north-west of Newman. The Yandicoogina mine field consists of the Junction Central mines, which began operations in 1998, and the Junction South East mines, which started operation in 2006. To achieve dry mining conditions, approximately 75 GL of water was withdrawn from the Junction Central and Junction South East fields in 2009 (Kirkpatrick & Dogramaci 2009). The decrease in groundwater caused by dewatering created a cone of depression with an impact area of around 12 km.

The Greater Paraburdoo operations include the 4 East Extension mining region. The Greater Paraburdoo operations are in the central Pilbara area, 7 km south-west of Paraburdoo. 80% of the mineralized Brockman Iron Formation deposit that needs to be removed from the field is below the water table (Rio Tinto 2018). Thus, it is necessary to provide safe mining conditions by reducing the water level from 170 mAHD to 110 mAHD by dewatering with an annual rate of 7.5 GL / year. The drawdown achieved as a result of dewatering results in a cone of depression extending up to 5 km.

As another example, Warramboo H3 mine is located to the west of the Mesa A operation, which is located between the Robe River and Warramboo Creek and is still operating. Sump pumping technique is used in dewatering studies, and total abstraction should be between 22 and 25 GL to achieve dry mine conditions. As a result, the area impacted by the drawdown expands to around 5 km (RioTinto, 2017).

2.5. Groundwater Recovery of Post Mining

During the mine closure phase, the groundwater level increases with the end of dewatering operations in open-cast areas, filling the mine pit. Groundwater flowing into the open pits, precipitation and runoff create open pit lakes. The reaching of the pre-mining groundwater table in the pit lake will depend on atmospheric and hydrogeological conditions. Groundwater recovery rate is the key problem of the mine closure process. In many instances, the recovery of mine water is a rather slow process that takes centuries. These long recovery times allow more precise assessments of water quality and forecasts of inflow volumes (Sadler et al. 1999). According to Rio Tinto (2017), numerical models developed for groundwater recovery suggest that due to low recharge rates, groundwater can take up to 140 years to recover to pre-mining levels.

Two different studies for the Belchatow and Szczercow lignite open cast mines show numerical models for groundwater rebound generated with the MODFLOW program (Szczepiński 2000; Szczepiński 2001) suggest that 2.4 billion m^3 of water is needed to fill the open pits post mining. It is predicted that it will takes roughly 60 years for the groundwater table to recover to pre-mining levels. According to Szczepiński (2000), the recovery process will take 28 and 18 years, respectively, as a result of the additional recharge provided for 120 m^3/min and 240 m^3/min for two mining sites. According to Szczepiński (2001), the recovery will take 45 years if the recharge rate applied to mining sites is 4m^3/sec.

According to Gandy and Younger (2007), groundwater recovery takes 100, 22, and 15 years in models prepared for the South Yorkshire Coalfield based on low, average, and high rainfall scenarios, respectively.

In addition, studies such as Yihdego and Paffard (2017), Tonder et al. (2007), Shevenell (2000), Ardejani and Singh (2004), Adams and Younger (2000), Sherwood and Younger (1994), Ardejani et al. (2003), Aryafar et al. (2009), Ardejani et al. (2013), Ardejani et al. (2007) examine post-mining groundwater recovery simulations and groundwater rebound problems using different models.

For groundwater recovery, various management methods are considered. Recovery in pit lakes is particularly slow in regions with high evaporation rates, such as the Pilbara. Backfilling may be a viable alternative for preventing groundwater sink development and accelerating groundwater recovery to reduce the impact of evaporation. According to Hall et al. (2006), it is stated that the optimum backfilling arrangement varies according to the size and shape of the final pit, and for dynamic water balance, rather than filling the void completely, it is recommended to leave a narrow void along one side of the mine or provide for a V-shaped backfill. Other management options include MAR, where water abstracted during the dewatering operations are re-used to accelerate groundwater levels returning to pre-mine levels once mining ceases. Other options may be the diversion of surface waters into the pit during rainy seasons or the use of reservoir resources such as dams to accelerate groundwater recovery (Johnson & Wright 2001, 2003).

2.6. Types of Mine Voids

After the cessation of mining operations, artificial lakes develop in mined-out areas. These artificial lakes are classified into 3 separate hydro-geological/chemical ecosystems, according to Commander et al. (1994), Johnson and Wright (2003) and McCullough and Lund (2006):

- **Groundwater Sink**

A groundwater sink occurs when the rate of groundwater inflow is surpassed by evaporation. Because of this, groundwater recovers very slowly, and water level always stays below the pre-mining level (Figure 2-2). No outflow and ongoing evaporation may cause salinity problems in the long term.

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Figure 2-2 Groundwater Sink

Source: Johnson and Wright (2003)

- **Groundwater Throughflow**

The mined-out area serves as a throughflow cell as groundwater inflow exceeds the quantity of evaporation (Figure 2-3). Salinity will rise due to relatively slow groundwater recovery and the brine plume will migrate down-gradient. Hence, the saline plume would also threaten water resources and its dependent habitats.

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Figure 2-3 Groundwater Throughflow

Source: (Johnson & Wright 2003)

- **Groundwater Recharge**

Groundwater inflow is largely higher compared to evaporation and it is likely to occur in areas of heavy rainfall (Figure 2-4). The water level in pit lakes rapidly rises to the pre-mining level and this generally avoids issues of water quality.

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Figure 2-4 Groundwater Recharge

Source: (Johnson & Wright 2003)

2.7. Managed Aquifer Recharge (MAR)

Managed aquifer recharge is the intentional replenishment of aquifers by the use of various water resources to have substantial recovery and environmental benefits (Dillon et al. 2009). Stormwater runoff, desalinated water, stormwater, rainwater, and reservoir dam water are the most common water supplies used for MAR applications. According to Gale (2005), Dillon et al. (2009) and Maliva (2014) the benefits of using MAR in general are as listed below.

- Protection and enhancement of water resources
- Preventing water depletion due to evaporation
- Improving the water quality
- Prevention of salt water intrusion
- Protecting the groundwater-dependent ecosystem
- Mitigation of flood risk
- Maintaining environmental flows

However, there are several MAR techniques, and although they differ from area to area, they are commonly implemented based on the type of aquifers, land use, and topography. The Figure 2-5 depicts the various MAR implementations that have been used.

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Figure 2-5 Different types of MAR

Source: Dillon (2005)

The use of MAR for mining operations is a significant opportunity for mine water management. In order to ensure safe conditions in mine pits that takes place below the water level, large volumes of water should be extracted, and the site should be dewatered (Smith 2014). However, since this extracted water is in excess of water used for the mining operations, the excess water is often discharged into the stream/creek/river as in the Hope Downs-1 North mining site. Thus, the discharged water is lost due to excessive evaporation in the Pilbara region. In this research, MAR experiments are conducted using injection wells at various distances from the mine pit in order to minimise evaporation loss, analyse the sustainability of the water balance during mine activities, and increase groundwater recovery level in different scenarios.

2.8. Mining Sites in Pilbara Region

Mining is the most economically important industry in the Pilbara region and there are many ongoing or abandoned mining sites of different sizes. In addition, there are springs, creeks, watercourses and heritage values that need to be protected in the region surrounding mines. Mining operations are mostly located in the main geological provinces of the Pilbara Craton, Hamersley Basin, and Paterson Orogen. The following are the major mining sites in the area, according to Johnson and Wright (2003).

2.8.1. Nifty Copper Operation

The mine, which commenced operations in 1992, is situated in the Great Sandy Desert in the eastern Pilbara region of Australia. The Nifty Copper operation's mine void began with 1000 m by 500 m dimensions and a depth of 75 m, but the dimensions are expected to be increased to 1700 m by 550 m and a depth of 155 m over time. During dewatering activities, 2.5 ML/day of water is removed using production bores, pit sumps, and horizontal seepage holes. Groundwater pollution and salinity are the most possible issues after Nifty Copper Mine operations cease. Backfilling would also be impractical since the final mine hole would be too deep to fill.

2.8.2. Orebody 18

Orebody 18 is an iron ore mining project proposed in the East Pilbara, 32 kilometres east of Newman. The open-cut mine is 4 km long, 500 m wide, and 120 m deep, and is situated on the south-eastern edge of the Ophthalmia Range. It is anticipated that the pit lake that will form after the completion of mining will act as a groundwater sink, and salinity will be a significant issue.

2.8.3. Mount Goldsworthy Mine

The Mount Goldsworthy Mine, which operated for 20 years before closing in 1982, was the Pilbara region's first major iron ore mine. The mine was located in the Ellarine Range, and the final mine void size was 1200 * 500 * 200 m (depth). Before the mining started, the mine void reached a depth of 177 m below groundwater level. The mine void reached 177 m deeper than the groundwater level of pre-mine activities. Since the dewatering operations were completed and the mine site was closed, the groundwater level increased by 60% and is now 50 m lower than it was before the mine activity. Water is recovered at a rate of 2.1 m/year. While salinity rises with pit lake formation, it does not pose any risk for aquifers close to the mine site.

3. DESCRIPTION OF STUDY AREA

The location of the Hope Downs-1 North mine is within the depositional basin of Hamersley, occupying an area of 100,000 km^2 (Smith et al. 1982). The Hamersley basin contains more than 1 km of sedimentary deposition sequence, as well as the banded iron formation which is one of the world's largest economically iron ore deposits. The Hope Downs-1 North mine is located in the southern half of Weeli Wolli Creek catchment, which covers an area of approximately 4000 km^2 to the east of the Hamersley Basin. It is an ephemeral surface water that only flows during heavy rains. The catchment of the Weeli Wolli creek is divided into 3 zones: upper catchment, lower catchment and big outwash on the Fortescue (Johnson & Wright 2001). The upper catchment is characterized by relatively flat and wide plains and hills with banded iron formations. In addition, this area is occupied by many open cast mine works and contains several streams flowing in an east-west direction. Later, into a narrow gorge, these tributaries flow where the Weeli Wolli spring is recharged by groundwater.

Hope Downs-1 North, which is the base mine site for this study, started its operations in 2007 and a total of 19 dewatering wells were used, and licensed water abstraction is 100 ML/day (Cook et al. 2017). Consequently, dewatering for mining operations reduces groundwater by up to 130 m and expands the cone of depression by up to 6 km (Cook & Dogramaci 2019).

3.1. Climate and Meteorology

The dry semi-arid climate prevails in the region in general and heavy rainfalls occur occasionally, most of which take place between January and March. According to the Newman station data (Station number:007151), which is nearest to the Hope Downs-1 North mine site, the highest annual rainfall between 1965 and 2003 was 538 mm, with a minimum rainfall of 135 mm and the average annual precipitation is 318 mm (Figure 3-1). Figure 3-2 shows the annual maximum and minimum temperature data for the given years. However, according to the daily data at the Newman station, temperatures climb to 46 °C in summer and fall to negative values in winter (BOM 2021). The evaporation rate is approximately 3100 mm/year, i.e. approximately ten-fold compared to annual average rainfall (McCallum et al. 2020).

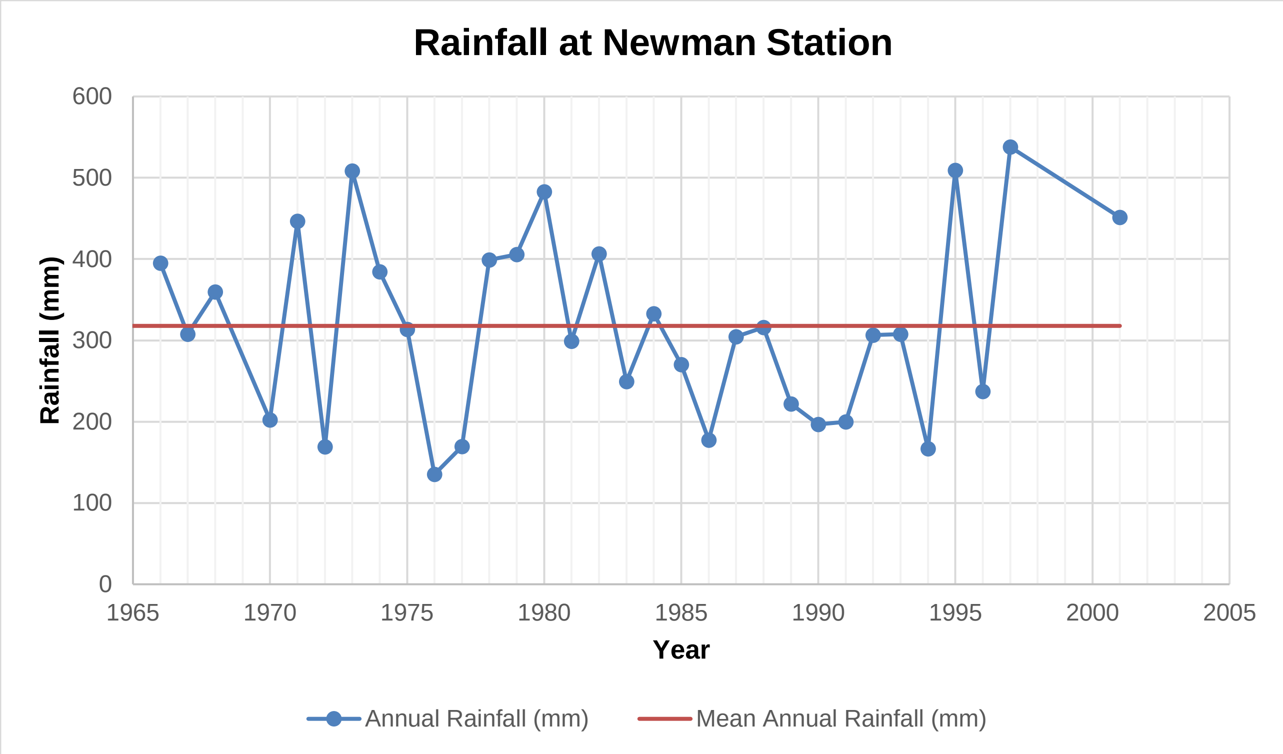

Figure 3-1 Average rainfall at Newman station in Pilbara

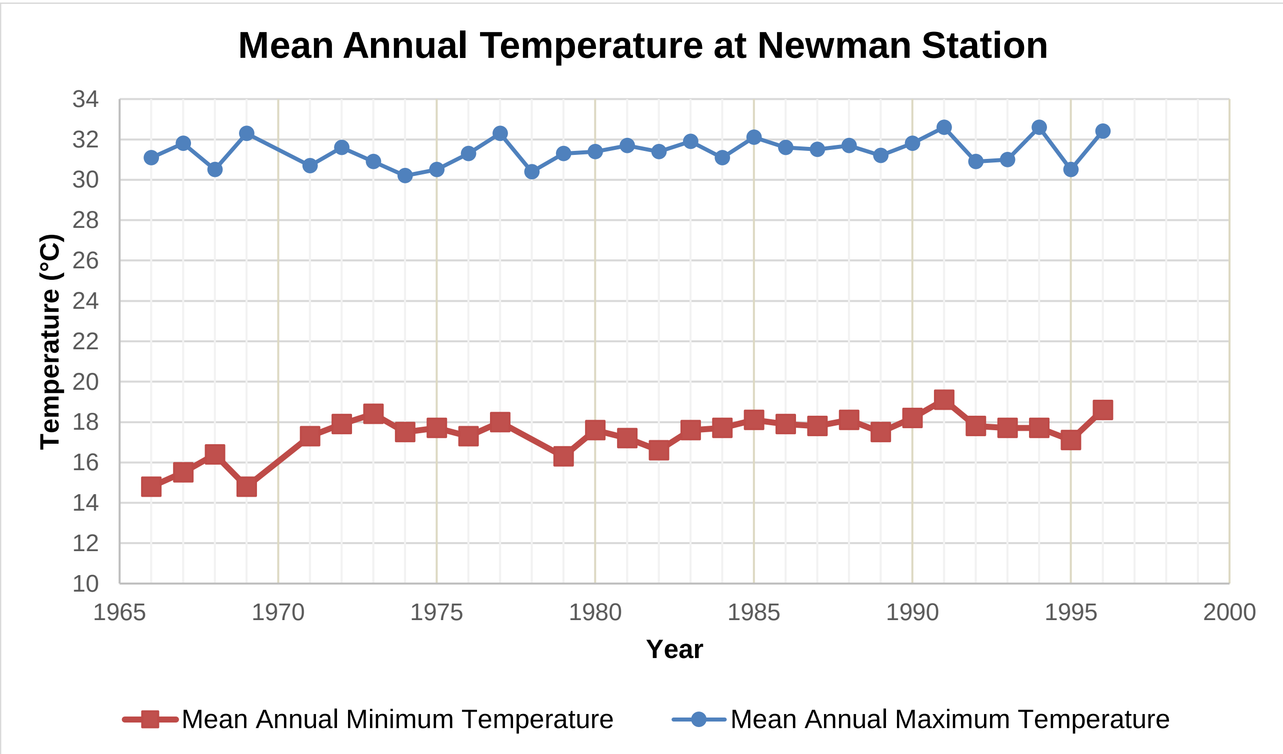

Figure 3-2 Mean annual minimum and maximum temperature at Newman station in Pilbara

3.2. Geology

Detailed geological surveys in the Pilbara have shown that it encompasses numerous geological groups at different ages. In the Hope Downs-1 North mine and its vicinity, the geological units are typically composed of the Wittenoom Formation and Marra Mamba formation, which are in the Hamersley group, and alluvial sediments cover these two formations (Dogramaci & Dodson 2009; Johnson & Wright 2001).

3.2.1. Wittenoom Formation

In terms of thickness, the Wittenoom formation is the Hamersley group's most important formation. It has a thickness ranging from 300-600 m. Large dolomite with medium thin bedded rare chert deposits make up the majority of the formation. Shale chert and iron formation are found in the upper section of the formation. It is also divided into 3 members, West Angela and Bee Gorge Paraburdoo (Hickman 1983; Trendall et al. 1998; Trendall & Blockey 1970). According to RPS (2015), the hydraulic conductivity of a Paraburdoo member ranges between 0.1 and 101 m/day, with an average of 10 m/day.

3.2.2. Marra Mamba Formation

The formation of Marra Mamba, which is the lowest layer of the Hamersley group, has a thickness of approximately 230 meters and is characterized by banded iron deposition as the key formation. It also includes chert, siltstone, mudstone and minor shale. The formation is divided into 3 members, i.e. the MacLeod, Mount Newman and Nammuldi (Hickman 1983; Trendall et al. 1998; Trendall & Blockey 1970). While the hydraulic conductivity of the Marra Mamba formation varies between 0.3 and 85 m/day, the average conductivity values obtained as a result of pumping test and modelling are 2 and 5 m/day, respectively (RPS 2015).

3.2.3. Tertiary and Quaternary Sediments

The deposition of weathered banded iron and fluvial materials occurred in the area during the early Tertiary period. Unconsolidated and coarse-grained banded iron, dolomitic gravel, calcrete, sand/clay matrix mix materials accumulate later, together with the Quaternary period (Dodson 2010; Hickman 1983). The hydraulic conductivity of tertiary sediments varies between 2.5 - 41 m/day, while the average is 11 m/day (RPS 2015).

3.3. Hydrogeology

For residents, ecology and the mining industry in the area, groundwater is critical. Generally, water resources are scarce given that evaporation is of greater magnitude than rainfall in the region. Groundwater generally occurs in hydrogeological environments such as surficial unconsolidated sedimentary aquifers, as well as weathered and fractured aquifers (Johnson & Wright 2001; Van Vreeswyk et al. 2004). Groundwater around Hope Downs is generally found in tertiary sediments and in the Wittenoom Formation and within the karstic dolomite underlying these sediments. Groundwater flows from south and west to north east. As a result of pumping tests, single well recovery tests and dual porosity tests, the average hydraulic conductivity, transmissivity and storativity of the Wittenoom formation is relatively well known: 2.14 m/day, 380 m^2/day and $2*10^{-3}$, respectively (Rojas et al. 2018). **Error! Reference source not found.** illustrates the hydraulic p arameters of various aquifers described in the Pilbara region. The regional groundwater recharge is supported directly by infiltration after rainfall and indirectly by losses of ephemeral creeks. However, groundwater recharge depends on the duration and magnitude of the rainfall events and the existence of ephemeral rivers (Rojas et al. 2018). Groundwater is discharged at Weeli Wolli spring, which is close to the research region (Figure 3-4). In addition, due to the shallow groundwater level in the upstream of the spring and the dense phreatophyte vegetation, there is loss from groundwater by evapotranspiration (Dogramaci & Dodson 2009).

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Figure 3-3 Hydraulic parameters of defined aquifer in Pilbara

Source: Rojas et al. (2018)

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Figure 3-4 Site location map of Hope Downs-1 North mine and Weeli Wolli Spring complex

Source: Johnson and Wright (2003)

4. GROUDWATER FLOW MODEL

In this study a generic groundwater flow model is established based on the general geological and climatic features of the Hope Downs-1 North mine. Generic models are developed primarily to understand idealized groundwater systems and flow processes. Simplified methods and assumption such as aquifer geometry and model layering used in these models do not reflect any particular region and cannot be used in actual site studies (Anderson et al. 2015; Merz 2012). Additionally, since they are hypothetical models, there are no processes like data collection, data analysis, or model calibration (Sheets et al. 2005). The model is used to explore groundwater recovery scenarios for open-case mines in the Pilbara with emphasis on the duration of groundwater recovery and the effects of water management options on recovery times.

4.1. Computer Code

In this study, the numerical groundwater model MODFLOW is used with the graphical user interface Processing Modelling for Windows (PMWIN) 8.0.45. PMWIN was originally developed in Germany and later versions have been published by Chiang and Kinzelbach (2003). PMWIN is integrated with a wide range of transport models, inverse codes and additional modelling tools (Chiang 2005).

4.2. Model Geometry and Layering

The model region is planned to be 100 km long E-W and 100 km long N-S, with a total area of 10,000 km^2. The model area has no streams, creeks, or reservoirs, and only the opencast mining area is specified.

4.2.1. Layer Design

Model layers are used to describe geological units that show hydrogeological characteristics. The model domain in this study consist of 6 layers, with topographic surface elevation and bottom elevation of 50 and -200 metres, respectively. Thus, the top aquifer is unconfined, the second aquifer is unconfined/confined (transmissivity varies), and other aquifers are defined in the model as confined (Figure 4-1).

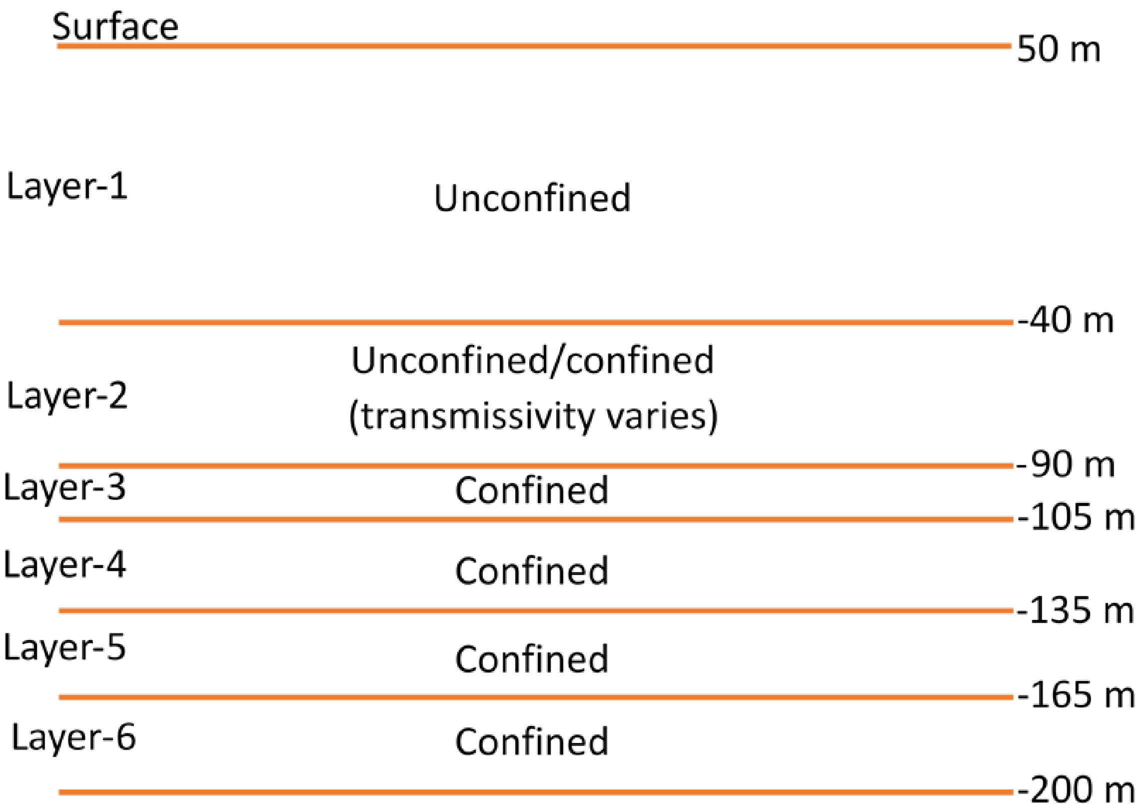

Figure 4-1 Layer design of generic model

4.2.2. Mesh Design

The model domain consists of 192 columns and 110 rows for each layer and comprises 21120 cells in total. Although the cell size is 50x50 m the vicinity of the planned mine pit area, it comprises coarse cells (3500 * 3500 m) towards the model domain boundary.

4.3. Boundary Conditions

The model domain is bounded by a General-Head Boundary (GHB). The GHB package provides flow in and out of a cell depending on a hydraulic conductance value and the difference between the head in the aquifer and that specified for the GHB. The head at the GHB and the hydraulic conductance equal 20 m and 200 m^2/day, respectively.

4.4. Hydrogeological parameters and recharge properties

The properties of the porous media were defined using generic model parameters such as recharge, horizontal/vertical hydraulic conductivity, and storage properties (Table 4-1). Recharge is specified at a rate of 5 mm/year based on study by Cook et al. (2017).

Table 4-1 Generic model parameters

Model Parameters	
Horizontal Conductivity (Kh)	1.5 m/day
Vertical Conductivity (Kv)	0.15 m/day
Specific Storage (Ss)	0.000023 m^{-1}
Specific Yield (Sy)	0.1
Recharge	5 mm/year

4.5. Initial Conditions

Before creating groundwater recovery scenarios, the generic model was run for 100 years with the recharge rate at 5 mm/year and all other parameters as given in Table 4-1. Thus, at the end of 100 years, the steady-state hydraulic head is 47.61 m at the centre of the model (Figure 4-2). The main aim of the steady hydraulic head is to compare the hydraulic head obtained at the end of 100 years with groundwater recovery scenarios that will be generated later.

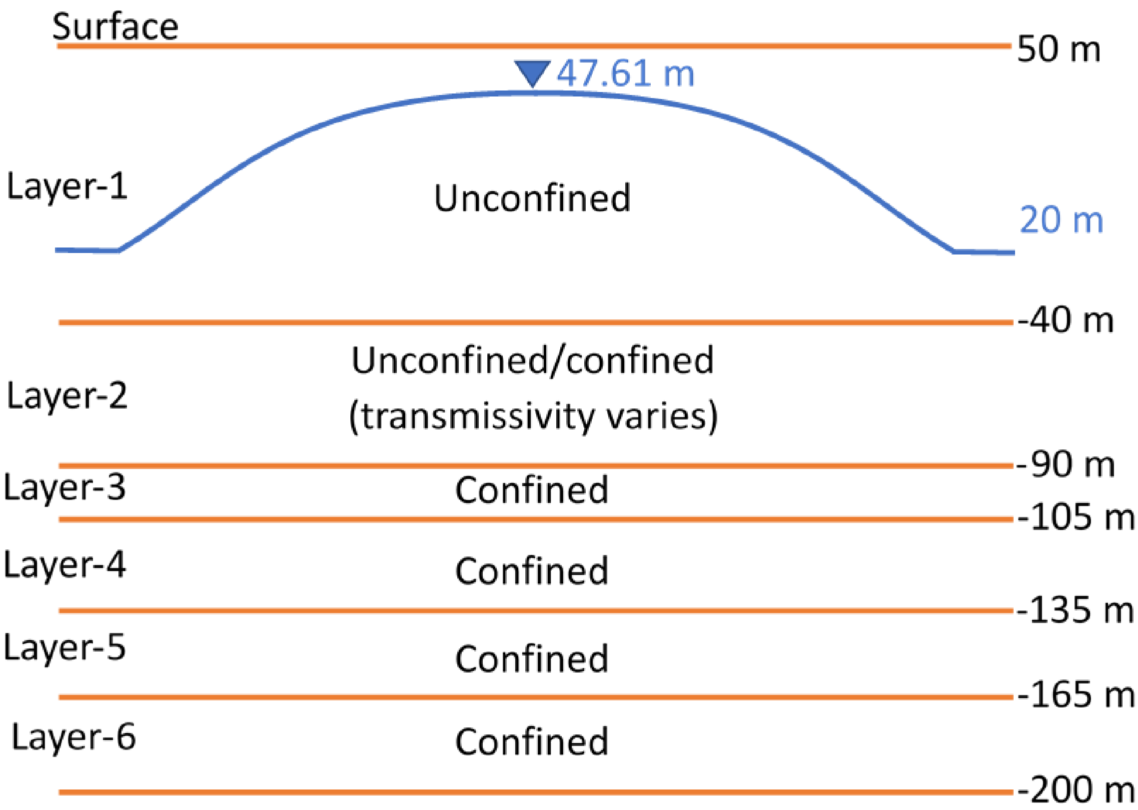

Figure 4-2 Hydraulic head of generic model after 100 years of steady recharge

4.6. Dewatering Activities

Dewatering was simulated through a total of 24 dewatering wells, located at 250 m intervals. Dewatering occurred for 20 years with wells situated at -200 m pumping at a rate of 6000 m^3/day (black circles in Figure 4-3) and 4500 m^3/day, respectively (see Figure 4-3). Hence, a total of 117,000 m^3/day of water is pumped to keep the groundwater level below -40 metres. As a result of dewatering, the water level is lowered to -43.26 m, i.e. a maximum drawdown of -78 metres, which results in a dry mining area (Figure 4-4) The dry mine site's area is estimated to be about 2.8 km^2. Hydraulic head observations are carried out in the generic model using 4 separate observation wells located at various distances from the mine site (Figure 4-3). Figure 4-5 shows the drawdown in observation bore 4 after 5, 10 and 20 years of dewatering, respectively. The drawdown at the end of 5 years is about half that of the drawdown at the end of 20 years.

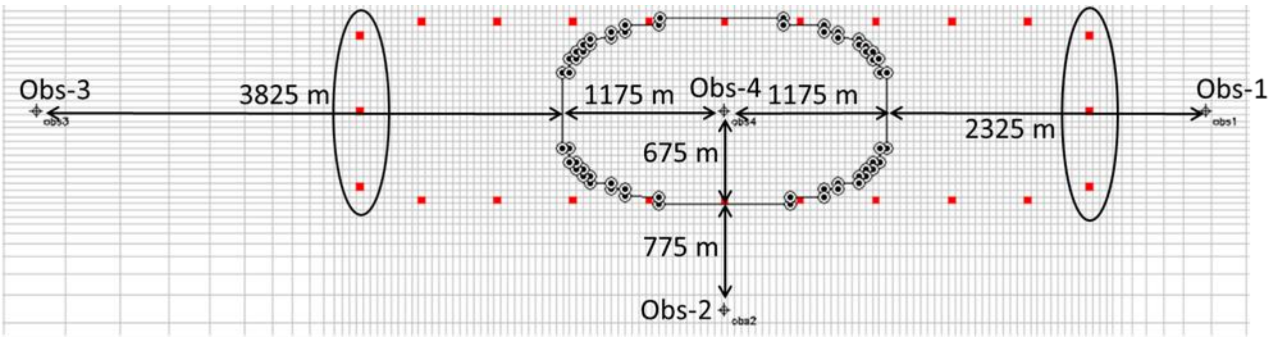

Figure 4-3 Location of dewatering wells and observation wells

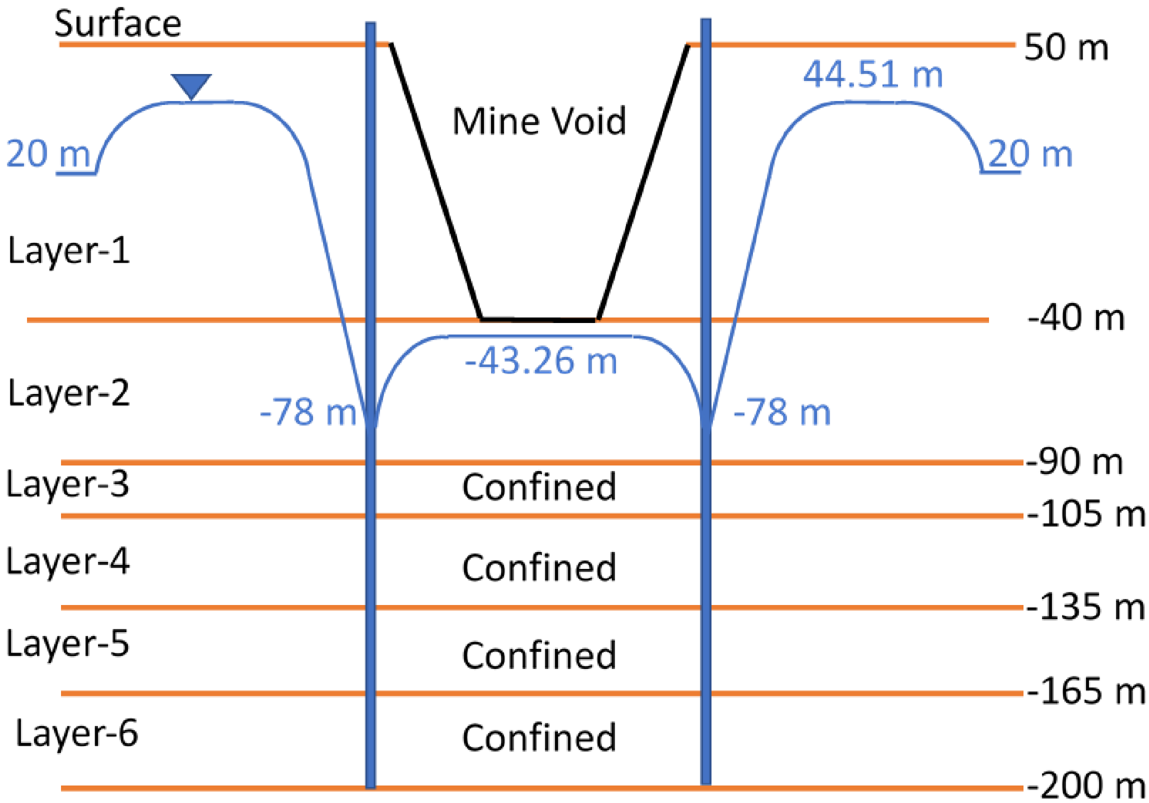

Figure 4-4 Hydraulic head of generic model after dewatering activities

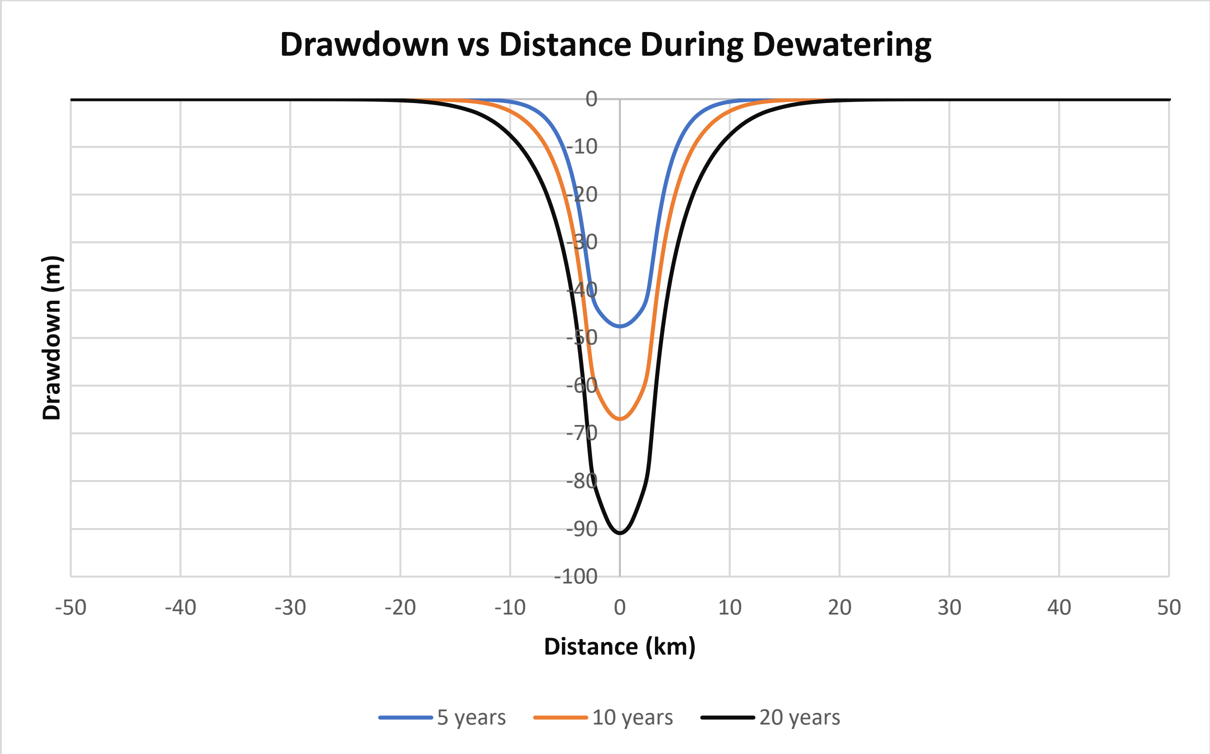

Figure 4-5 Drawdown difference during the dewatering activities for different time periods

4.7. Model Scenarios

Following 20 years of dewatering, all bores were turned off and recovery of the water level was observed under different recovery scenarios (Table 4-2). Model parameters are different in the mine void for different scenarios. Comparisons between different scenarios allowed impacts of management scenarios to be evaluated.

Table 4-2 Groundwater recovery scenarios

	Description	**Mine void parameters**	**Recharge Package**	**Evapotranspiration Package**
Scenario-1	Examining the groundwater recovery without mine void	-	5 mm/year	-
Scenario-2	Examining the groundwater recovery with open pit	Kh: 1000 m/day Kv: 1000 m/day Ss: 1 m-1 Sy: 1	5 mm/year	-
Scenario-2-a	Investigating the effect of backfilling material with different conductivity on recovery	Kh: 0.01, 0.5, 1.5, 10, 500, 1000 m/day Kv: 0.001, 0.05, 0.15, 1, 50, 100 m/day Ss: 1 m-1 Sy: 1	5 mm/year	-

Scenario-2-b	Investigating the effect of backfilling material with different storage parameters on recovery	Kh: 1.5 m/day Kv: 0.15 m/day Ss: 0.01, 0.000023, 0.0000001 m-1 Sy: 0.005, 0.1, 0.15, 0.4	5 mm/year	-
Scenario-3	Examining the effect of ET on groundwater recovery	Kh: 1000 m/day Kv: 1000 m/day Ss: 1 m-1 Sy: 1	5 mm/year	ET rate: 3 m/year ET surface: -40 m Extinction depth: 3 m
Scenario-3-a	Examining the effect of different ET on groundwater recovery	Kh: 1000 m/day Kv: 1000 m/day Ss: 1 m-1 Sy: 1	5 mm/year	ET: 3 m/year ET: 2 m/year ET: 1 m/year Without ET
Scenario-4	Investigating the direct effect of rainfall	Kh: 1000 m/day Kv: 1000 m/day Ss: 1 m-1 Sy: 1	5 mm/year + (Rainfall of 318 mm/year for only mine pit)	ET rate: 3 m/year ET surface: -40 m Extinction depth: 3 m
MAR	Investigating the effect of injection wells on how to speed up recovery	MAR scenarios are performed for Scenario-1-2-3-4, respectively		

4.8. Theis Solution

Before any recovery scenarios were simulated, the accuracy of the model was tested by comparing its results to the Theis solution (Theis 1935). The observation wells for this solution differ from the wells used in the numerical model somewhat, as illustrated in the Figure 4-6. The parameters used for Theis solution are given in the Table 4-3. Results show that the Theis solution and the results of the numerical model are consistent, and the hydraulic head change in pumping and recovery processes close to identical (Figure 4-7, Figure 4-8, Figure 4-9, Figure 4-10).

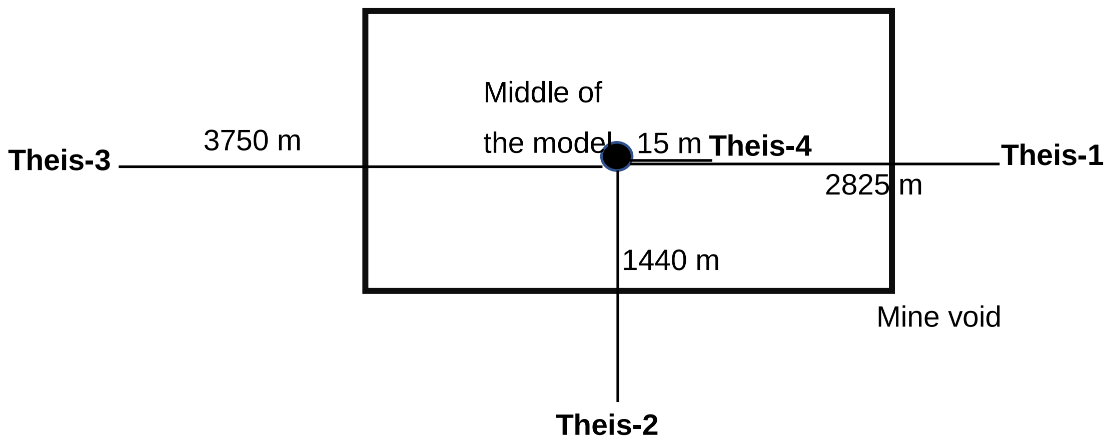

Figure 4-6 Location of observation for Theis solution

Table 4-3 Aquifer parameters for Theis solution

Theis Solution		
Pumping rate (Q)	-40000	m^3/day
Transmissivity (T: K*b)	330	m^2/day
Storativity (S: Ss*b)	0.00506	
Time (t)	7305	day
Saturated thickness (b)	220	m
Conductivity (K)	1.5	m/day
Specific Storage (Ss)	0.000023	m^{-1}

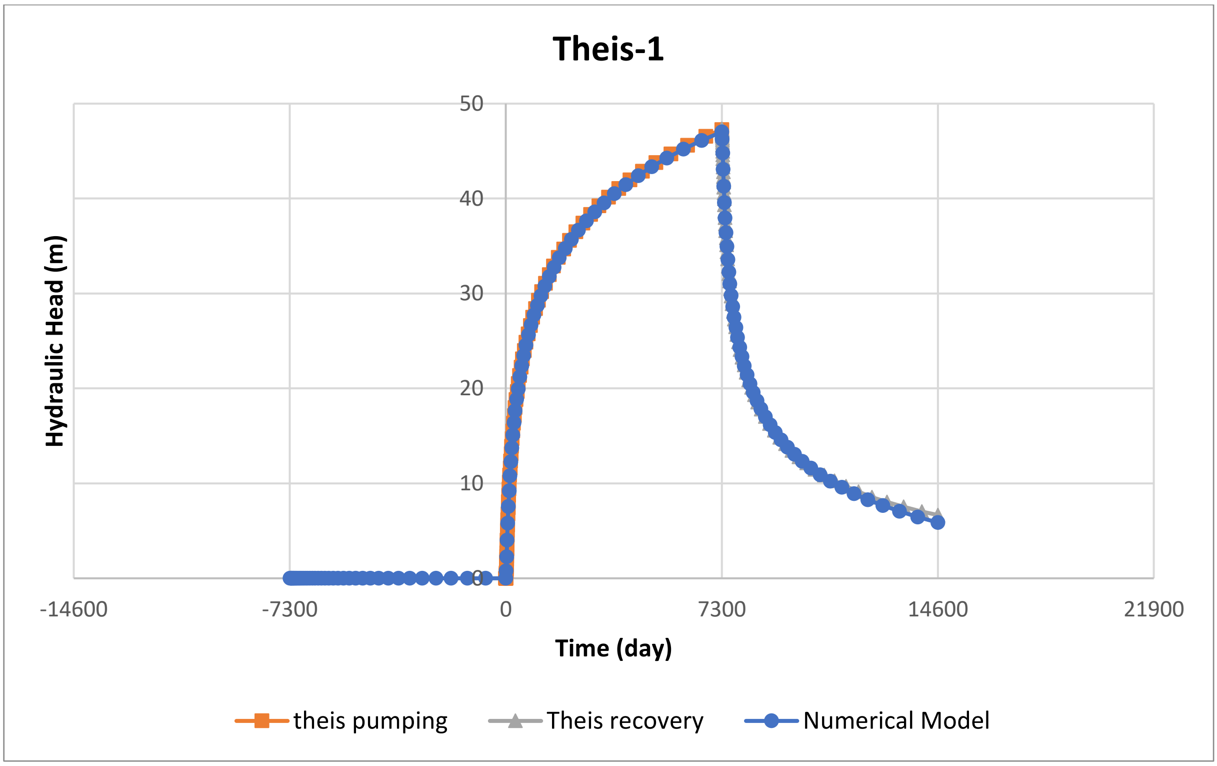

Figure 4-7 Comparison of hydraulic heads of Theis solution and numerical model for Theis-1

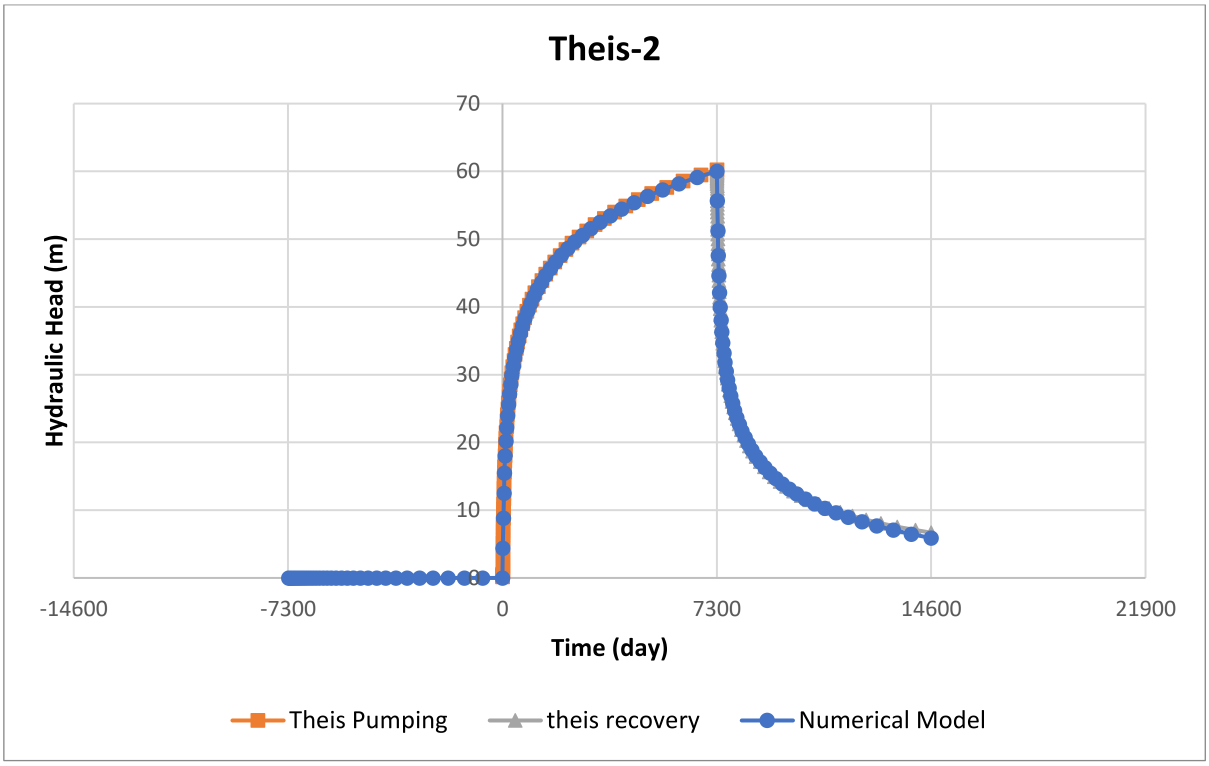

Figure 4-8 Comparison of hydraulic heads of Theis solution and numerical model for Theis-2

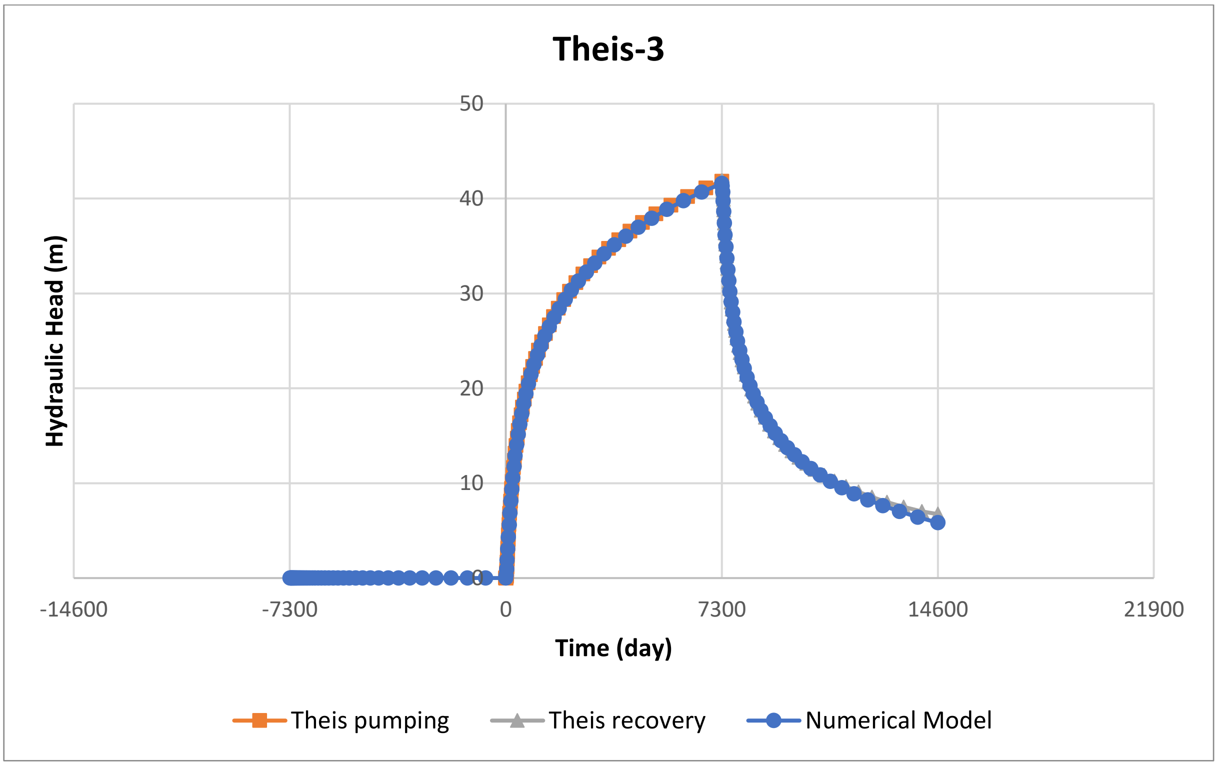

Figure 4-9 Comparison of hydraulic heads of Theis solution and numerical model for Theis-3

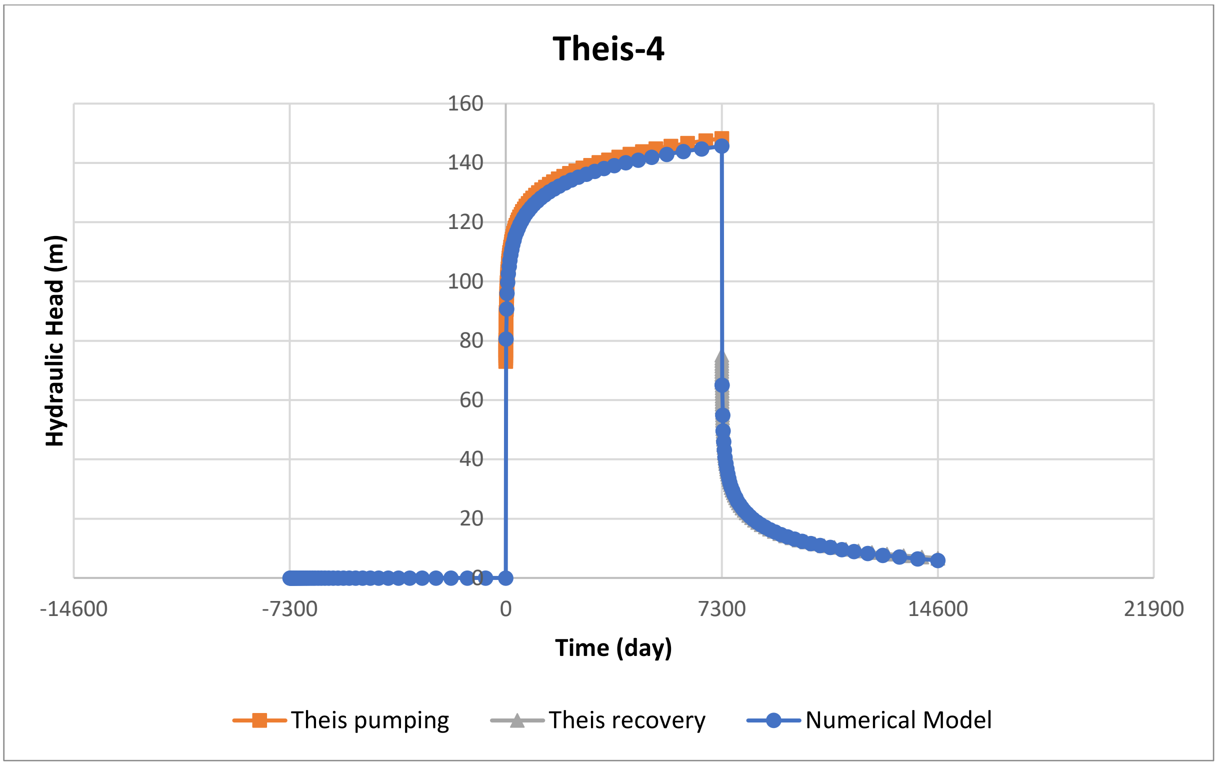

Figure 4-10 Comparison of hydraulic heads of Theis solution and numerical model for Theis-4

5. RESULT AND DISCUSSION

5.1. Backfilled Pit (Scenario-1)

Backfilling is regarded as one of the best practises in the mine closure plan in terms of mine site restoration and land use. Backfilling allows for the re-use of waste rock and tailings produced during mining operations and may improve environmental outcomes post-mining. Backfilling operations provide cost-effective management of waste rock, at the same time preventing the development of pit lakes with poor water quality in pit areas and water loss caused by evaporation (Puhalovich & Coghill 2011).

Backfill scenario 1 was run by re-filling the mine pit with material which was identical to the aquifer material prior to mining. Five graphs illustrate the drawdown in the water level under scenario 1 as the distance from the mine pit increases (Figure 5-1, Figure 5-2, Figure 5-3, Figure 5-4). The drawdown vs time graph created for the backfilled pit scenario shows the decrease that occurred over time (Figure 5-5). Thus, groundwater recovery between periods of 5 and 10 years is greater than that between periods of 50 and 100 years. In other words, as time progresses after the mining operations are completed, the hydraulic head becomes more horizontal, which reduces the flow into the mine pit, causing the groundwater recovery to slow down.

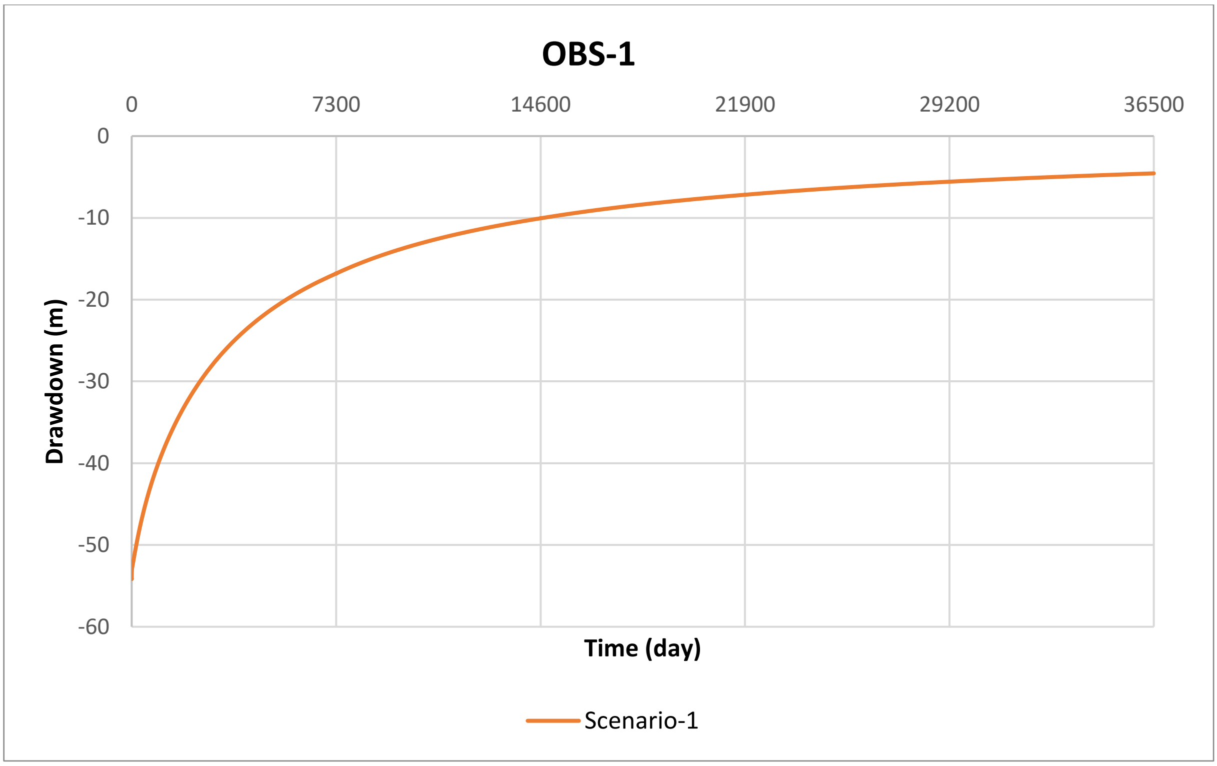

Figure 5-1 Drawdown of backfilled pit scenario for OBS-1

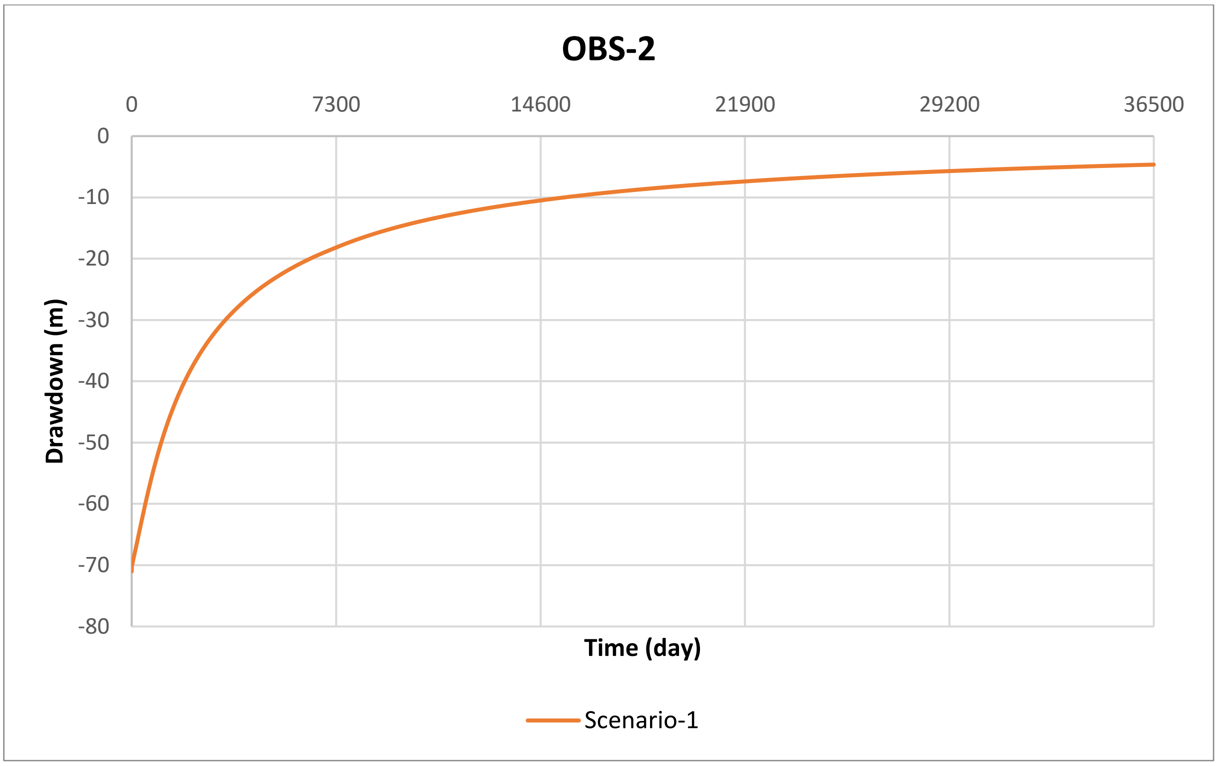

Figure 5-2 Drawdown of backfilled pit scenario for OBS-2

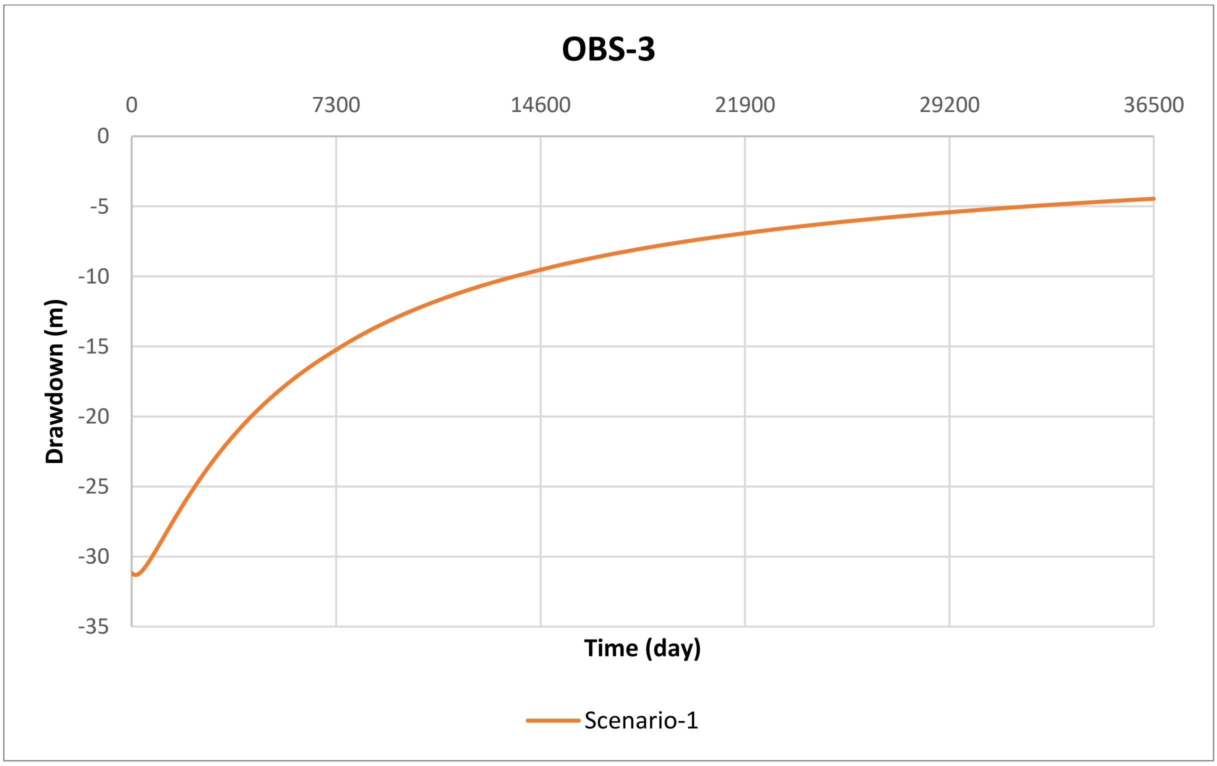

Figure 5-3 Drawdown of backfilled pit scenario for OBS-3

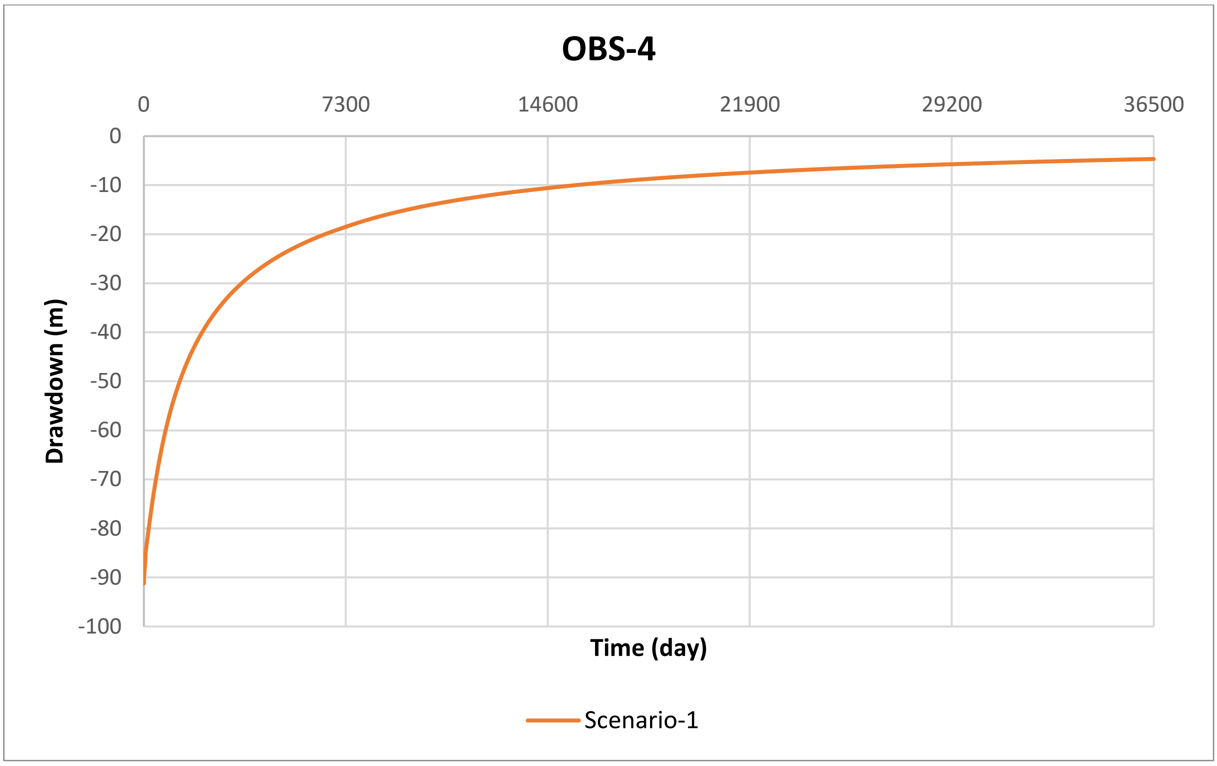

Figure 5-4 Drawdown of backfilled pit scenario for OBS-4

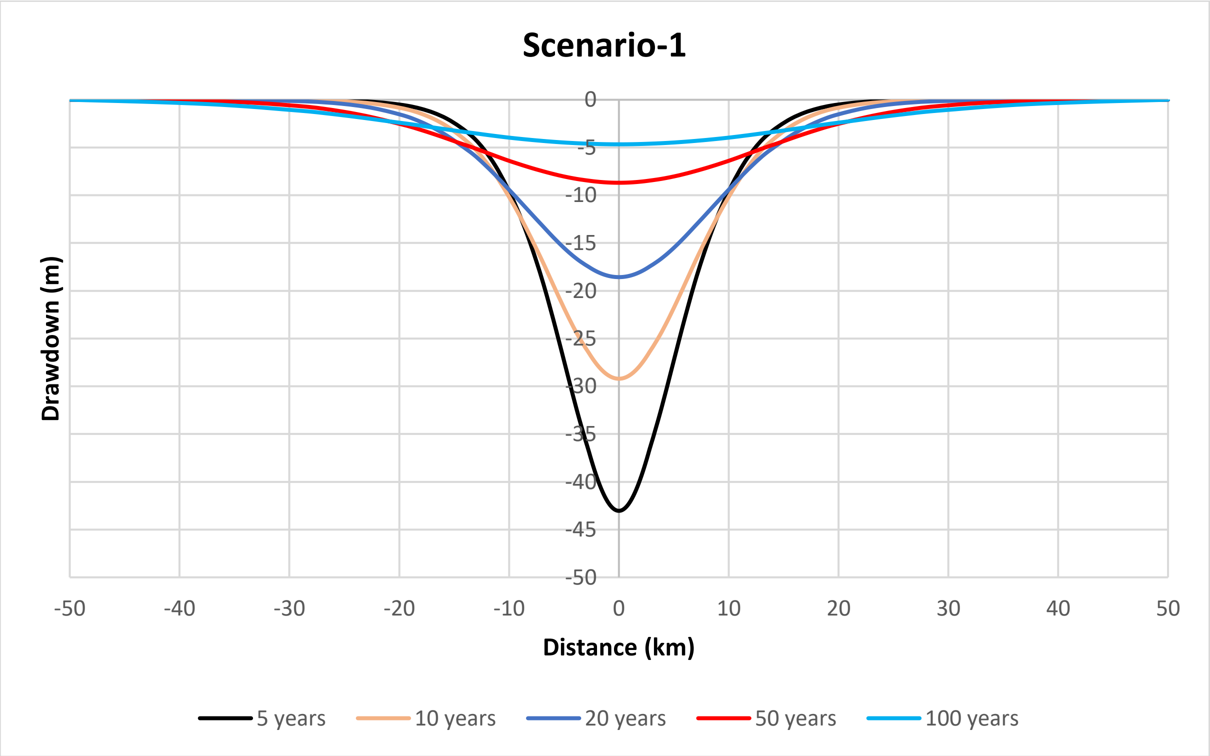

Figure 5-5 Drawdown difference of backfilled pit scenario for different time periods

5.2. Comparison of Backfilled Pit and Open Pit Scenario (Scenario-1 and Scenario-2)

The open pit scenario (Scenario 2) investigates groundwater recovery as a result of leaving the mine pit as a void without any backfilling. It omits evapotranspiration from pit lake as groundwater recovers over time. The groundwater recovery model is run for 100 years after the void parameters in Table 4-2 for Scenario-2 are specified. The Figure 5-6 depicts the relative recovery level of the backfilled pit compared to the open pit scenarios for OBS-4, which is situated in the middle of the mine pit. Since more water is needed to fill the void in Scenario-2 as a result of the inclusion of the mine void, the drawdown in Scenario-2 is slower than in Scenario-1. The Figure 5-7 shows how the drawdown varies with distance over various time intervals for Scenario-2. Comparative scenarios generated for OBS-1-2 and 3 are given in Appendix-1.

Figure 5-6 Comparison of drawdowns of backfilled pit and open pit scenarios

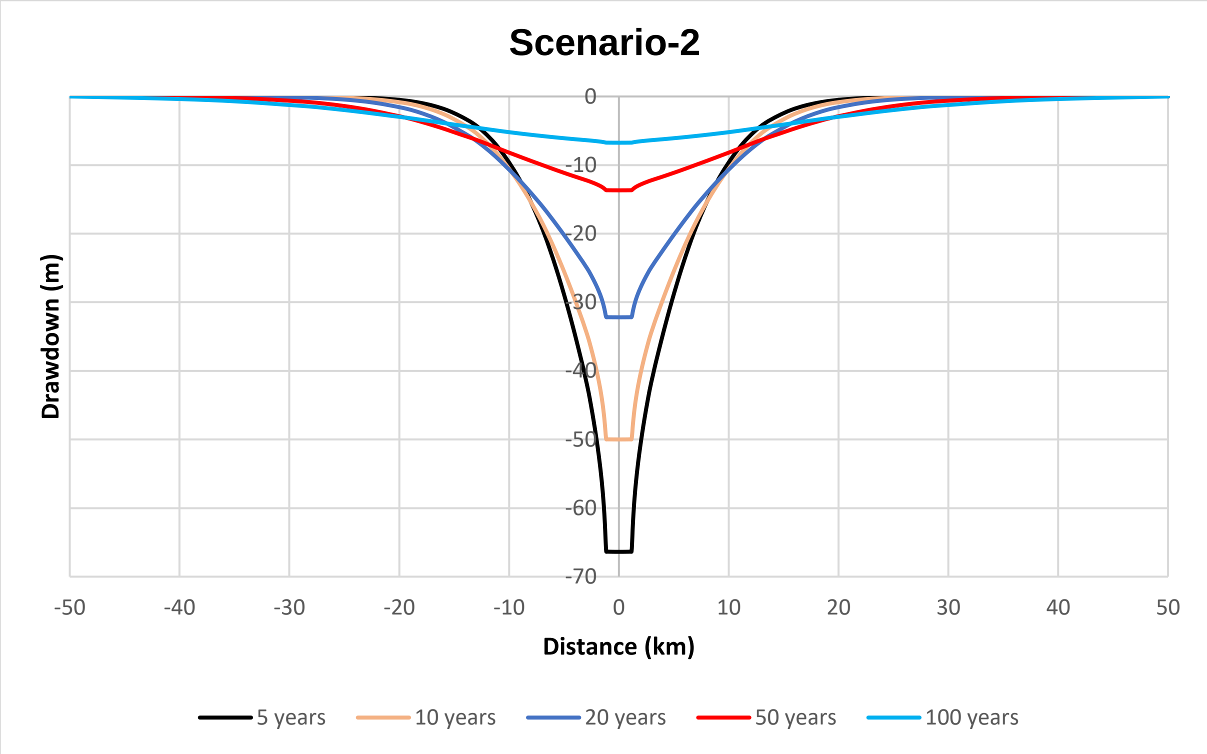

Figure 5-7 Drawdown difference of mine void scenario for different time periods

5.3. Comparison of Backfilled Pit and ET Scenario (Scenario-1 and Scenario-3)

The excessive evapotranspiration rate in the Pilbara region compared to the amount of precipitation slows the recovery of groundwater in the mine sites. To investigate the impact of the high ET rate on groundwater recovery, an ET rate (ET: 3m/year) is applied to the open pit scenario (scenario 2), and the groundwater recovery model is run for 100 years. As can be seen in the Figure 5-8, the drawdown in Scenario-3 after 100 years of recovery stabilises at -38 m, i.e. high evaporation rate leads to a difference in groundwater level compared to Scenario-1 of approximately 33 m. The difference to Scenario-2 is approximately 31 m. This illustrates that groundwater recovery in a mine pit in the Pilbara is driven largely by ET. Figure 5-9 shows how the distance-based drawdown for Scenario-3 changes according to different time periods. Comparative scenarios prepared for OBS-1-2 and 3 are given in Appendix-2.

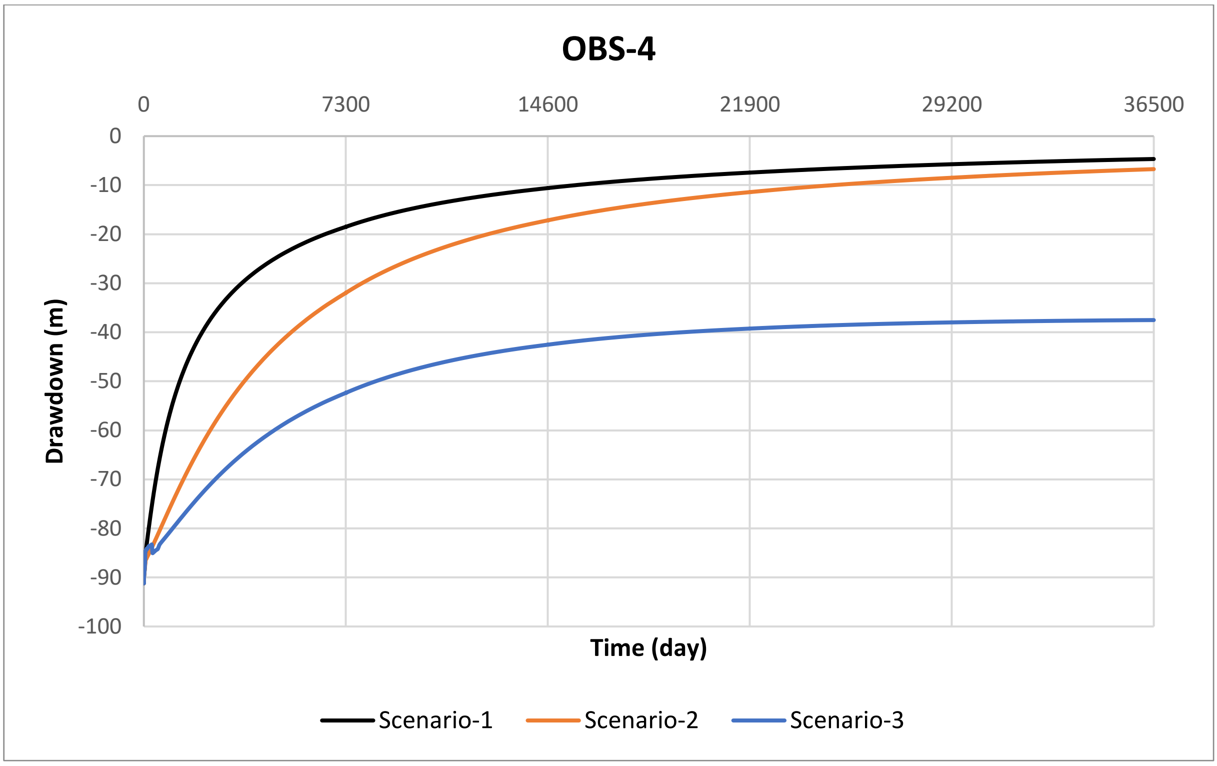

Figure 5-8 Comparison of drawdowns of backfilled pit, open pit and ET scenarios

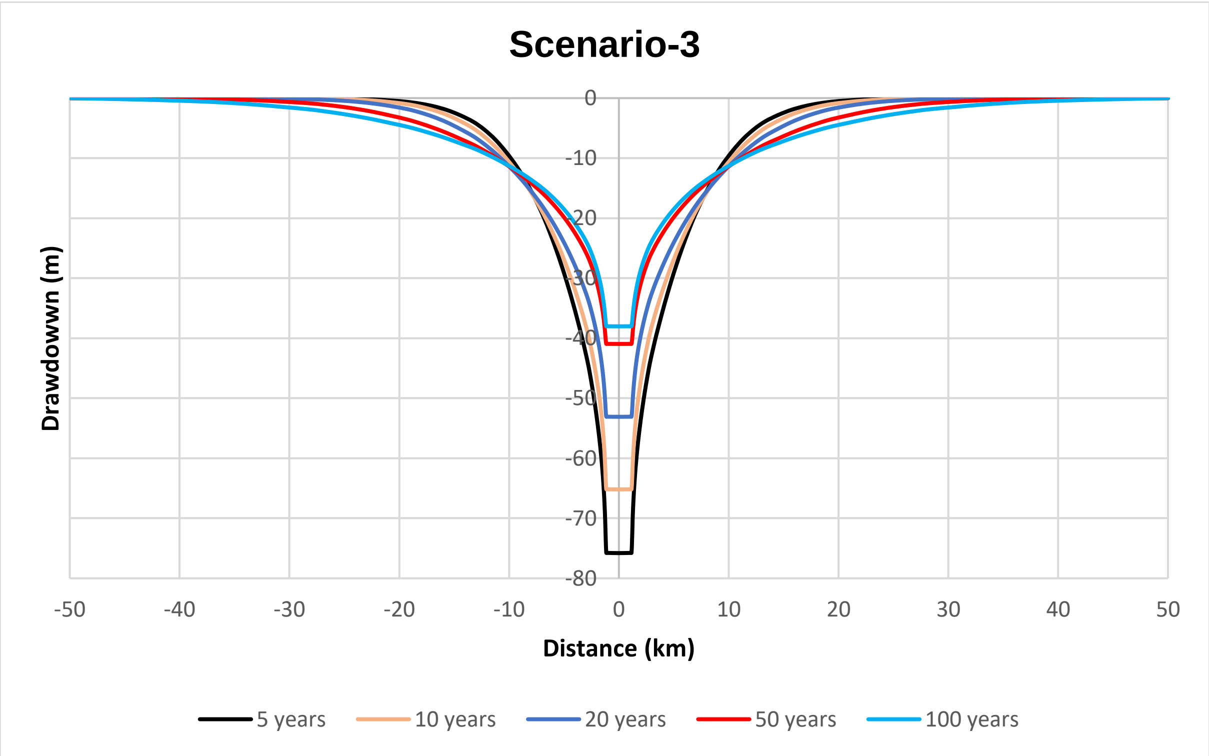

Figure 5-9 Drawdown difference of ET scenario for different time periods

5.4. Comparison of Backfilled Pit and Direct Rainfall Scenario (Scenario-1 and Scenario-4)

Scenario-4 explores the effect of rainfall to the pit. Thus, in addition to Scenario-3, the rainfall rate (318 mm/year) is applied for the mine pit area. Compared to the backfilled pit scenario for the OBS-4 in Figure 5-10, the direct rainfall scenario provides roughly 3.5 m increase in groundwater recovery level, however groundwater level remains well below pre-mining levels. The Figure 5-11 shows how the distance-based drawdown for Scenario-4 changes according to different time periods. Comparative scenarios prepared for OBS-1-2 and 3 are given in Appendix-3.

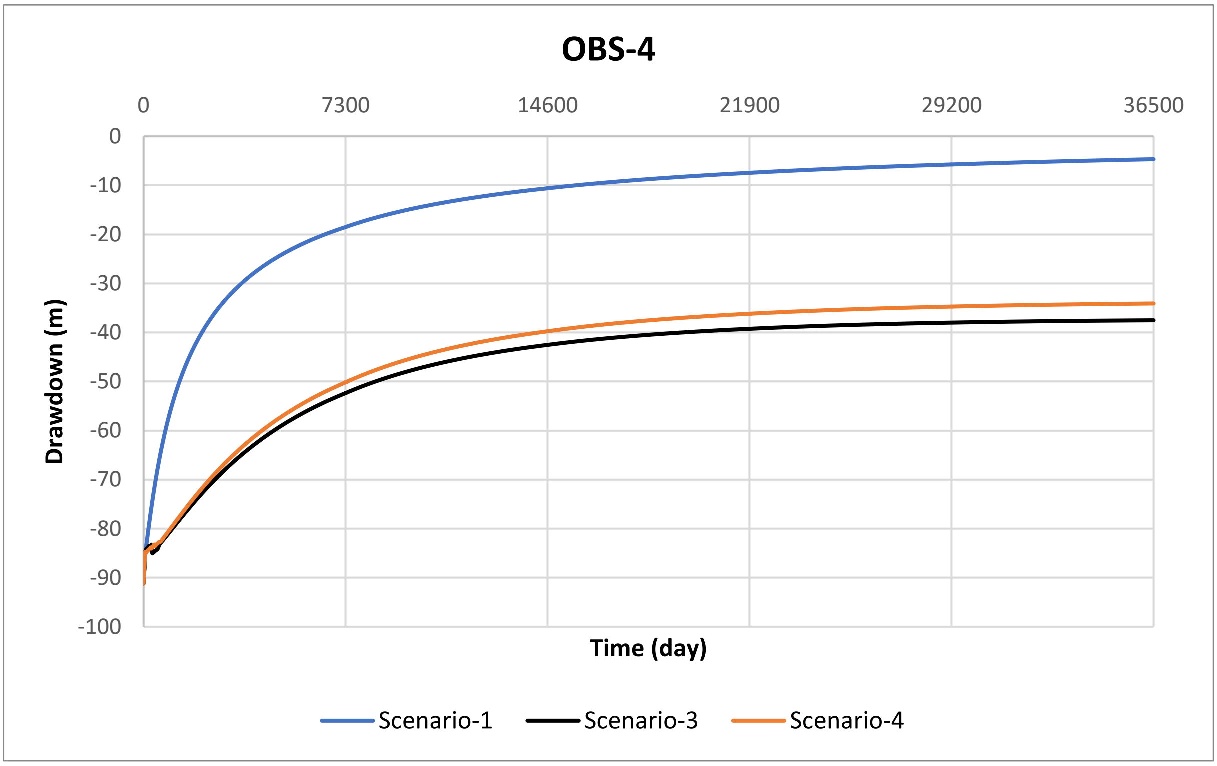

Figure 5-10 Comparison of drawdowns of backfilled pit, ET and direct rainfall scenarios

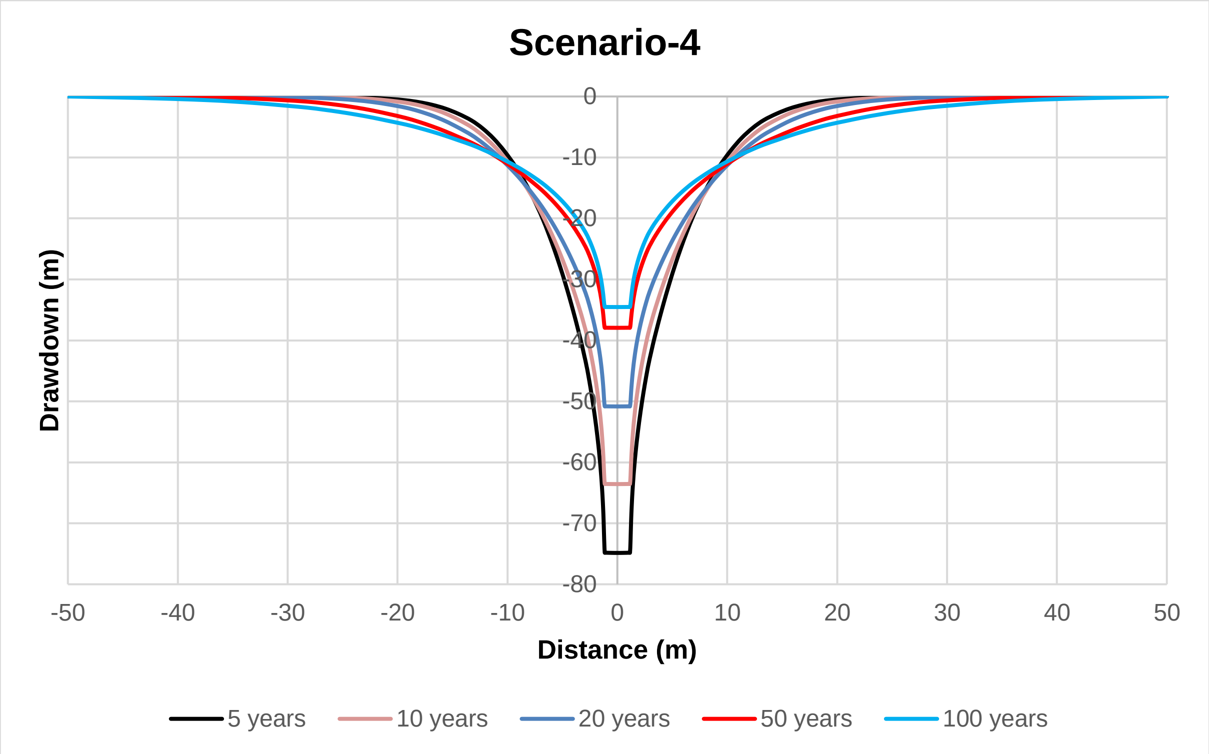

Figure 5-11 Drawdown difference of direct rainfall scenario for different time periods

5.5. Effect of Different Evapotranspiration Rate (Scenario-3-a)

Given that the ET rate appears to bear a large influence on groundwater level recovery in the Pilbara (see Scenario-3), the effect of different ET rates was further explored. The Figure 5-12 shows the drawdown in OBS-4 at various ET rates and without ET. With the gradual decrease in the value of ET, the drawdown seems to decrease steadily. Comparative ET charts prepared for OBS-1-2 and 3 are given in Appendix-4. In the Figure 5-13 it is seen that the ET effect decreases with distance from the mine pit.

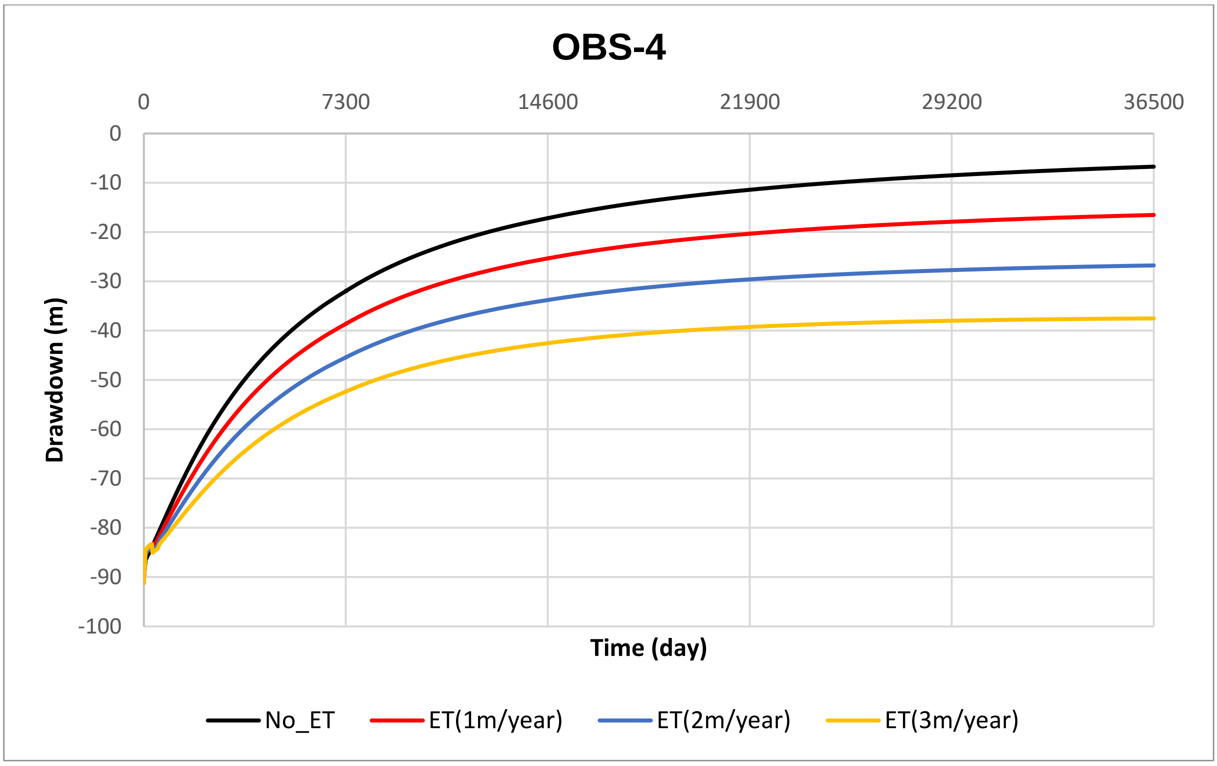

Figure 5-12 Comparison of drawdowns for different ET rate

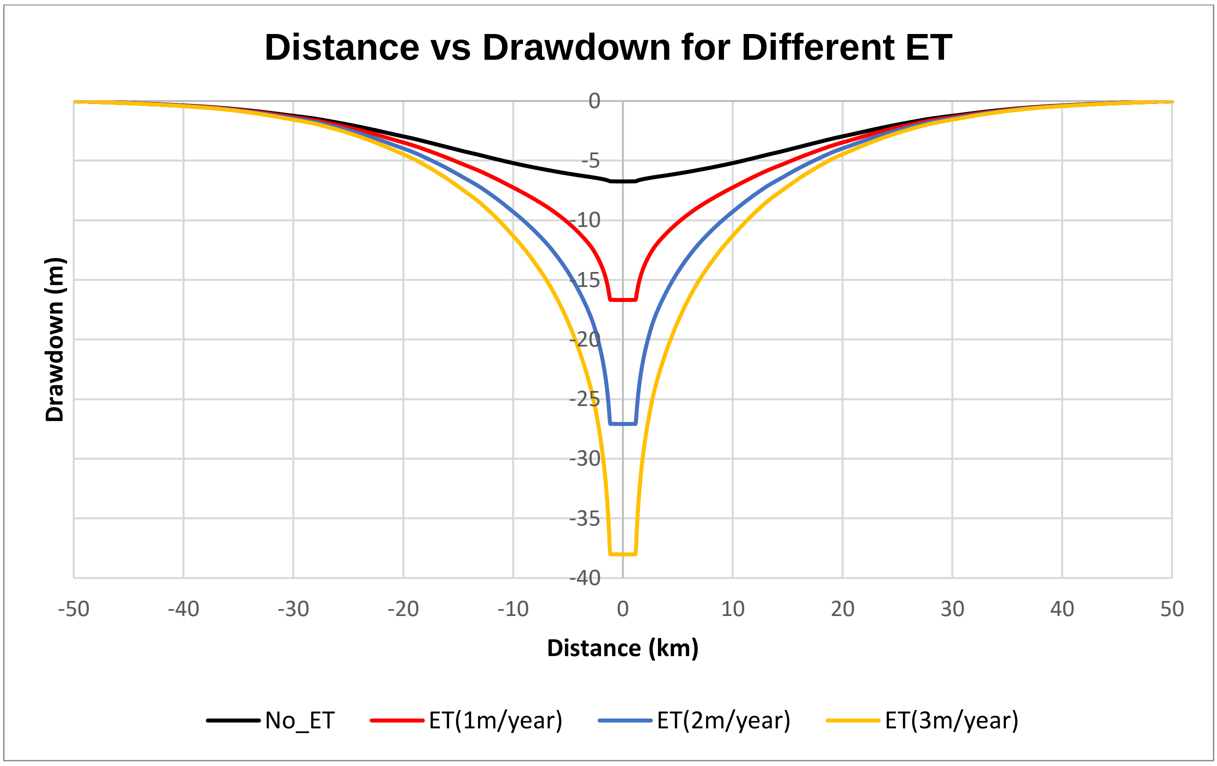

Figure 5-13 Drawdown difference of different ET rate over distance

5.6. Backfilling Scenarios with Different Hydraulic Conductivities (Scenario-2-a)

In the generic model, 8 different backfilling scenarios are created by changing only the horizontal and vertical conductivity for the area of the mine pit, while keeping the storage parameters constant (Table 5-1). As can be seen in the Figure 5-14 prepared for OBS-4, there is no change in terms of drawdown compared to other scenarios except scenarios with K: 0.0001 m/day and K: 0.01 m/day. The reason for the broadly similar drawdown is that the groundwater flow from the outside of the mine to the mine pit is the same as a result of keeping the horizontal conductivity value used for the model domain, except the mine pit, which his constant at 1.5 m/day. However, when using material with low conductivity (K: 0.0001 m/day and K: 0.01 m/day) as backfilling material, the groundwater level cannot reach the level of other scenarios. This is because high conductivity materials transmit more water than low conductivity materials (Fitts 2013). Figures prepared by applying different backfilling parameters to other observation wells are given in Appendix-5.

Table 5-1 Model parameters of backfilling scenarios for different hydraulic conductivity

	Model Parameters			
	Horizontal Conductivity (Kh) (m/day)	**Vertical Conductivity (Kv) (m/day)**	**Specific Storage (Ss) (m-1)**	**Specific Yield (-)**
Backfilling Scenarios	0.00001	0.000001	0.000023	0.1
	0.01	0.001	0.000023	0.1
	0.5	0.05	0.000023	0.1
	1.5	0.15	0.000023	0.1
	3	0.3	0.000023	0.1
	10	1	0.000023	0.1
	500	50	0.000023	0.1
	1000	100	0.000023	0.1

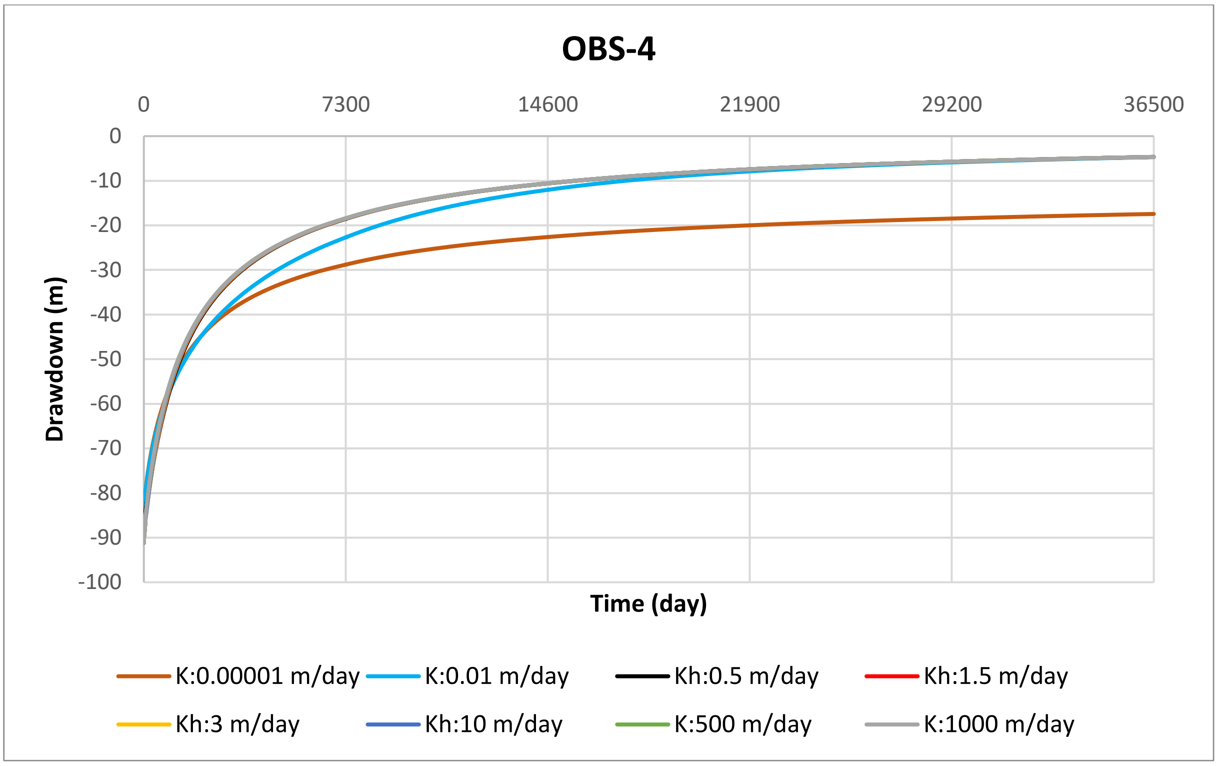

Figure 5-14 Comparison of drawdowns of backfilling scenarios for different hydraulic conductivity

5.7. Backfilling Scenarios with Different Storage Parameters (Scenario-2-b)

In the generic model, 4 different backfilling scenarios are created by changing only the specific yield (Sy) for the area of mine pit, while keeping the hydraulic conductivities constant (Table 5-2). In unconfined aquifers, storage is known as Sy and is defined as the amount of water discharged from the unit surface area of the aquifer under the effect of gravity for a unit decline in hydraulic head (Fitts 2013). Therefore, as Sy increases, the amount of water stored in the aquifer also increases. Figure 5-15 graphs the recovery of water levels in OBS-4 under different Sy values for the mine void area. As the Sy value rises, the drawdown of groundwater increases, as the storage to be filled by recovering water levels becomes larger. Figures created by applying different storage parameter to other observation wells are given in Appendix-6

Table 5-2 Model parameters of backfilling scenarios for different Sy

	Model Parameters			
	Horizontal Conductivity (Kh) (m/day)	Vertical Conductivity (Kv) (m/day)	Specific Storage (Ss) (m-1)	Specific Yield (-)
Backfilling Scenarios	1.5	0.15	0.000023	0.005
	1.5	0.15	0.000023	0.1
	1.5	0.15	0.000023	0.15
	1.5	0.15	0.000023	0.4

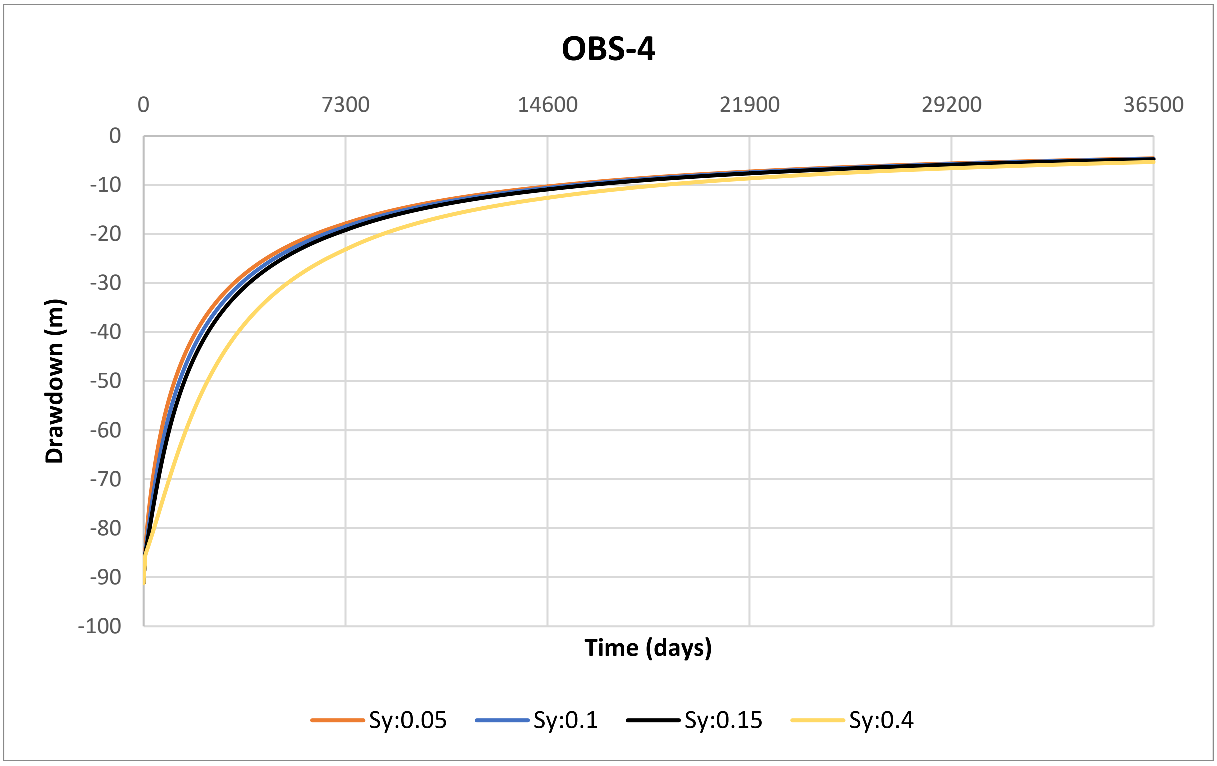

Figure 5-15 Comparison of drawdowns of backfilling scenarios for different Sy

5.8. MAR Dewatering

In order to explore the impact of MAR, 16 injection wells were located around the mine pit (red and black circles in Figure 5-16). The injection wells in the black circle are approximately 9 km away from the mine pit and each well injects approximately 2500 m^3/day water. The injection wells in the red circle are closest to the mine site and are only 3.1 km away from the pit. Each of these wells pump 2000 m^3/day of water back. Thus, the total injection rate is 36.000 m^3/day, which is 29.5% of the total MAR dewatering rate. Injection occurred during dewatering only. This required, however, to increase the abstraction rate from the dewatering bores, in order to maintain a dry pit void of the same size as model scenarios without MAR. Subsequently, the pumping rate of the wells shown in the red circles in the Figure 5-17 is increased from 4500 m^3/day to 4693 m^3/day, while the pumping rate of the wells in blue circles is increased from 4500 m^3/day to 5520 m^3/day. Thus, the total abstraction was 121.852 $m^{3/}$day for MAR scenarios. In Figure 5-18, it is observed that the drawdown decreases due to the increase in hydraulic head in locations where injection wells are installed.

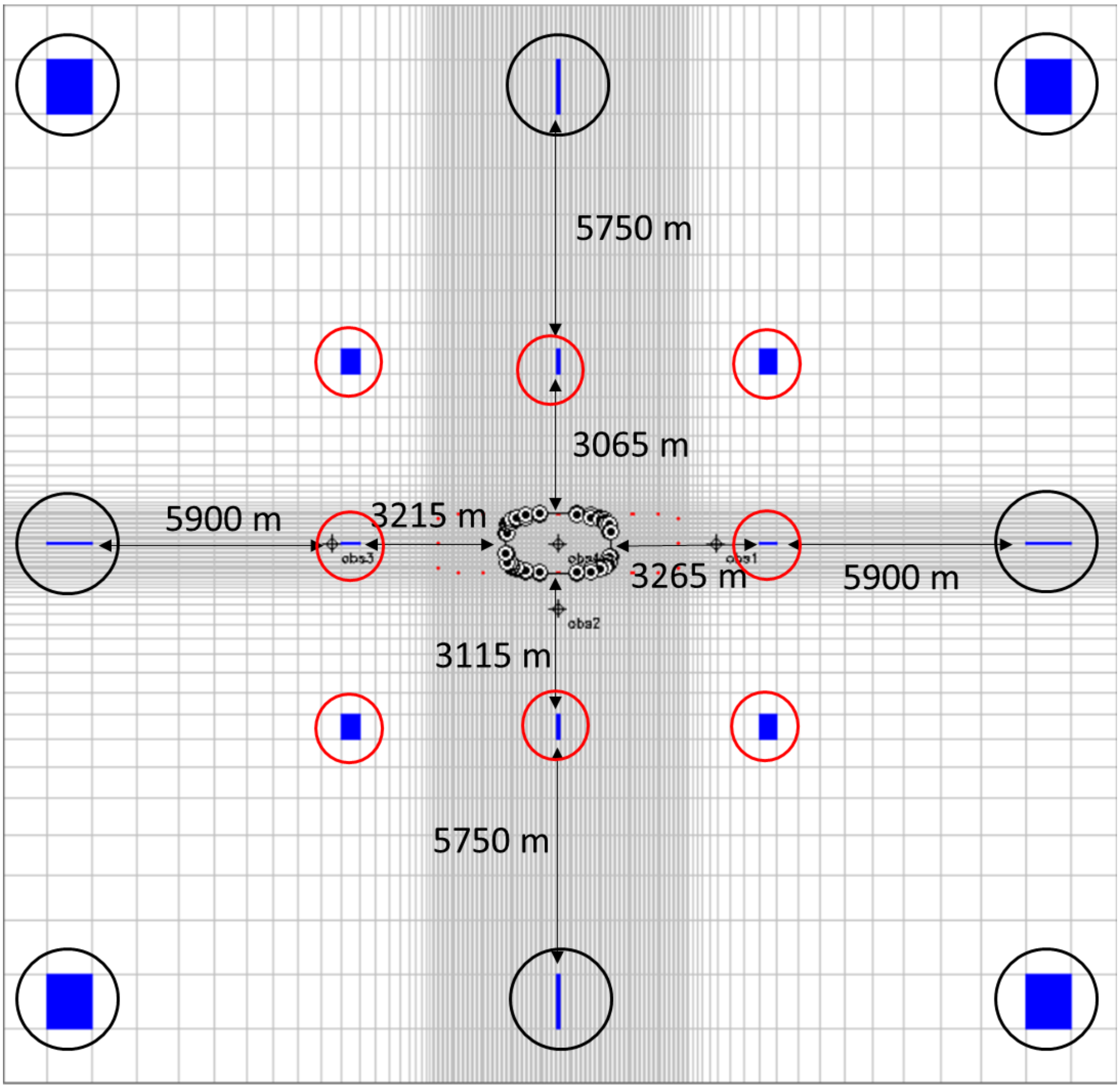

Figure 5-16 Location of injection wells

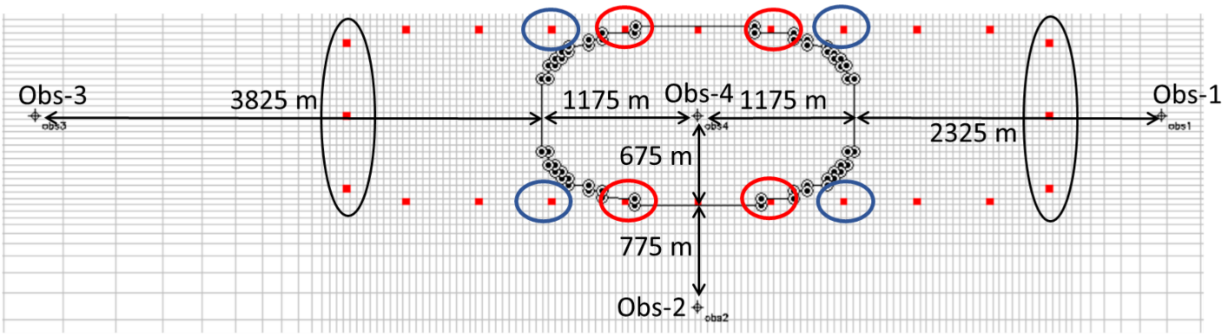

Figure 5-17 Increased pumping rates of dewatering wells (red and blue circles) for MAR dewatering

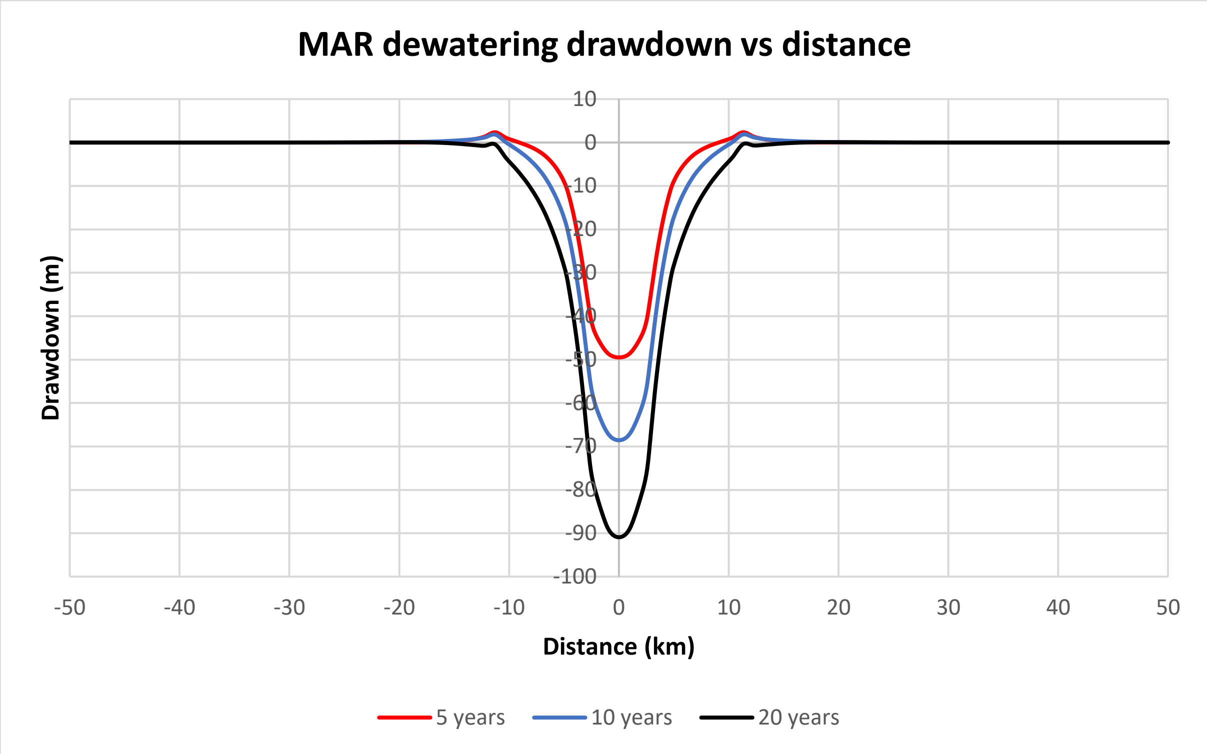

Figure 5-18 Drawdown difference during the MAR dewatering activities for different time periods

5.9. Comparison of Backfilled Pit Scenario (Scenario-1) with/without MAR

By implementing MAR in the backfilled pit scenario, drawdown graphs for 4 different observation wells are compared to drawdown charts generated without applying MAR. The drawdown difference in OBS-2 and OBS-4 under Scenario-1 is approximately 1 m (Figure 5-20, Figure 5-22). However, it is seen that the drawdown in OBS-1 and OBS-3 is more than 1 m (Figure 5-19, Figure 5-21). This is due to the proximity of the injection wells used in the MAR application to these observation points. The Figure 5-23 shows how the distance-based drawdown for Scenario-1 including MAR changes according to different time periods. The Figure 5-23 also reveals that as time passes, the water level becomes flat and groundwater recovery starts to slow.

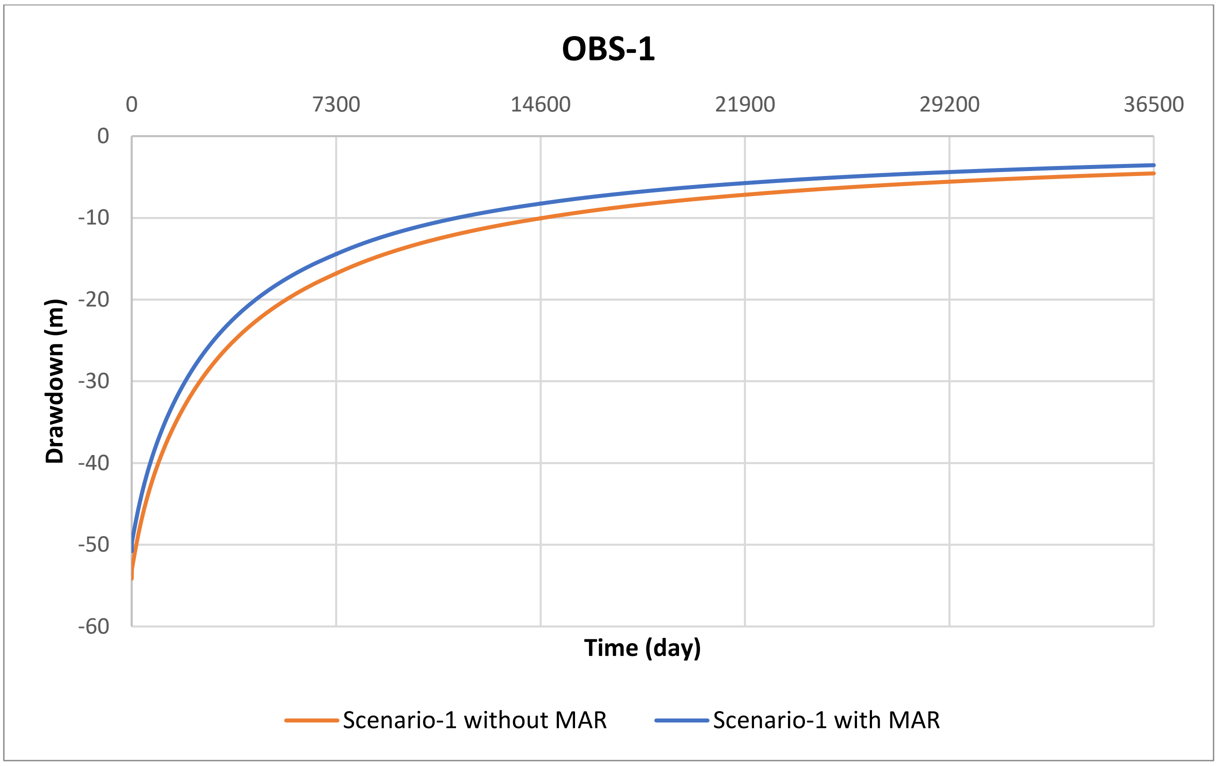

Figure 5-19 Comparison of drawdowns of backfilled pit scenario with/without MAR for OBS-1

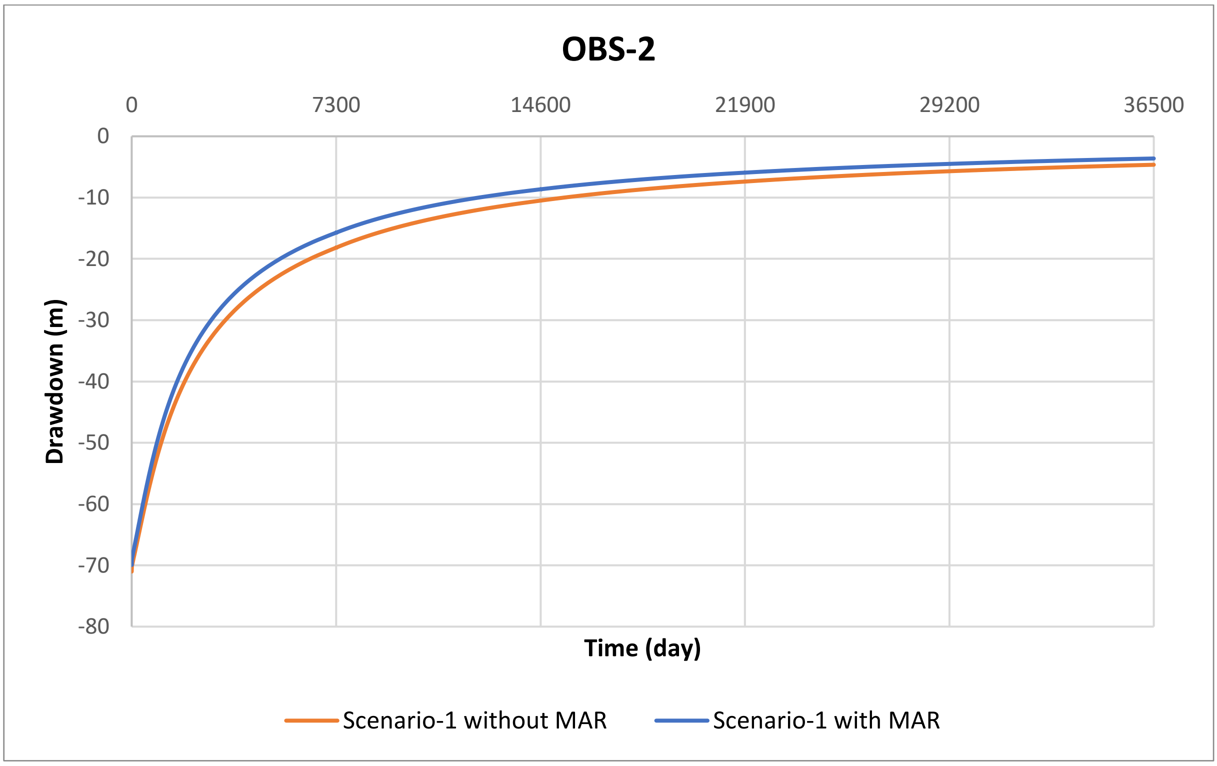

Figure 5-20 Comparison of drawdowns of backfilled pit scenario with/without MAR for OBS-2

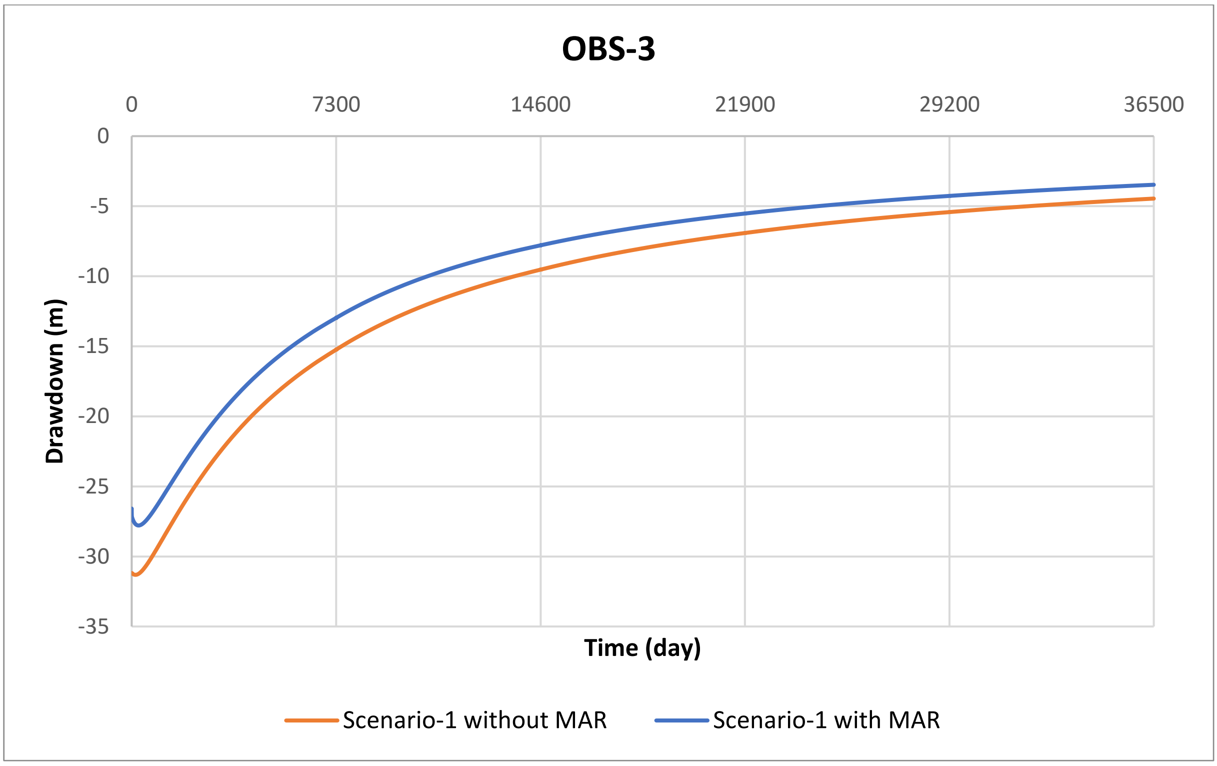

Figure 5-21 Comparison of drawdowns of backfilled pit scenario with/without MAR for OBS-3

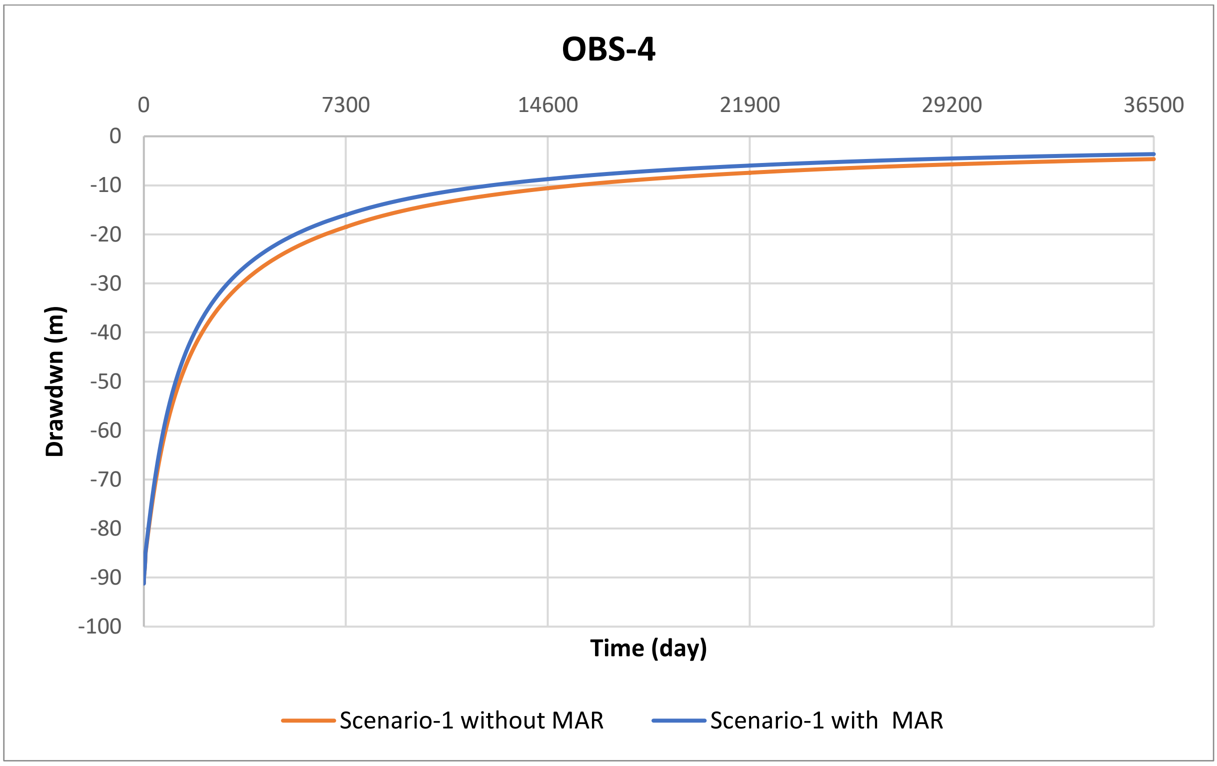

Figure 5-22 Comparison of drawdowns of backfilled pit scenario with/without MAR for OBS-4

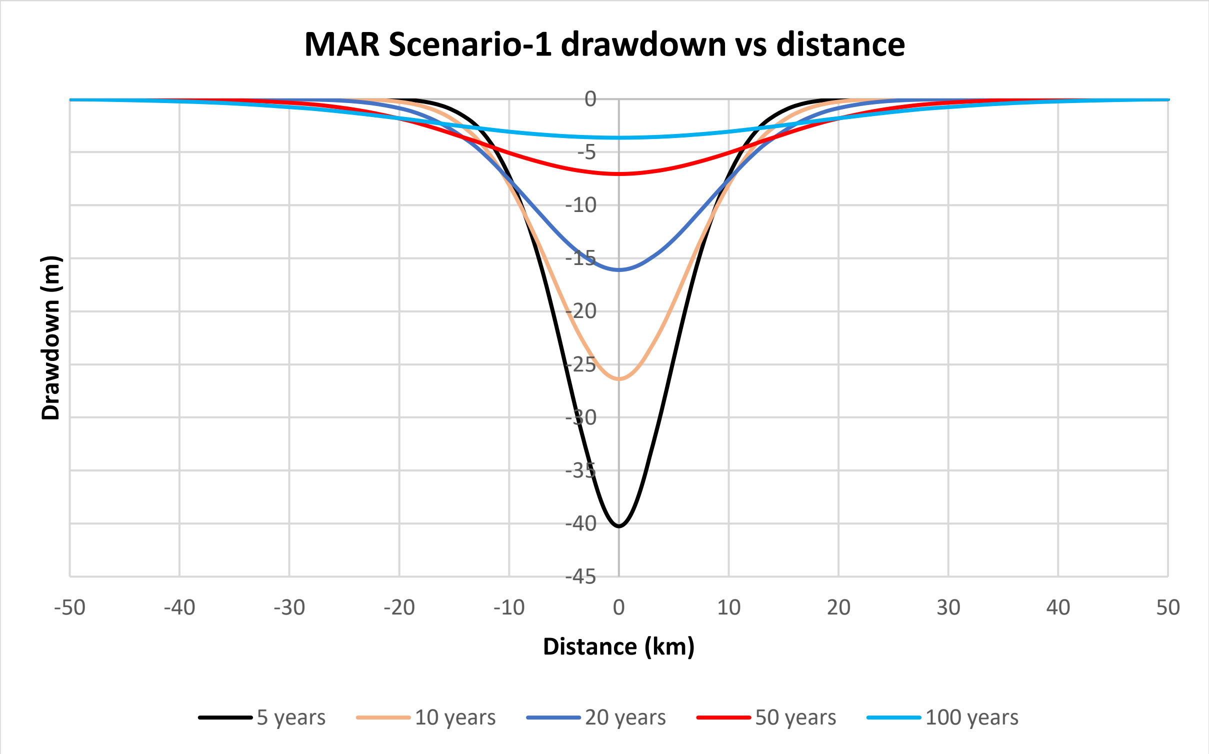

Figure 5-23 Drawdown difference of backfilled pit scenario with MAR for different time periods

5.10. Comparison of Open Pit Scenario (Scenario-2) with/without MAR

The Figure 5-24 compares the 100-year groundwater recovery models of the open pit scenario prepared for OBS-4 with and without MAR. After 100 years, the open pit scenario with MAR demonstrates a recovery increase of approximately 1 m. The Figure 5-25 represents the drawdown of groundwater as a function of time and distance in the open pit scenario with MAR. In addition, comparative graphics prepared for OBS-1-2 and 3 are given in Appendix-7.

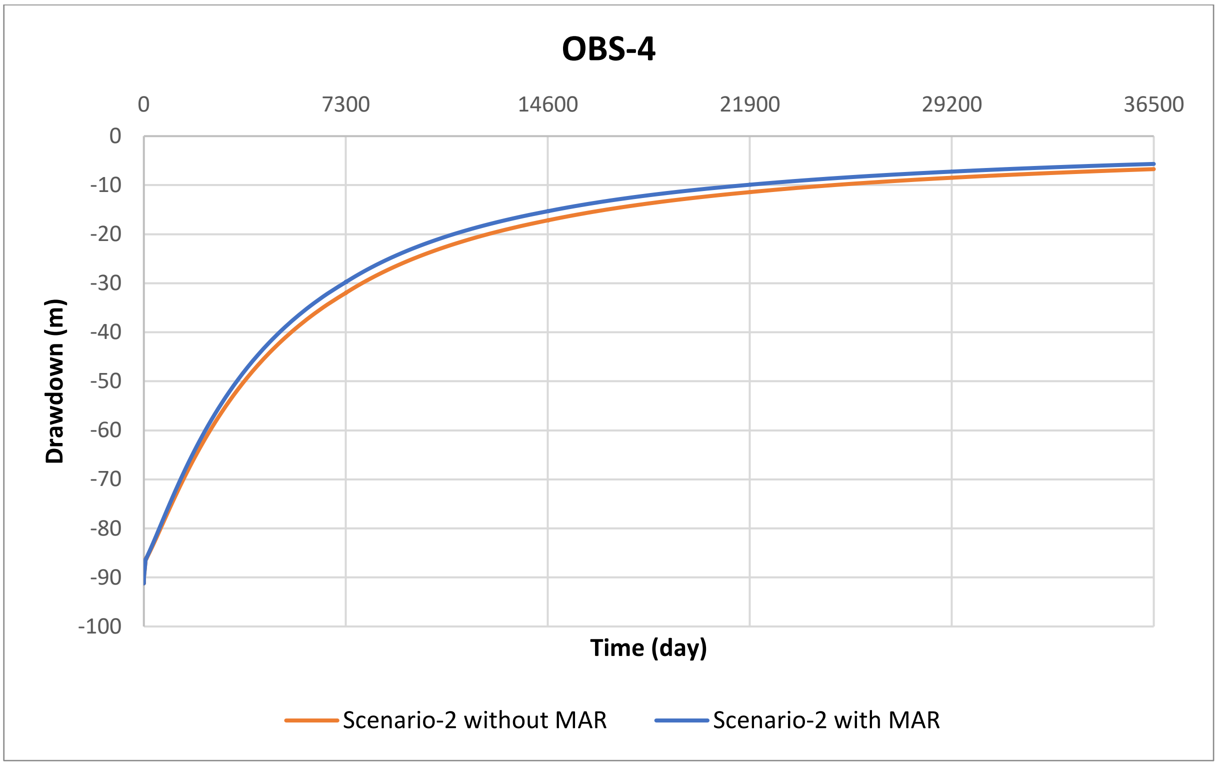

Figure 5-24 Comparison of drawdowns of open pit scenario with/without MAR for OBS-4

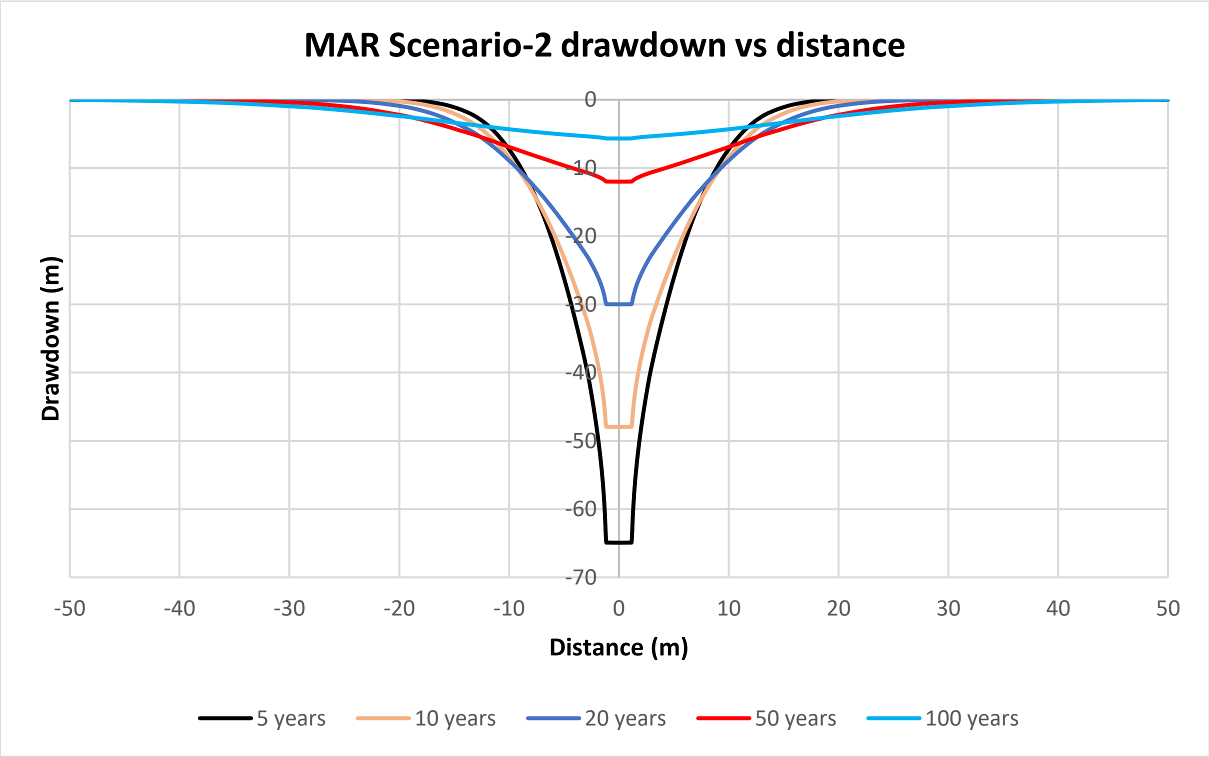

Figure 5-25 Drawdown difference of open pit scenario with MAR for different time periods

5.11. Comparison of ET Scenario (Scenario-3) with/without MAR

The Figure 5-26 compares the 100-year groundwater recovery models of the evapotranspiration scenario prepared for OBS-4 with and without MAR. The evapotranspiration scenario with MAR reveals a 1 m increase at the end of 100 years. The Figure 5-27 shows the drawdown in groundwater as a function of distance and variations over time in the evapotranspiration scenario involving MAR. Thus, it shows that evaporation prevents the acceleration of the groundwater recovery and it will take many years for the water level to reach the desired level. Comparative graphics prepared for OBS-1-2 and 3 are given in Appendix-8.

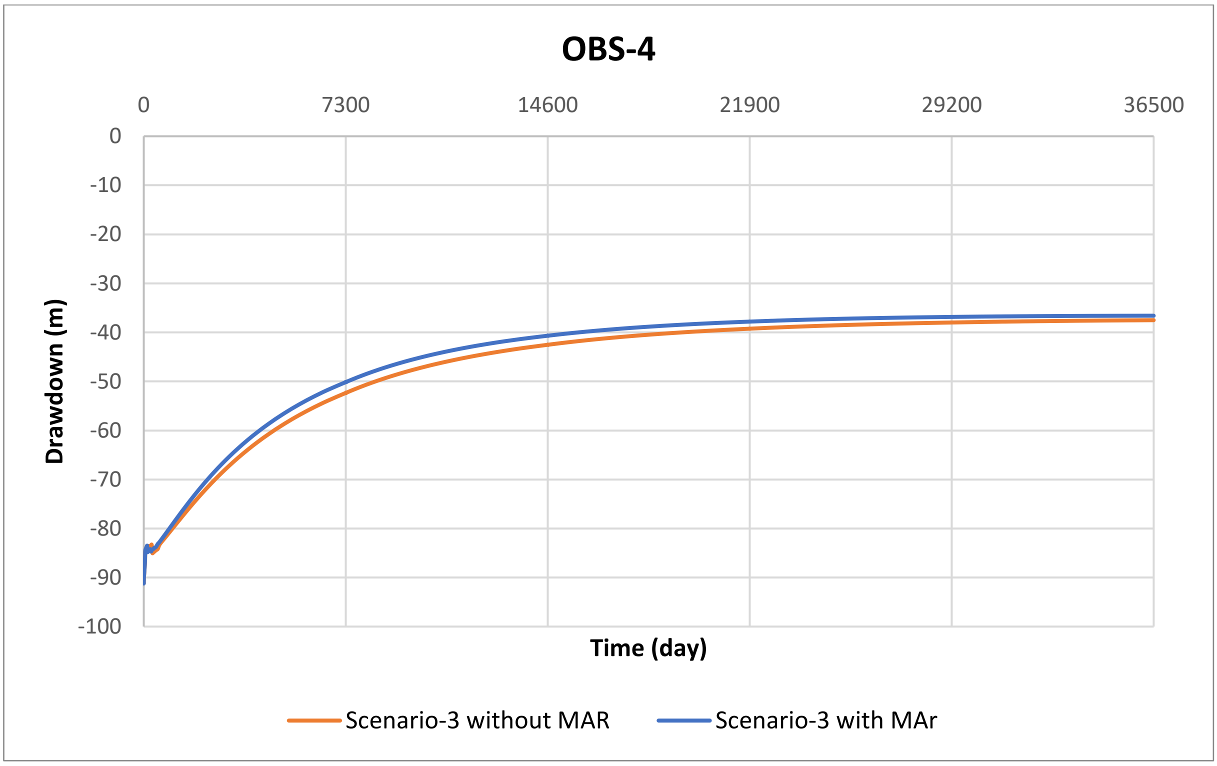

Figure 5-26 Comparison of drawdowns of ET scenario with/without MAR for OBS-4

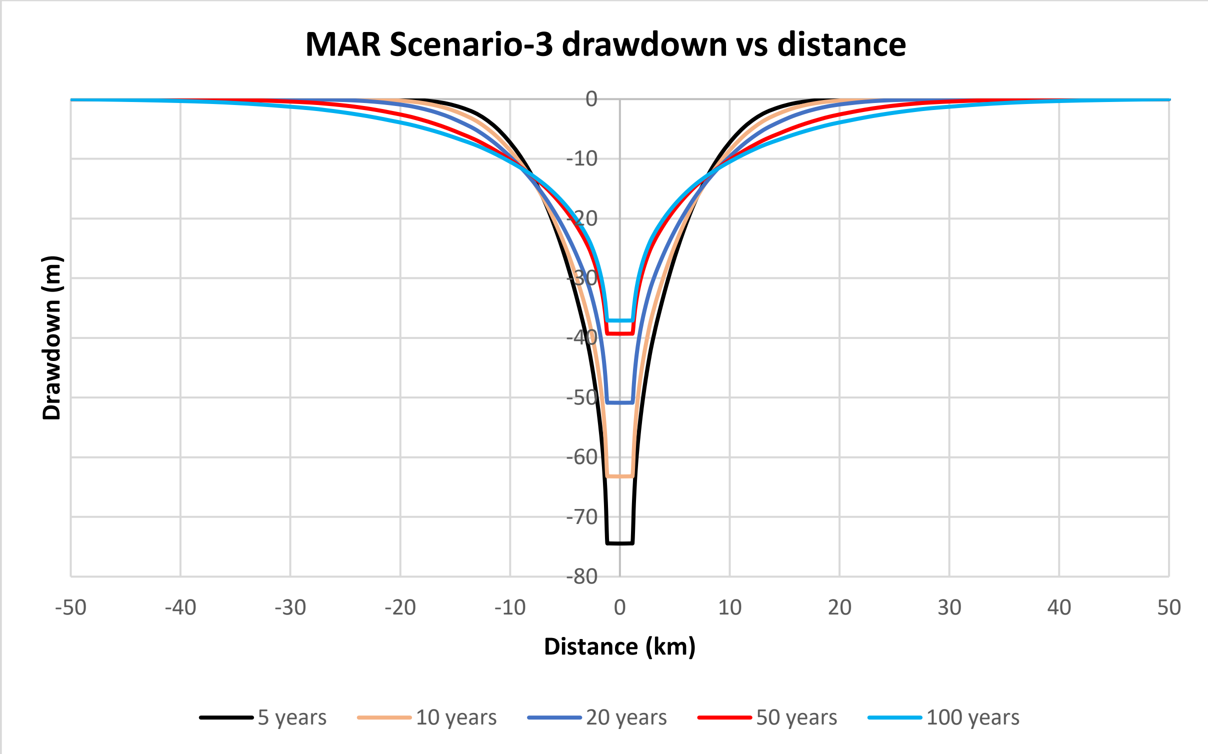

Figure 5-27 Drawdown difference of ET scenario with MAR for different time periods

5.12. Comparison of Direct Rainfall Scenario (Scenario-4) with/without MAR

In the Figure 5-28, 100-year groundwater recovery models for OBS-4 with and without MAR of the direct rainfall scenario are given comparatively. At the end of 100 years, the direct rainfall scenario with MAR shows groundwater recovery level increase approximately 1 meter as in other scenarios. The Figure 5-29 shows the drawdown in groundwater depending on the distance and changes according to the different time periods of the evapotranspiration scenario involving MAR. Comparative graphics prepared for OBS-1-2 and 3 are given in Appendix-9.

Figure 5-28 Comparison of drawdowns of direct rainfall scenario with/without MAR for OBS-4

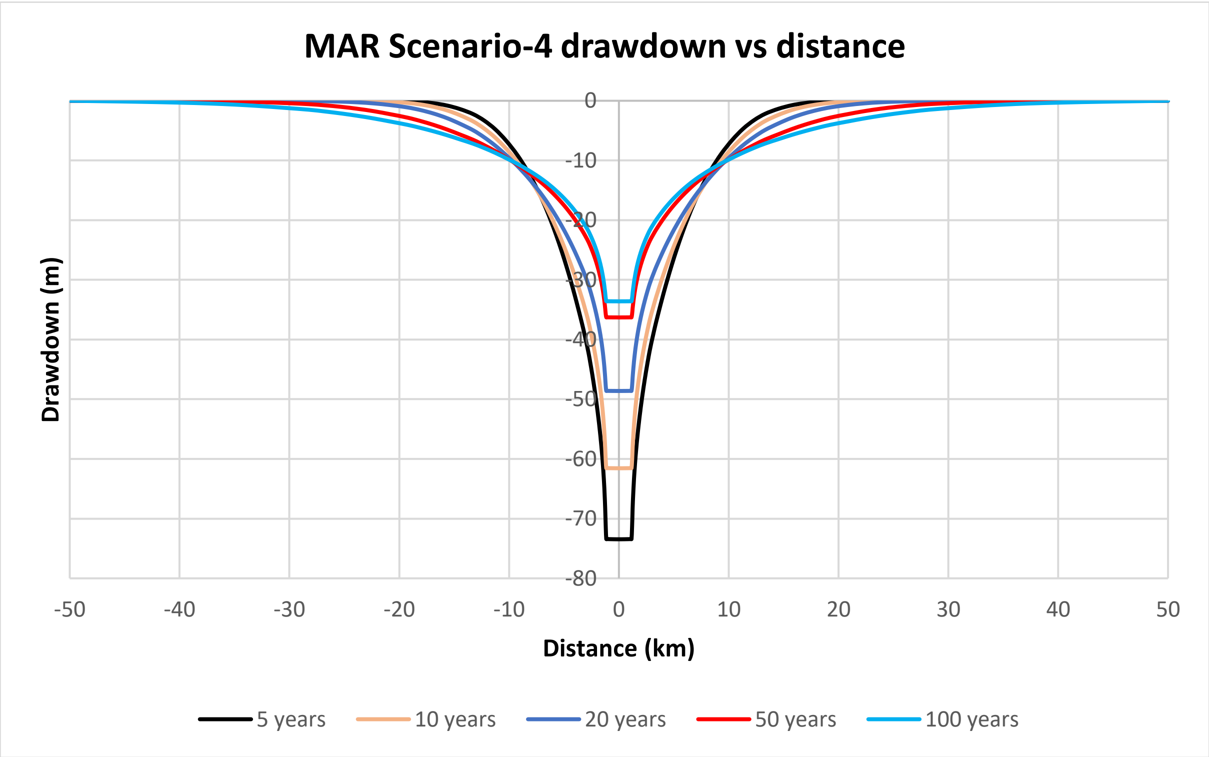

Figure 5-29 Drawdown difference of direct rainfall scenario with MAR for different time periods

5.13. Comparison of Groundwater Recovery Level of Scenarios With/Without MAR

The drawdown figures based on the distance obtained at the end of 100 years of the scenarios with and without MAR are compared (Figure 5-30, Figure 5-31, Figure 5-32, Figure 5-33). Groundwater recovery of approximately 1 m in scenarios including MAR may be critical in terms of water management and groundwater-dependent ecosystem during mine operations and mine closure but it is not enough for the groundwater level to reach pre-mining levels. The distance dependent drawdown graphs prepared for different time periods of the scenarios are given in Appendix-10.

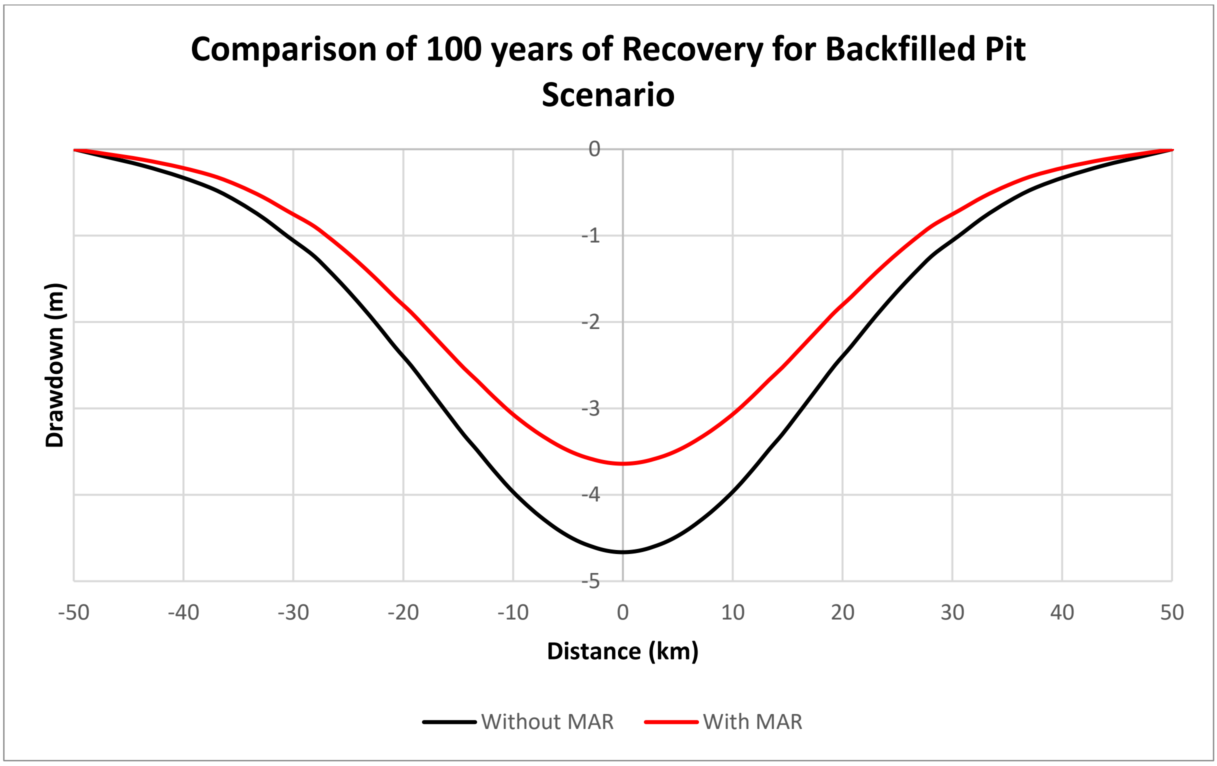

Figure 5-30 Comparison of 100 years of recovery for backfilled pit scenario with/without MAR

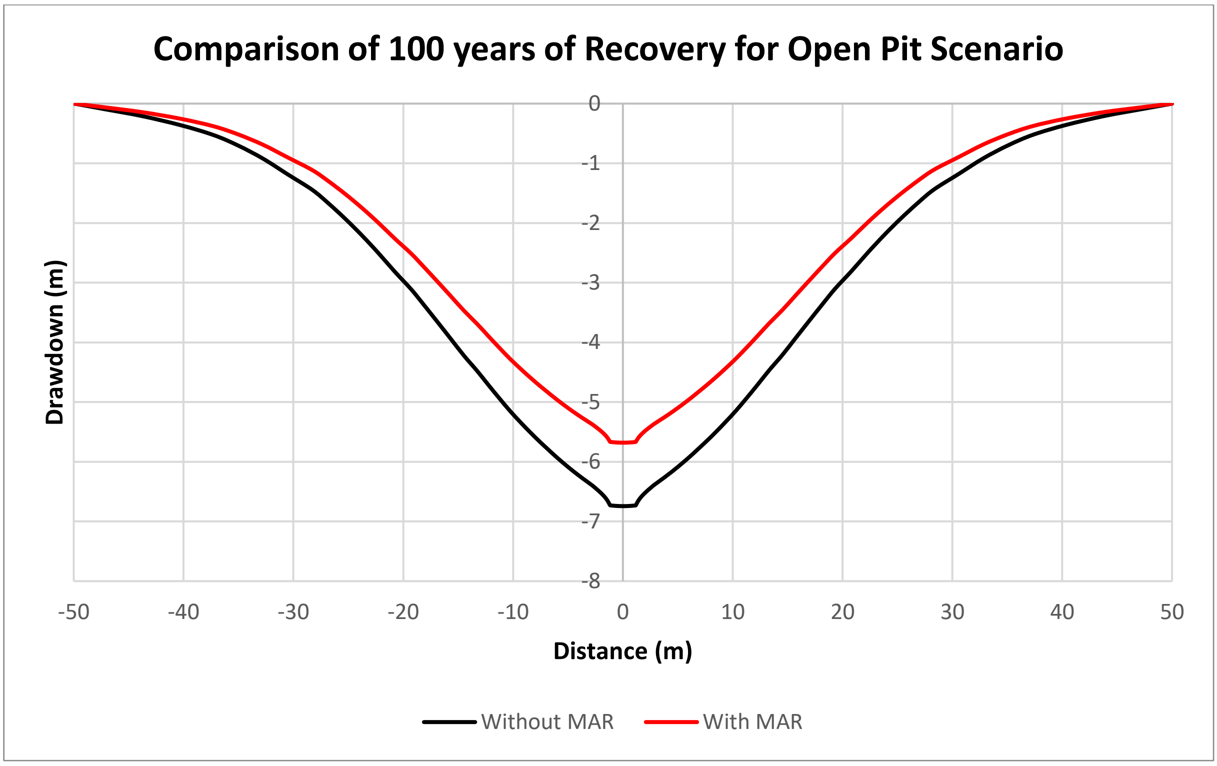

Figure 5-31 Comparison of 100 years of recovery for open pit scenario with/without MAR

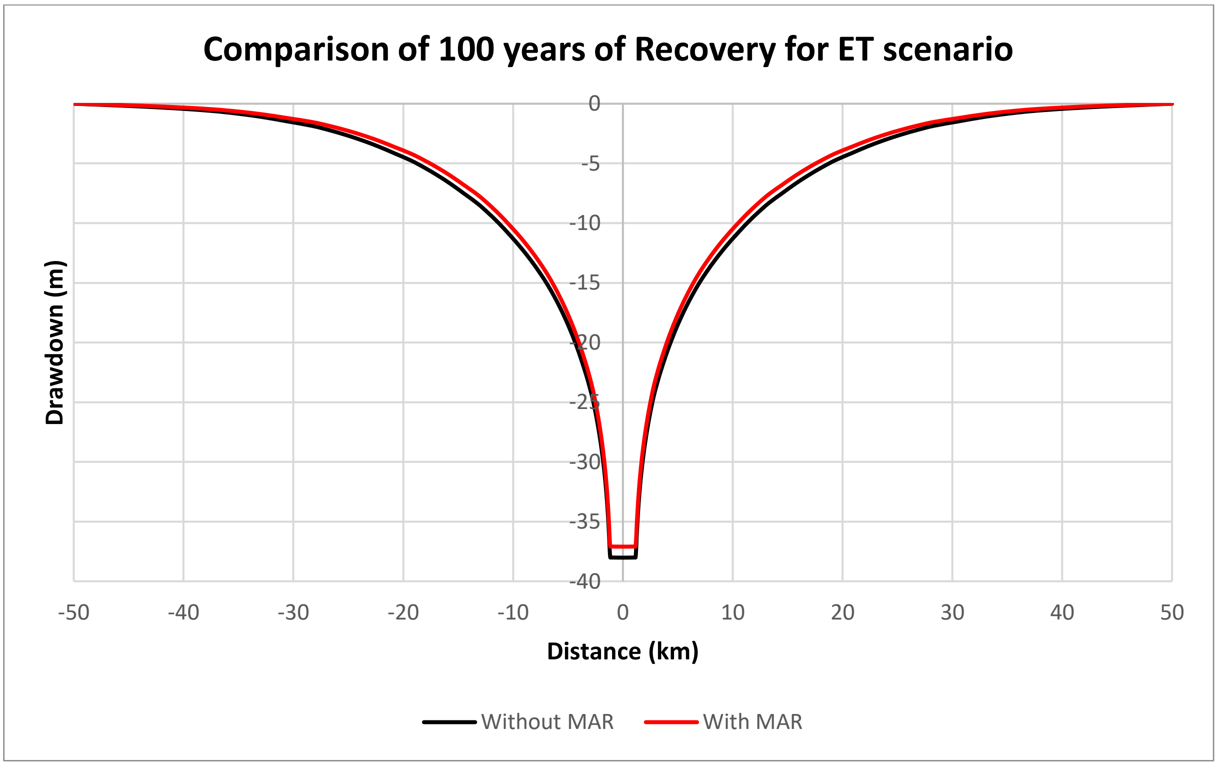

Figure 5-32 Comparison of 100 years of recovery for ET scenario with/without MAR

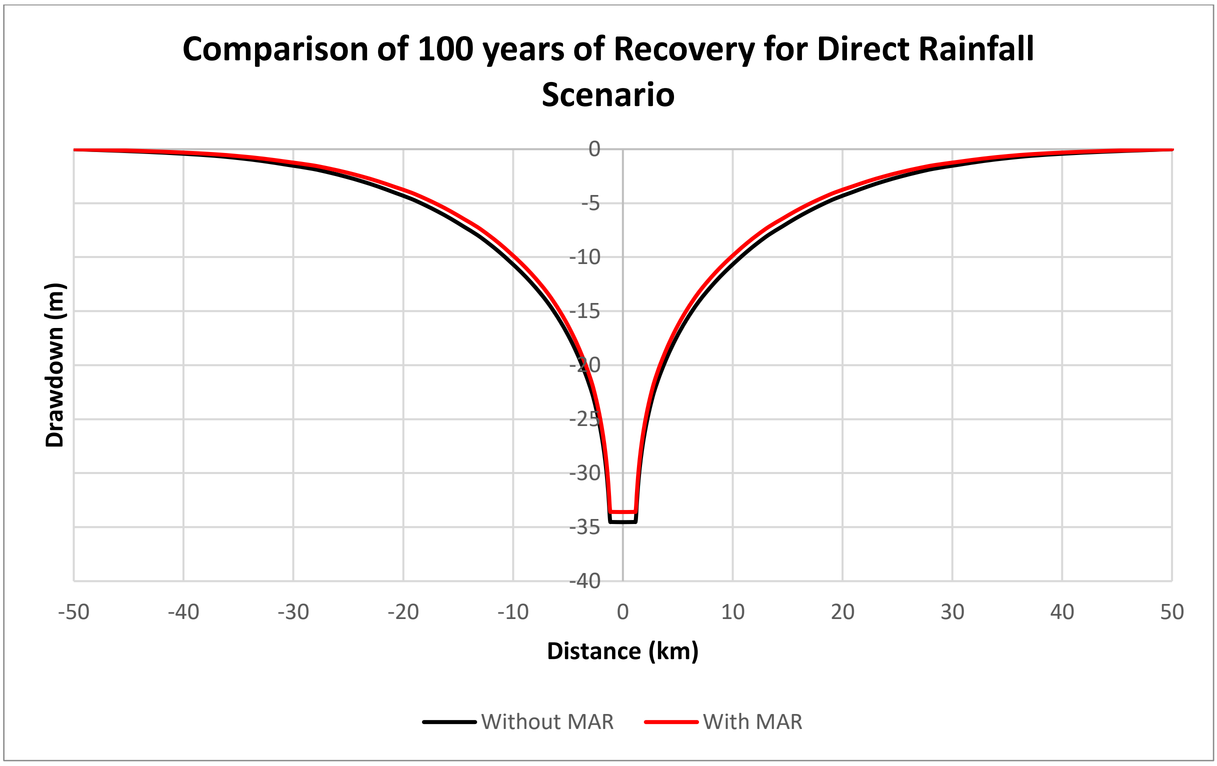

Figure 5-33 Comparison of 100 years of recovery for direct rainfall scenario with/without MAR

6. CONCLUSION & RECOMMENDATION

Mine water management is critical during the whole of mine life. Before mining activities start, significant amounts of water are extracted during dewatering. This decrease in the water level seen regionally may affect the natural environment, groundwater dependent ecosystem and communities in the long term. Many mining sites in Australia, as in the rest of the world, are reaching their end of life soon. Post-mining, the water level in the mine pits, which are the biggest heritage left in the region, recovers and forms pit lakes. However, in arid-dry climates such as Australia, the water level in the mine pit cannot reach the pre-mine level because evaporation exceeds rainfall. In this study, the Hope Downs 1 North mine site is used as a base site to explore factors affecting groundwater level recovery flowing mine closure using numerical modelling. Scenarios with 100-year observations generally show that while the water level rises rapidly in the first 5-10 years, it slows down towards the end of the simulated 100-year recovery period.

In the backfilled pit scenario, although the mine void is filled with material that is the same as the parameters used for the model domain, the 100-year groundwater recovery level is approximately 5 m lower than the pre-mining level. If a mine void remains, more water is required for recovery, and water levels recover slower than in the backfilled pit scenario.

In order to assess the impact of the large evaporation rates typical in the Pilbara region, model scenarios were run, which included open-pan evaporation within the area of the pit. This resulted in a decrease in groundwater recovery levels of approximately 33 m compare to the backfilled pit scenario. Water level recovery could be shown to accelerate as ET rates were decreased. If rainfall was added to the pit area, in addition to ET, groundwater recovery was faster, but water levels remained considerably below pre-mining levels.

Applying MAR through the simulation of 16 injection wells resulting in a return of approximately 29.5% of the water taken by dewatering resulted only in minor improvements to the post-mining groundwater recovery levels.

The following recommendations are made from this research;

- Instead of the generic model, a real site model can be developed using data collected from field studies, and more precise results representing the mine site can be obtained.
- The effect of the hydraulic conductivity of the faults on the dewatering and recovery scenarios in the flow model should be investigated.
- Recovery scenarios can be diversified by using different backfilling parameters.
- Australia is known to experience extreme dry periods at times. Thus, worst case scenarios should be created by using higher ET rates in the groundwater flow model.

- To speed up groundwater recovery even further, the number of injection wells used in the MAR application should be increased, and the wells should be placed closer to the mine pit.
- The effect of additional recharge on recovery from different water sources such as surface waters, dams and lakes close to the mine site should be evaluated.

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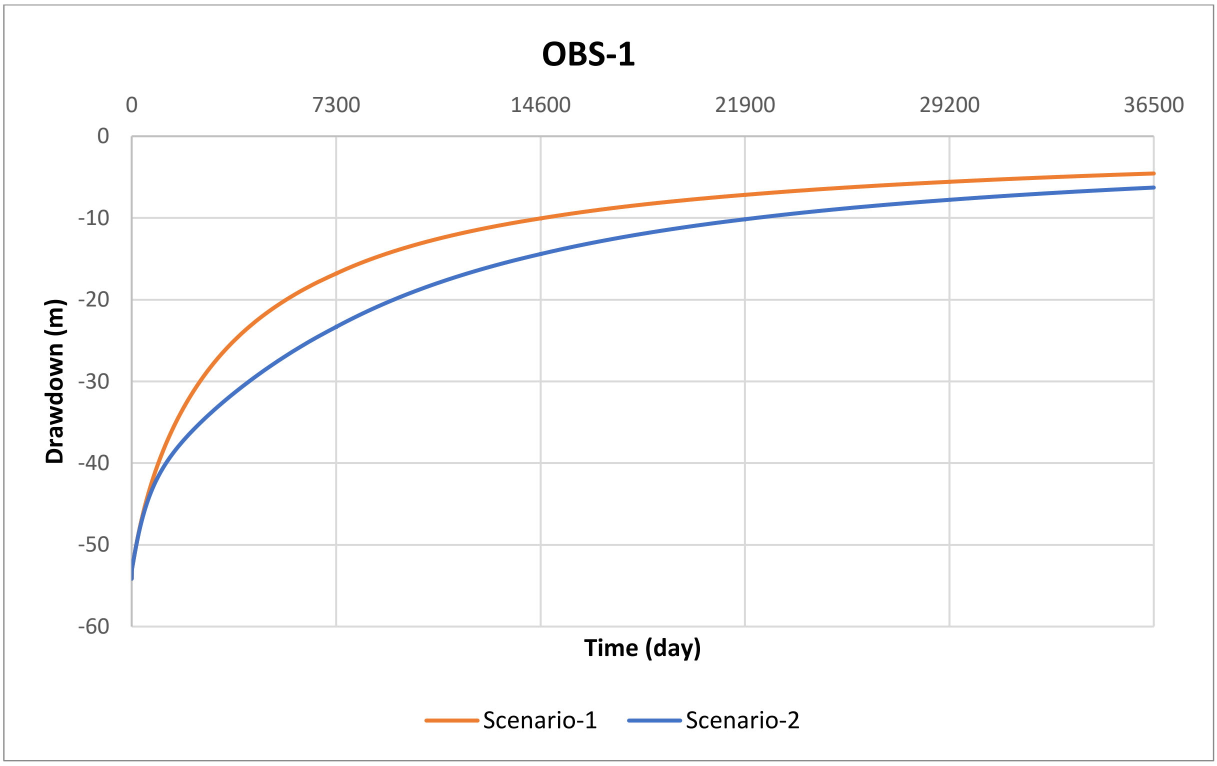
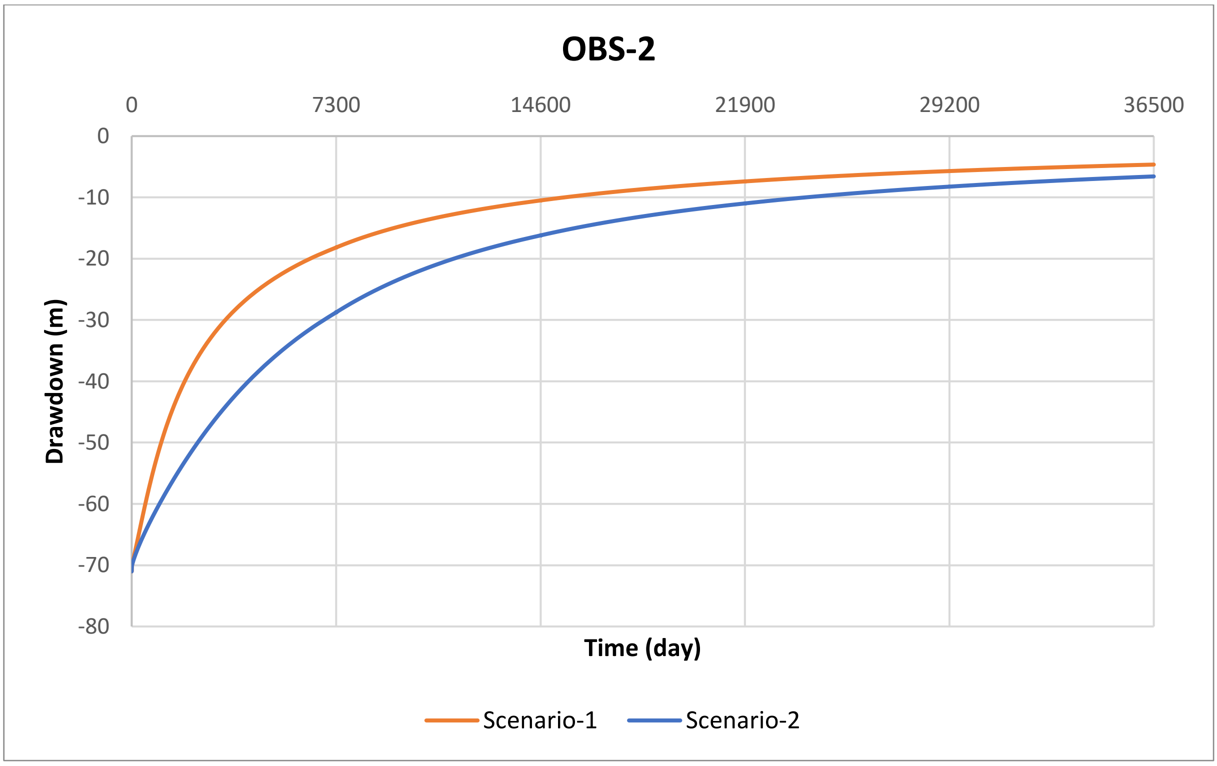
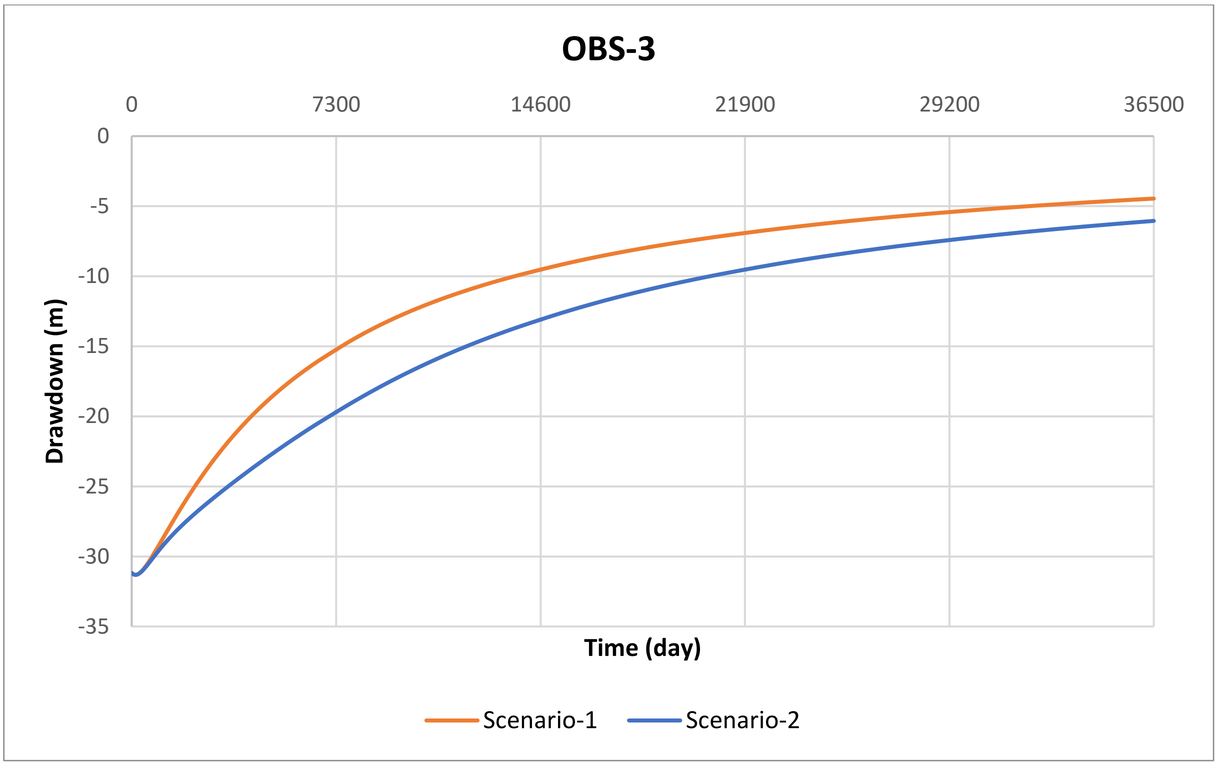
APPENDICES

Appendix-1



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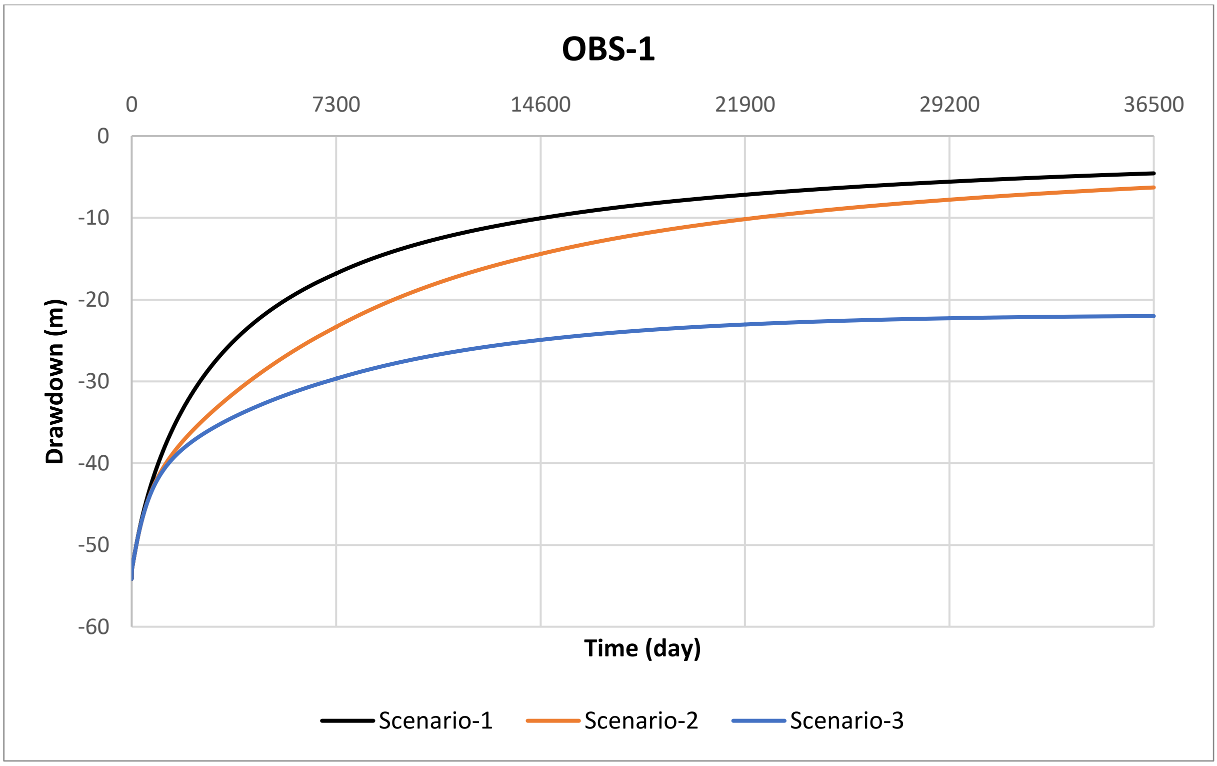
0
7300
14600
21900
29200
36500
0
-5
-10
-15
-20
-25
-30
-35
Drawdown (m)
Time (day)
Scenario-1
Scenario-2

Appendix-2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7300
14600
21900
29200
36500
0
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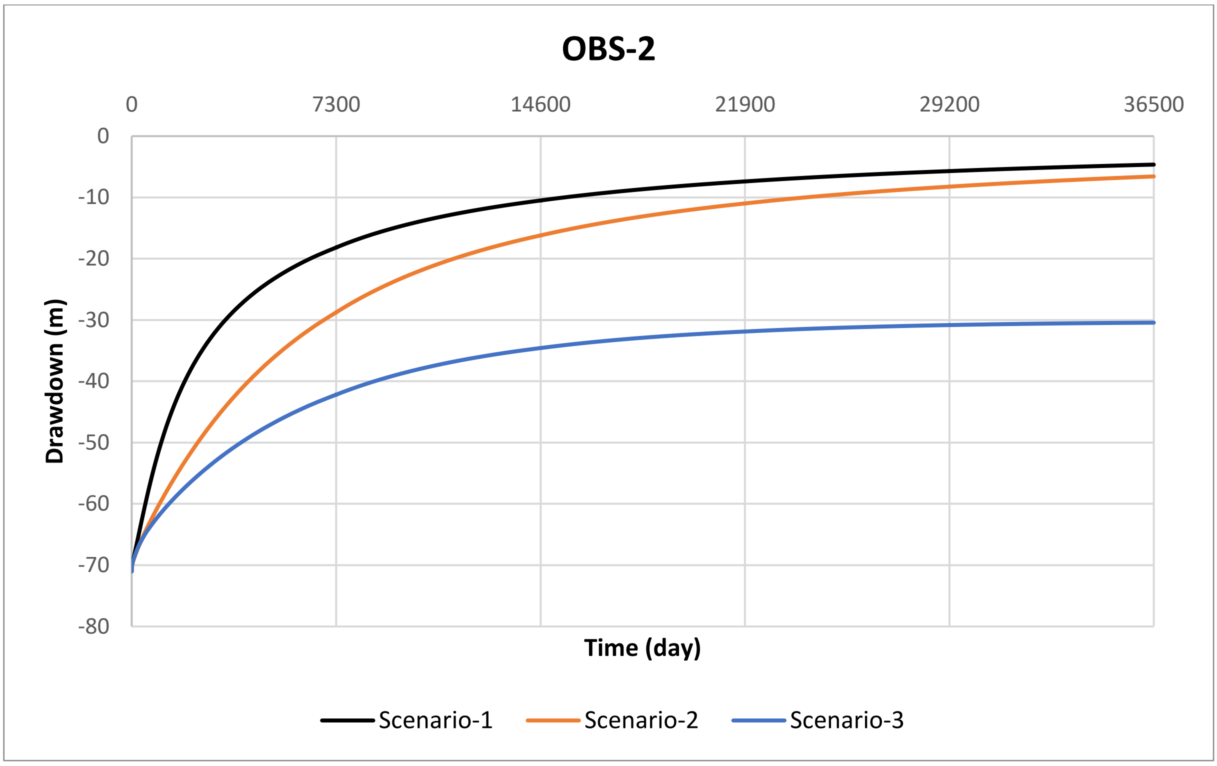
-30
-40
-50
-60
Drawdown (m)
Time (day)
Scenario-1
Scenario-2
Scenario-3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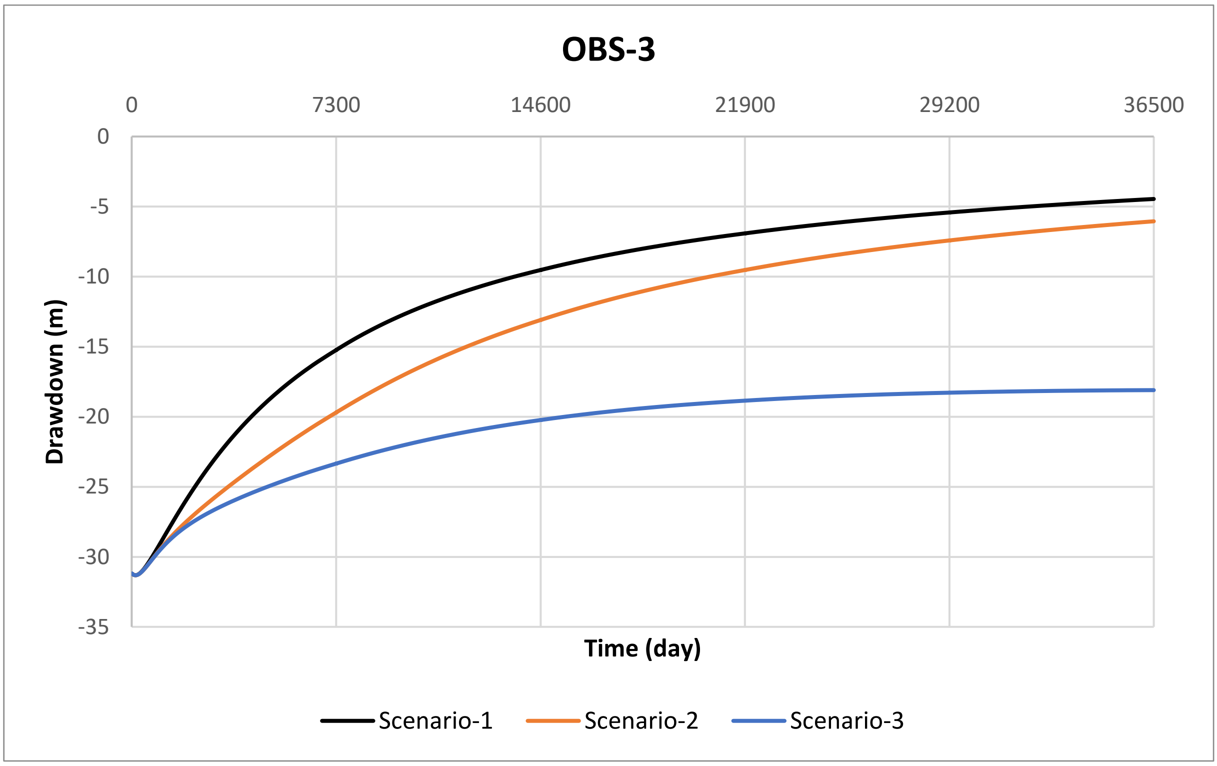
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
-70
-80
Drawdown (m)
Time (day)
Scenario-1
Scenario-2
Scenario-3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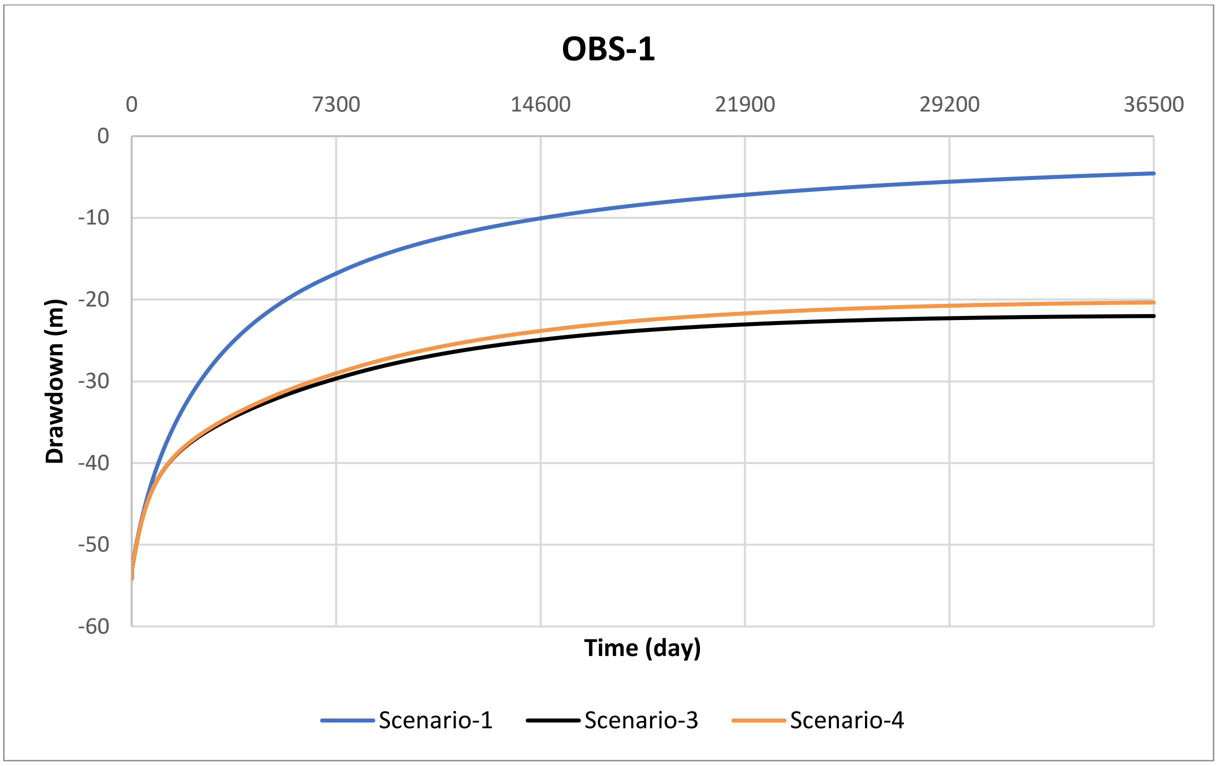
14600
21900
29200
36500
0
-5
-10
-15
-20
-25
-30
-35
Drawdown (m)
Time (day)
Scenario-1
Scenario-2
Scenario-3

Appendix-3


OBS-1
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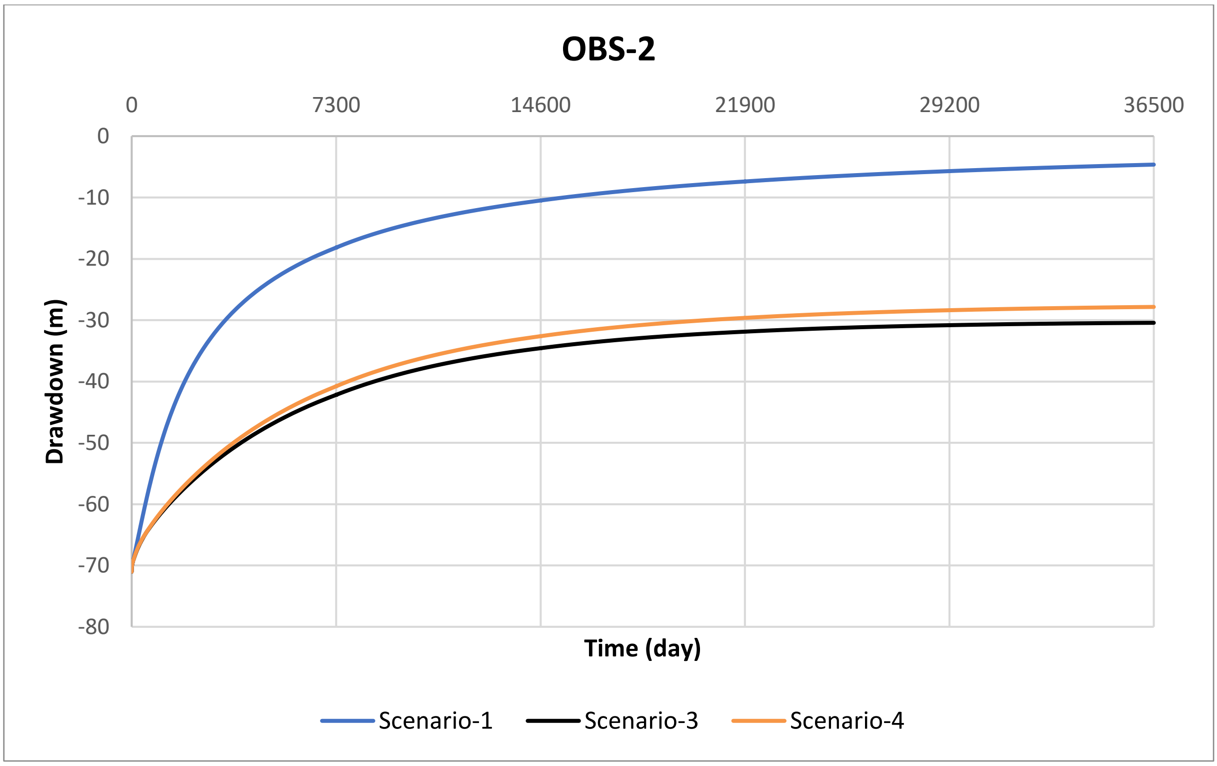
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
Drawdown (m)
Time (day)
Scenario-1
Scenario-3
Scenario-4


OBS-2
0
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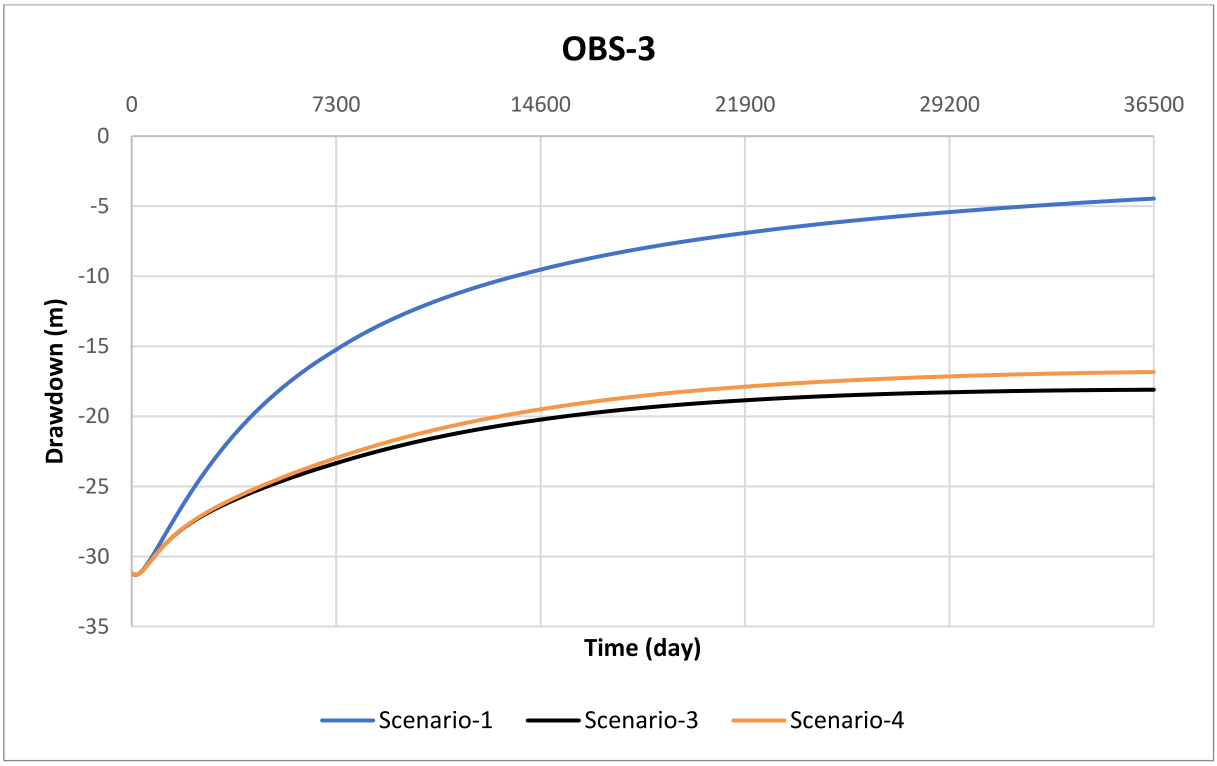
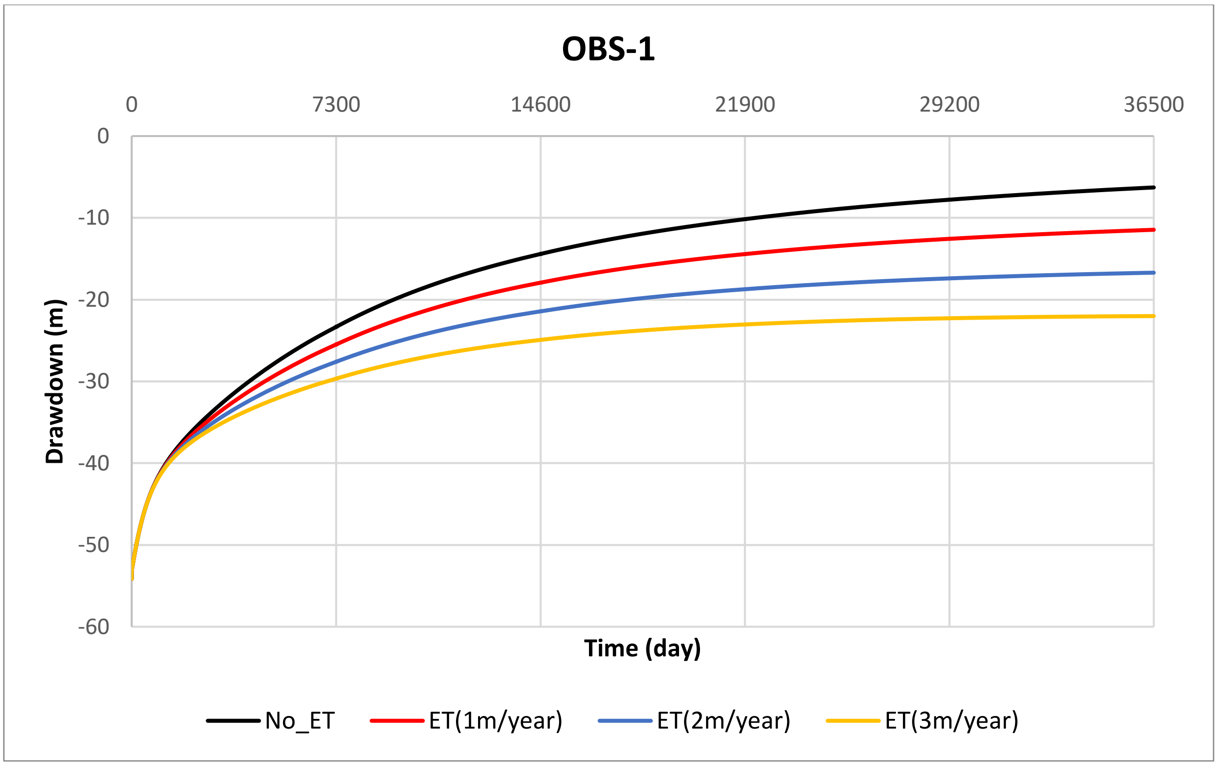
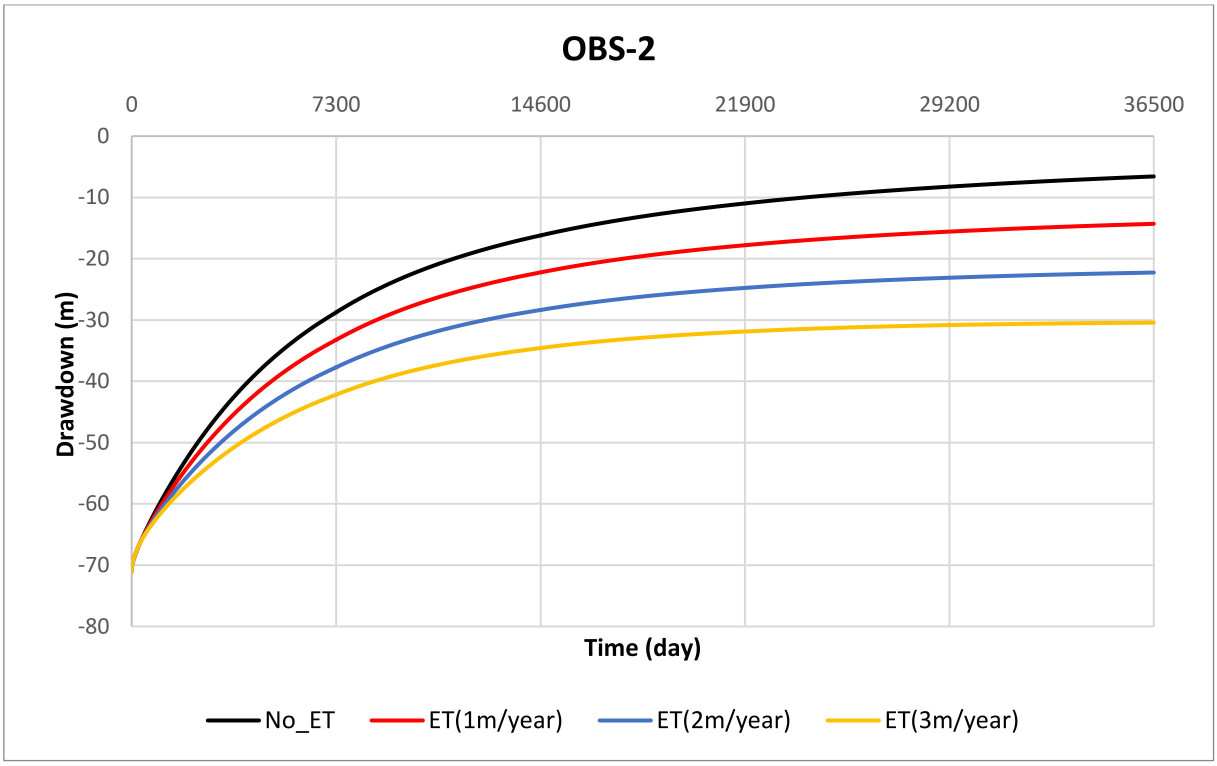
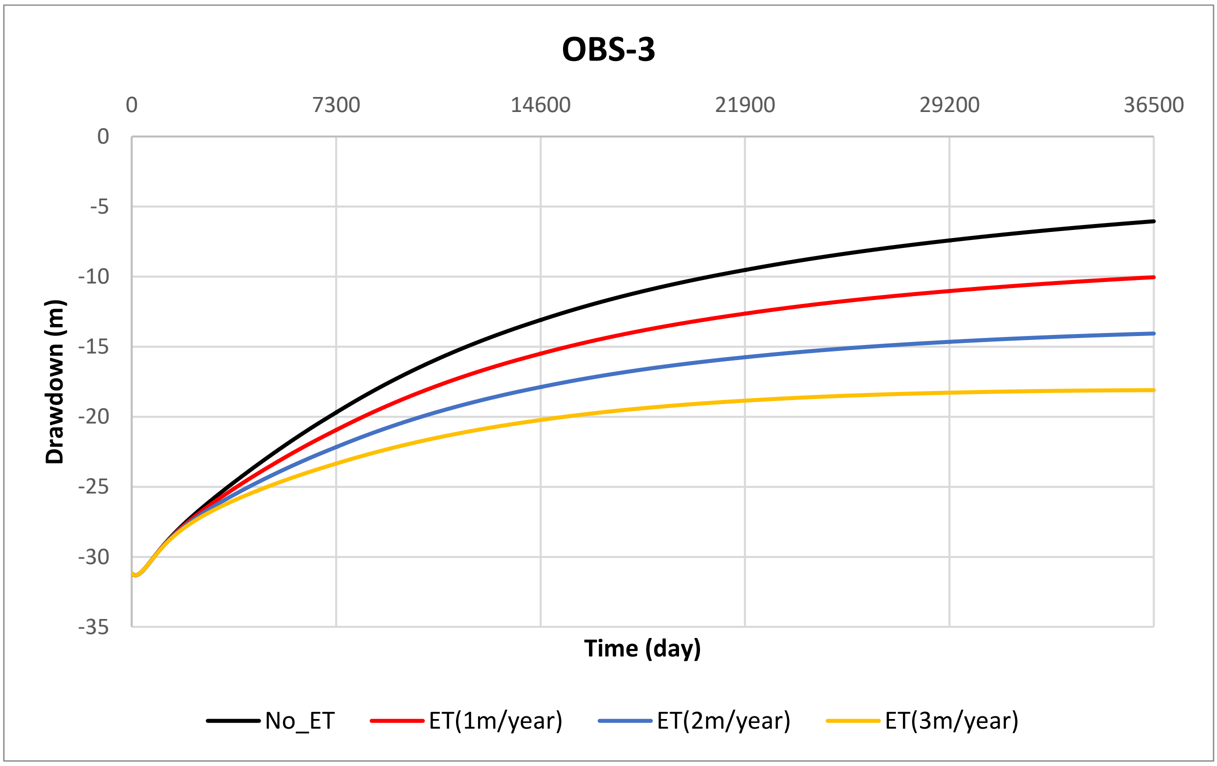
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
-70
-80
Drawdown (m)
Time (day)
Scenario-1
Scenario-3
Scenario-4


OBS-3
0
7300
14600
21900
29200
36500
0
-5
-10
-15
-20
-25
-30
-35
Drawdown (m)
Time (day)
Scenario-1
Scenario-3
Scenario-4

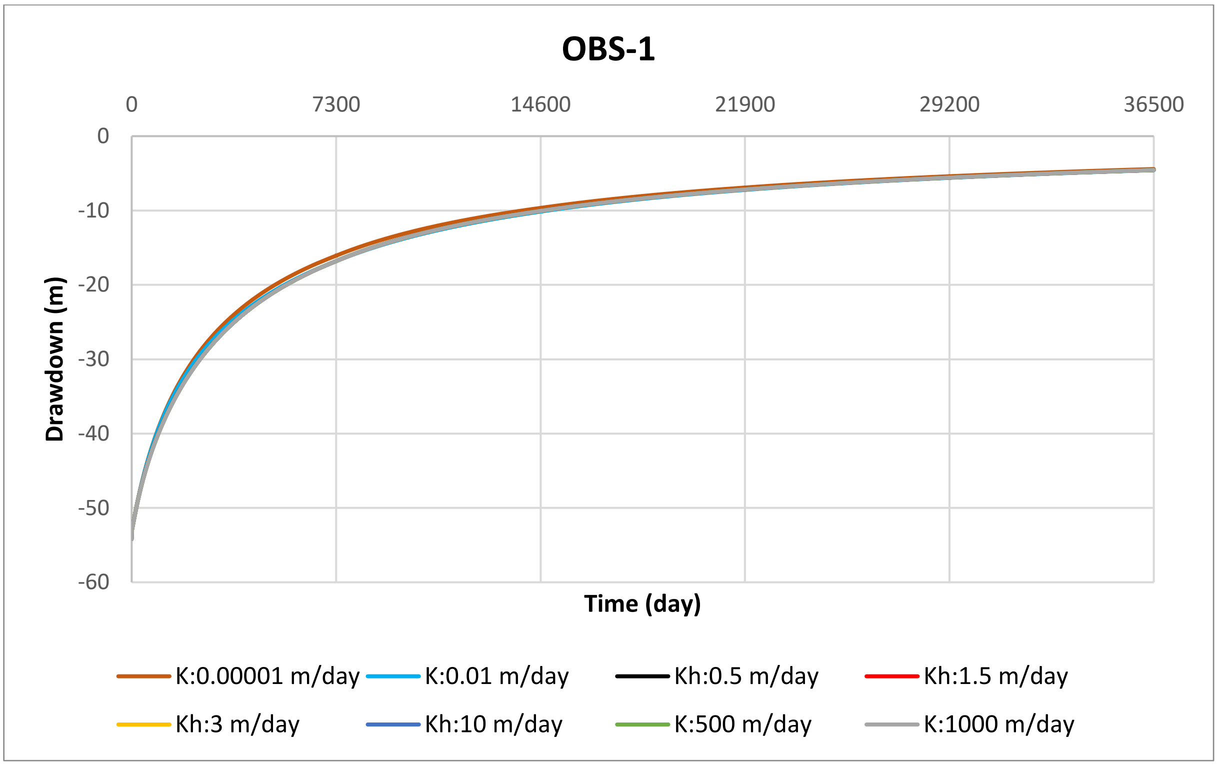
Appendix-4


OBS-1
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
Drawdown (m)
Time (day)
No_ET
ET(1m/year)
ET(2m/year)
ET(3m/year)

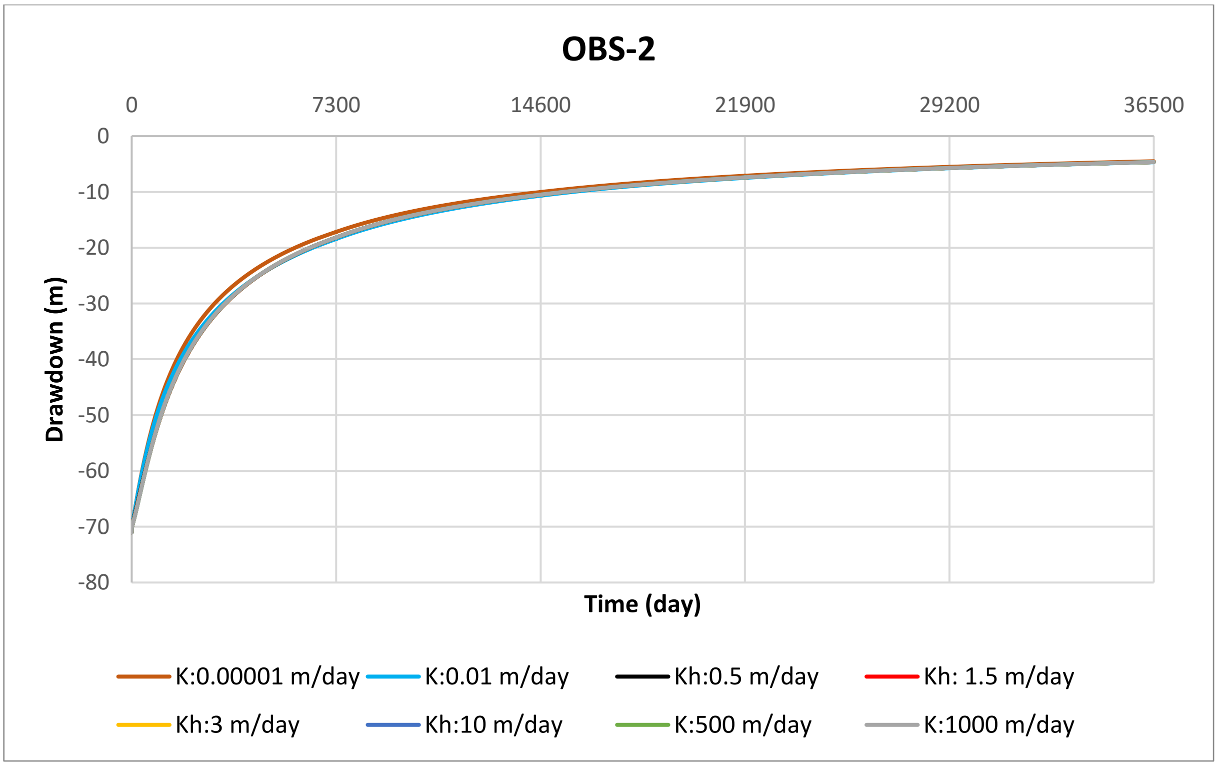

OBS-2
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
-70
-80
Drawdown (m)
Time (day)
No_ET
ET(1m/year)
ET(2m/year)
ET(3m/year)


OBS-3
0
7300
14600
21900
29200
36500
0
-5
-10
-15
-20
-25
-30
-35
Drawdown (m)
Time (day)
No_ET
ET(1m/year)
ET(2m/year)
ET(3m/year)

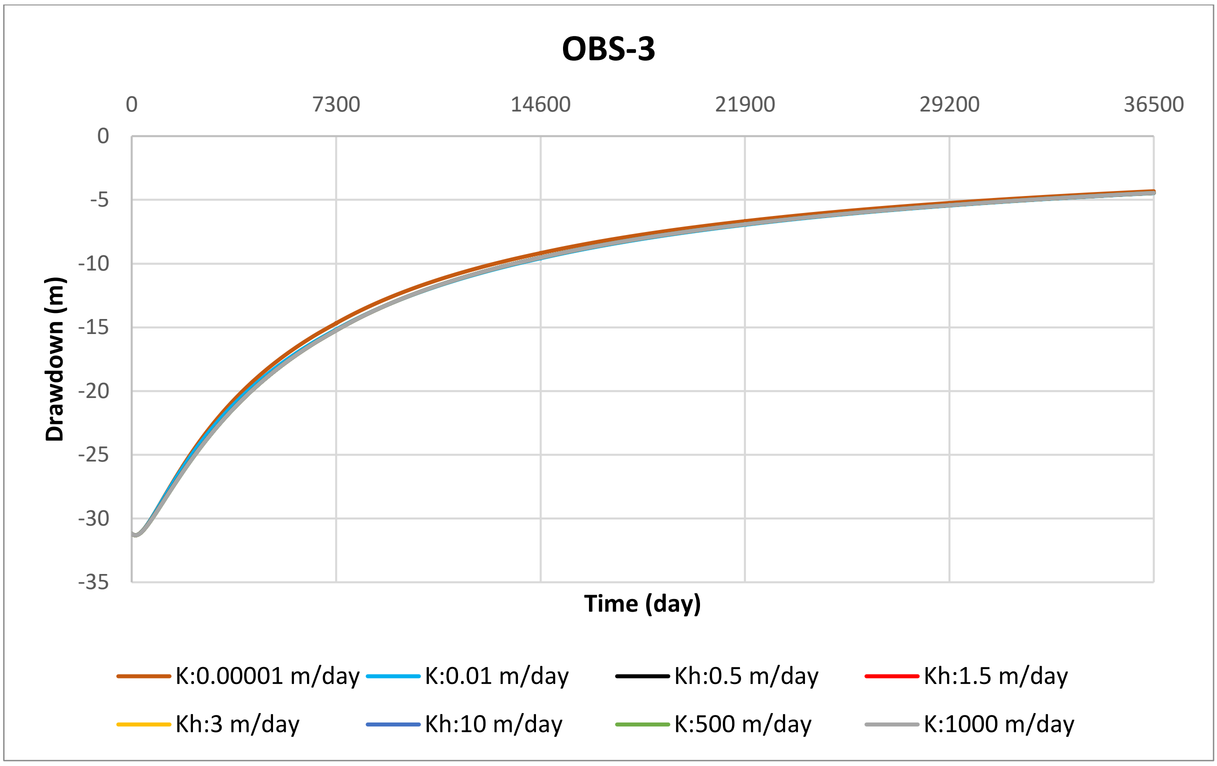
Appendix-5



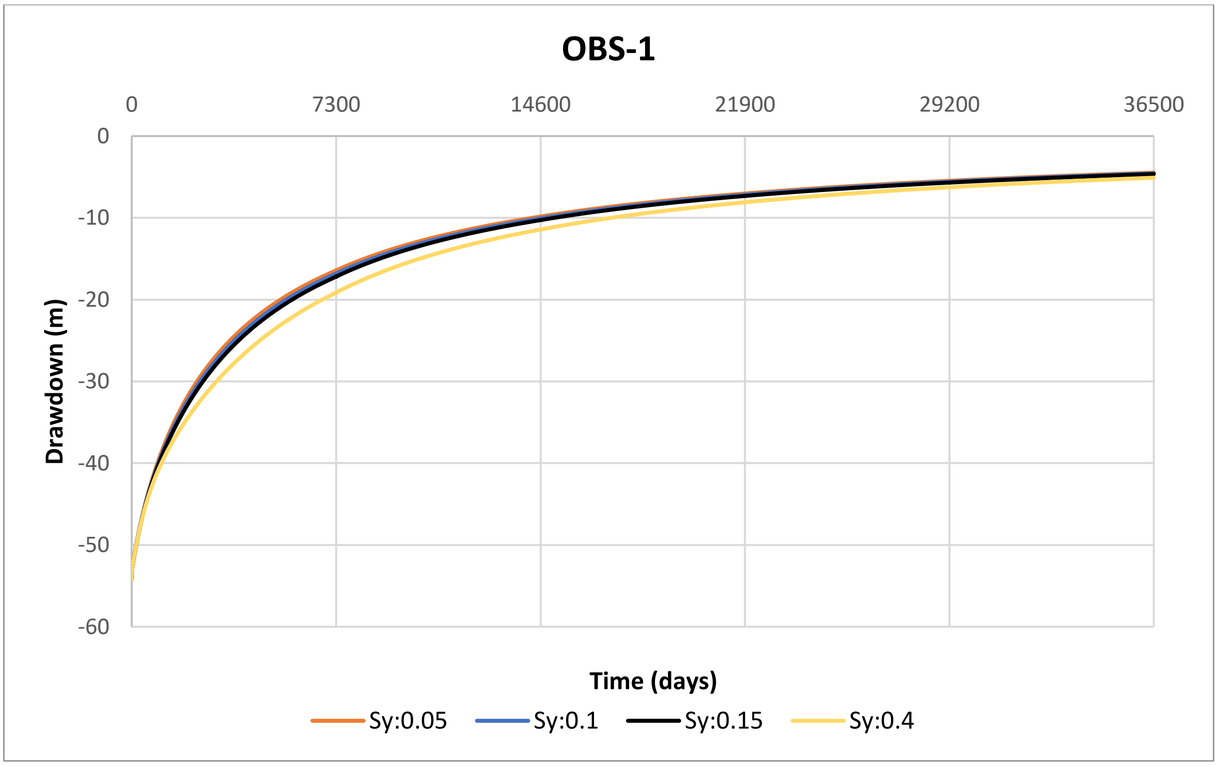
OBS-1
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
Drawdown (m)
Time (day)
K:0.00001 m/day
K:0.01 m/day
Kh:0.5 m/day
Kh:1.5 m/day
Kh:3 m/day
Kh:10 m/day
K:500 m/day
K:1000 m/day

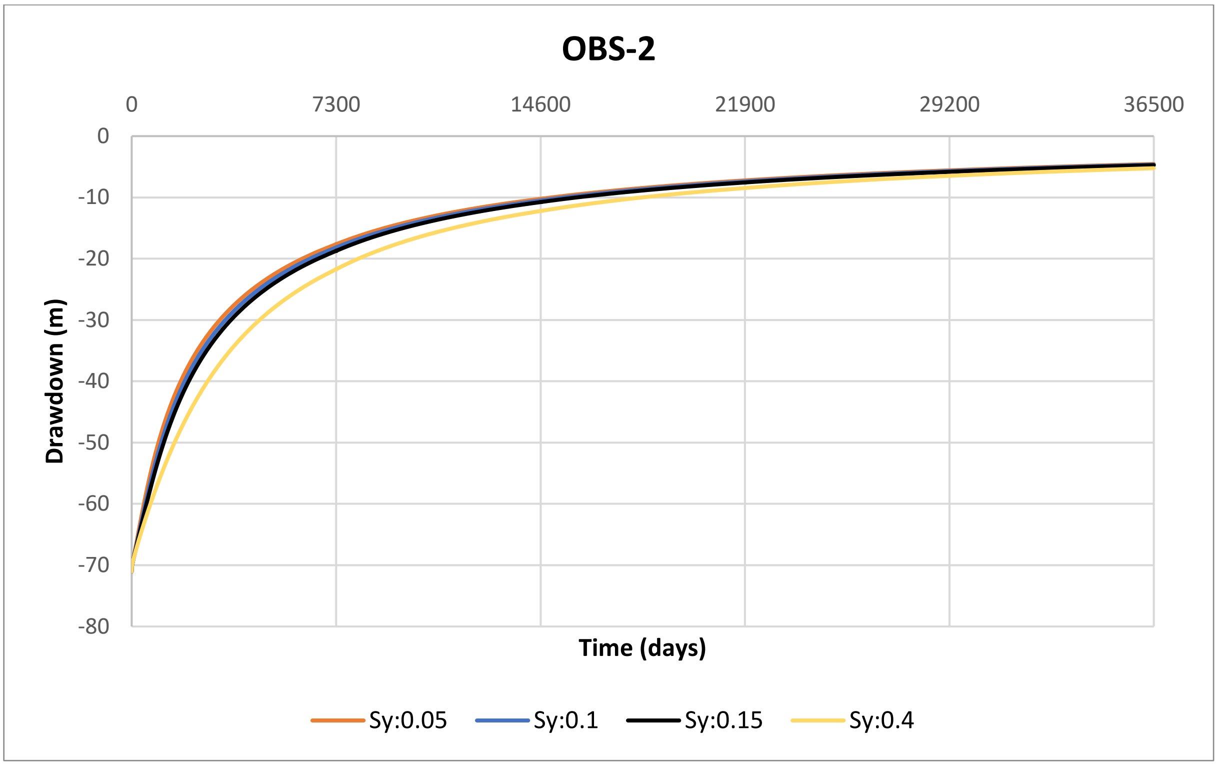


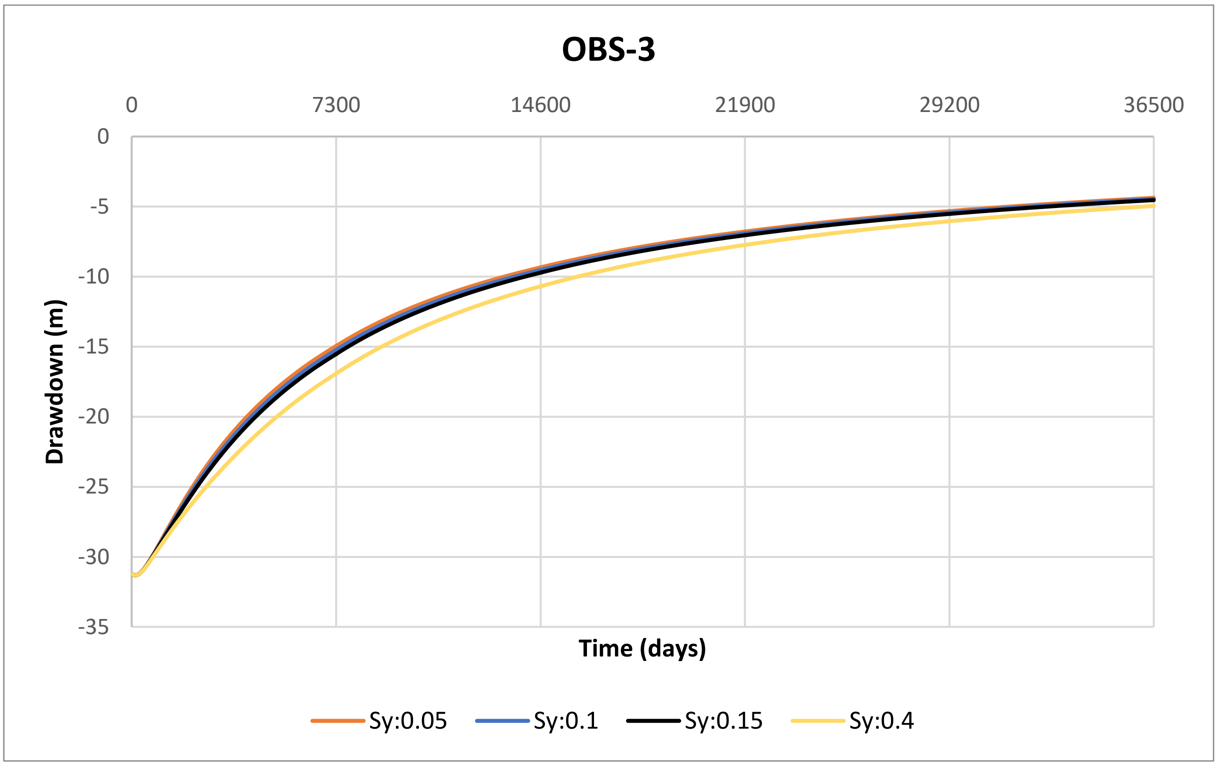
OBS-2
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
-70
-80
Drawdown (m)
Time (day)
K:0.00001 m/day
K:0.01 m/day
Kh:0.5 m/day
Kh: 1.5 m/day
Kh:3 m/day
Kh:10 m/day
K:500 m/day
K:1000 m/day


OBS-3
0
7300
14600
21900
29200
36500
0
-5
-10
-15
-20
-25
-30
-35
Drawdown (m)
Time (day)
K:0.00001 m/day
K:0.01 m/day
Kh:0.5 m/day
Kh:1.5 m/day
Kh:3 m/day
Kh:10 m/day
K:500 m/day
K:1000 m/day

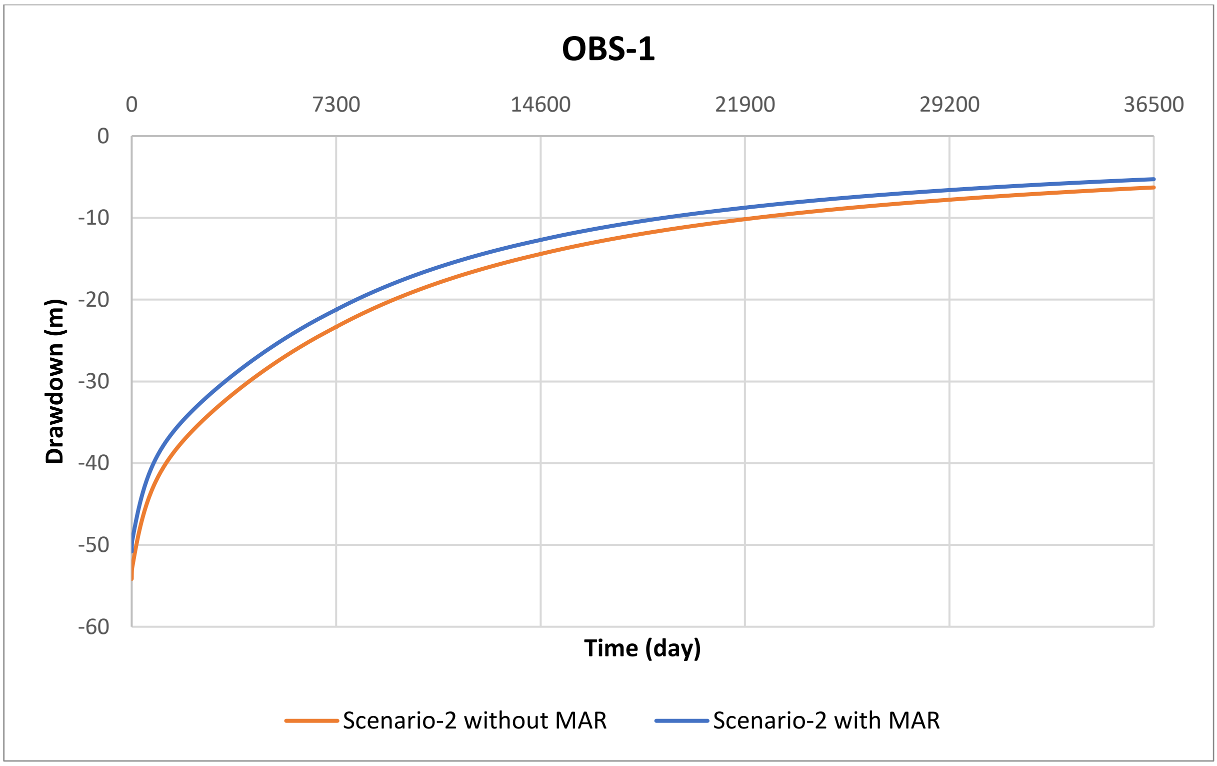
Appendix-6


OBS-1
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
Drawdown (m)
Time (days)
Sy:0.05
Sy:0.1
Sy:0.15
Sy:0.4

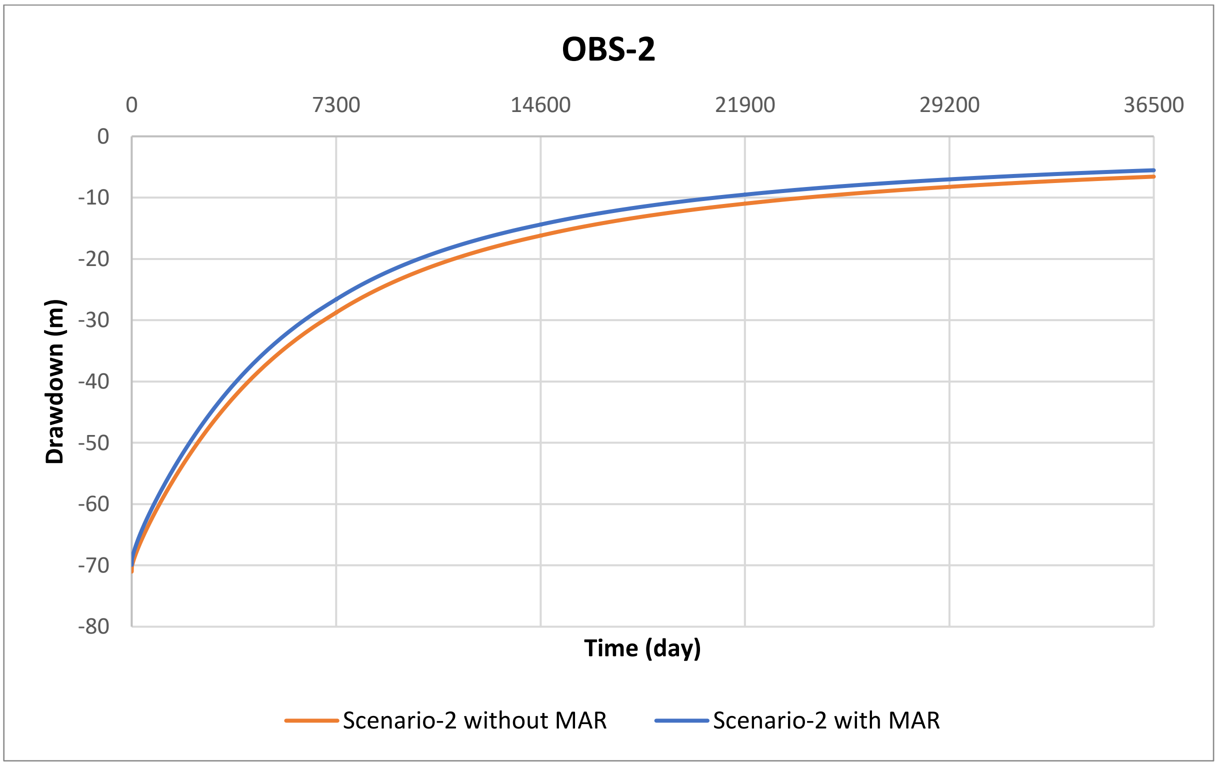

OBS-2
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
-70
-80
Drawdown (m)
Time (days)
Sy:0.05
Sy:0.1
Sy:0.15
Sy:0.4


OBS-3
0
7300
14600
21900
29200
36500
0
-5
-10
-15
-20
-25
-30
-35
Drawdown (m)
Time (days)
Sy:0.05
Sy:0.1
Sy:0.15
Sy:0.4

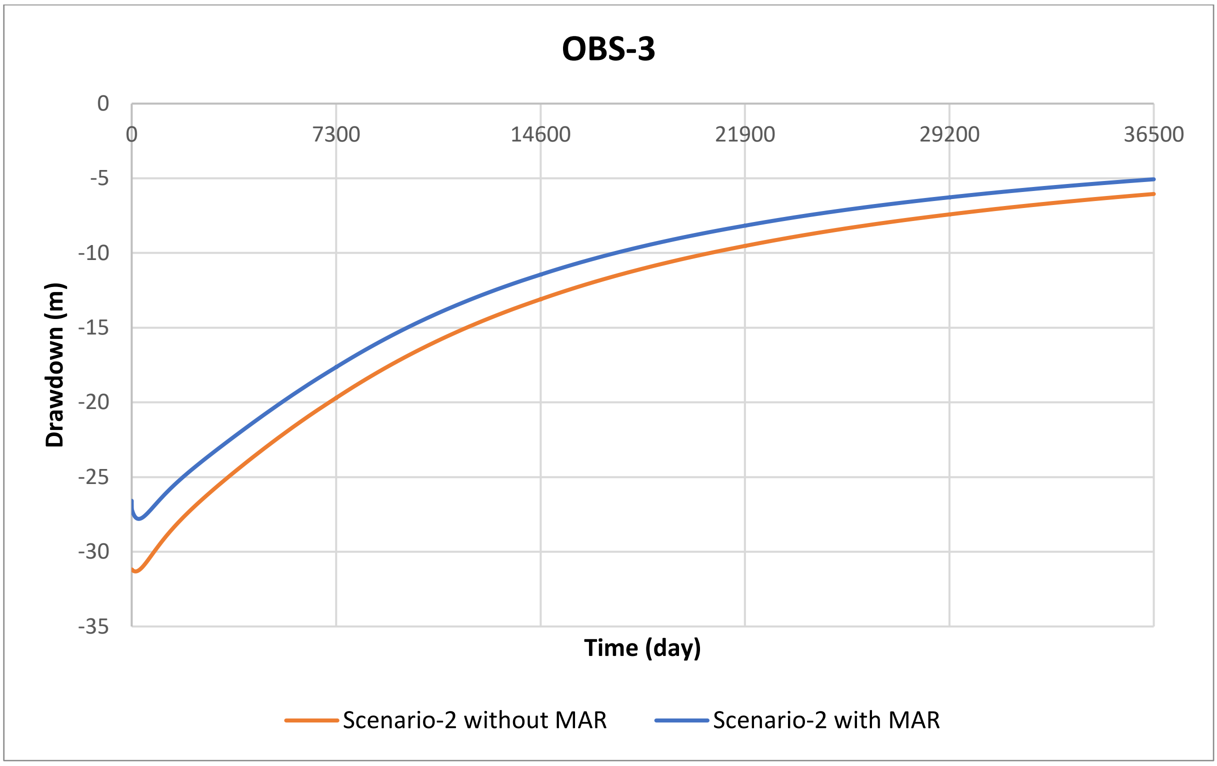
Appendix-7



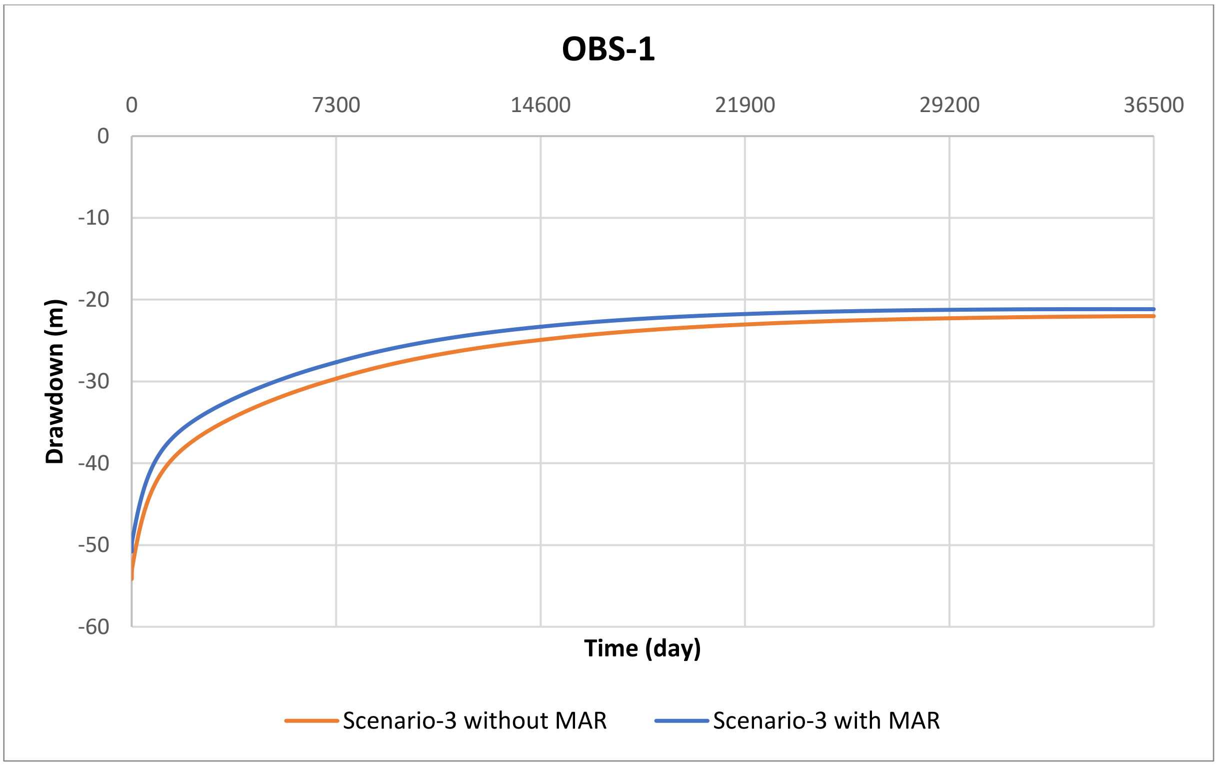
OBS-1
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
Drawdown (m)
Time (day)
Scenario-2 without MAR
Scenario-2 with MAR

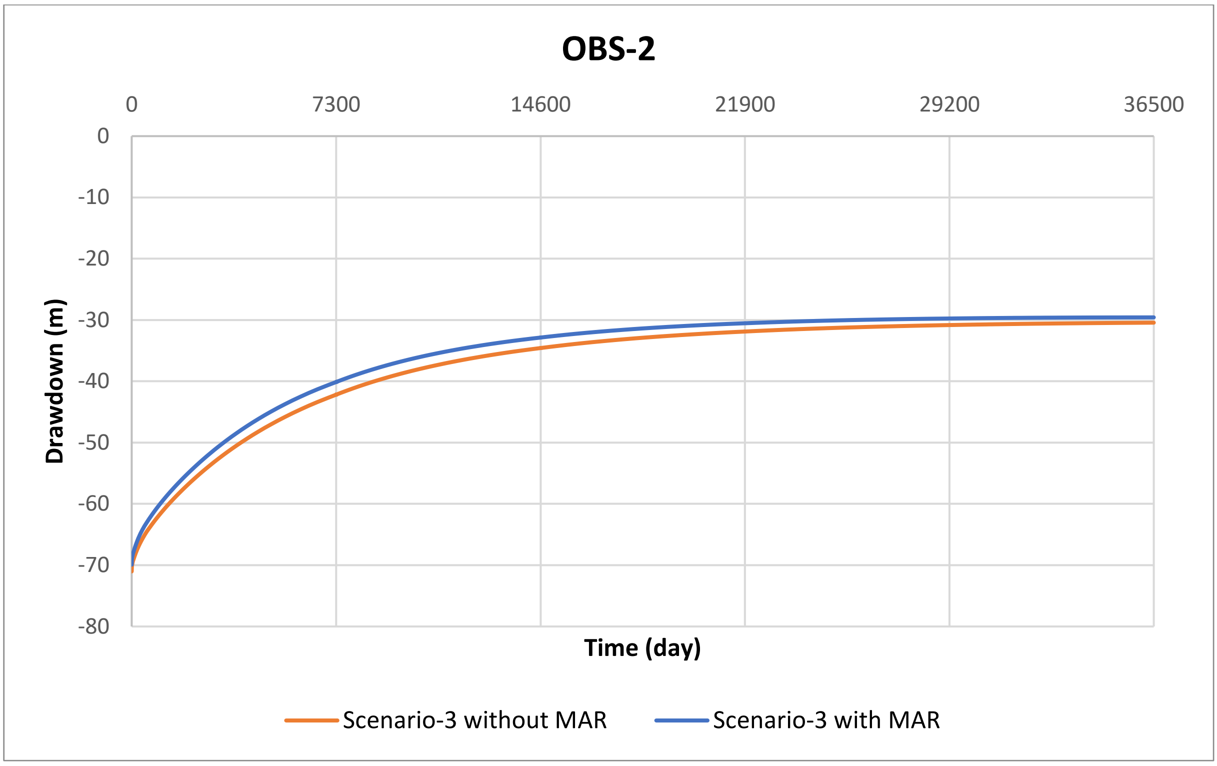


OBS-2
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
-70
-80
Drawdown (m)
Time (day)
Scenario-2 without MAR
Scenario-2 with MAR


OBS-3
0
-5
-10
-15
-20
-25
-30
-35
0
7300
14600
21900
29200
36500
Drawdown (m)
Time (day)
Scenario-2 without MAR
Scenario-2 with MAR

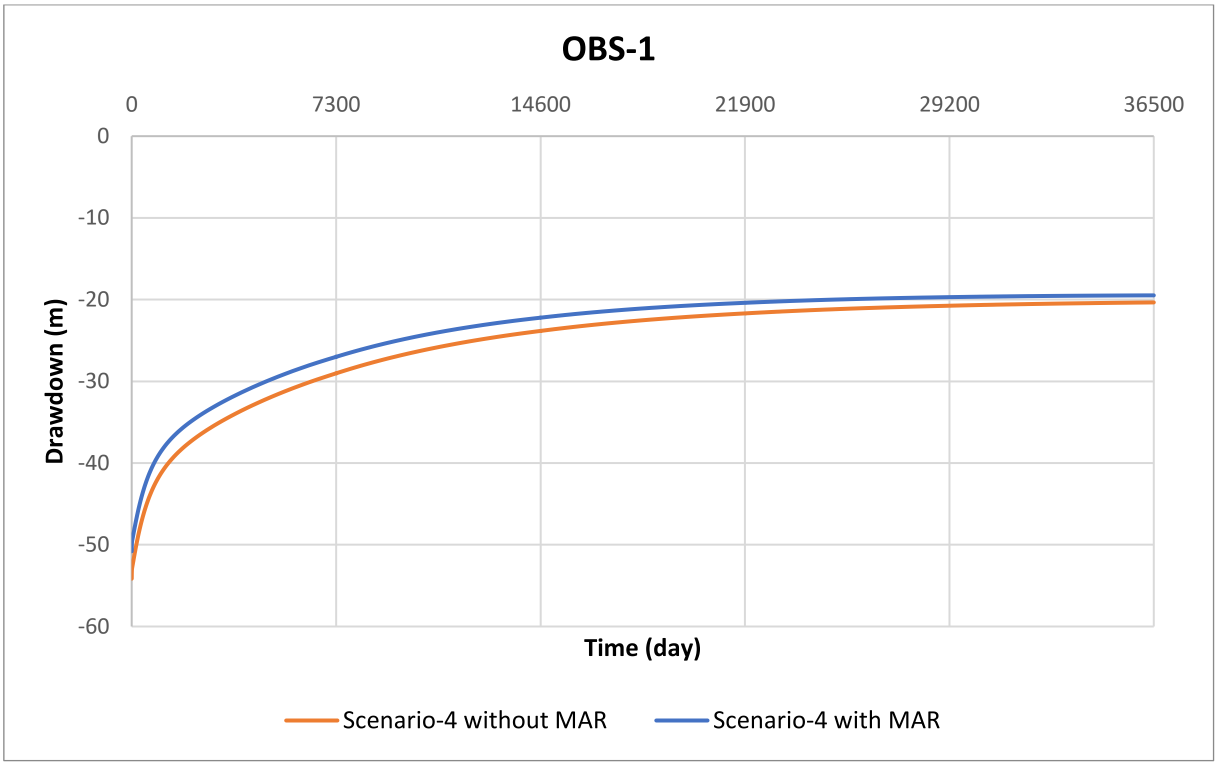
Appendix-8


OBS-1
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
Drawdown (m)
Time (day)
Scenario-3 without MAR
Scenario-3 with MAR

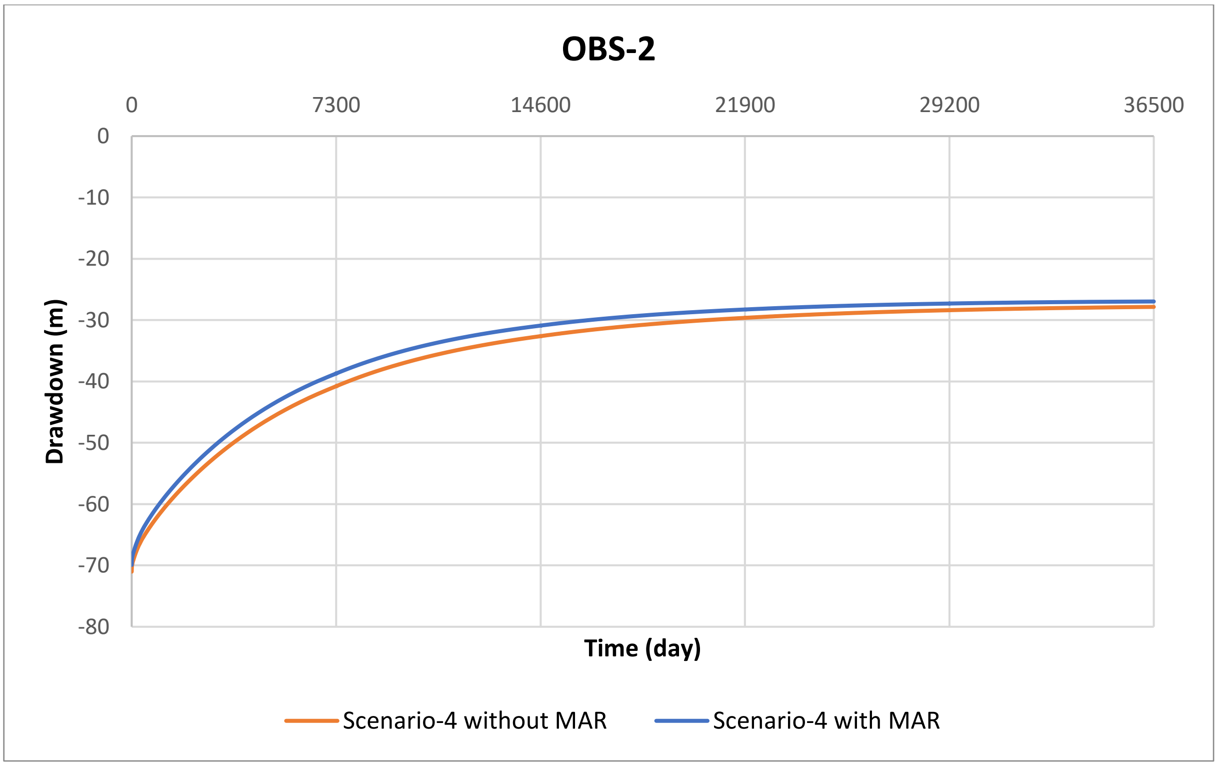

OBS-2
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
-70
-80
Drawdown (m)
Time (day)
Scenario-3 without MAR
Scenario-3 with MAR


OBS-3
0
7300
14600
21900
29200
36500
0
-5
-10
-15
-20
-25
-30
-35
Drawdown (m)
Time (day)
Scenario-3 without MAR
Scenario-3 with MAR

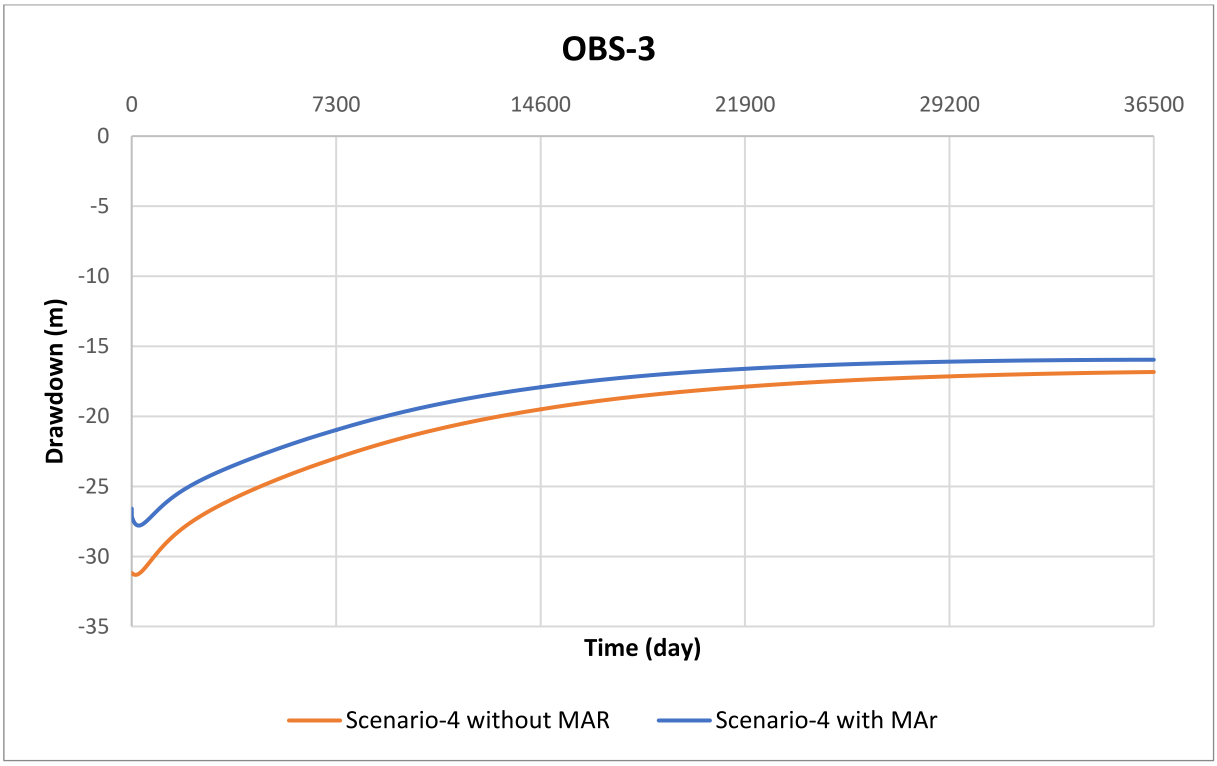
Appendix-9



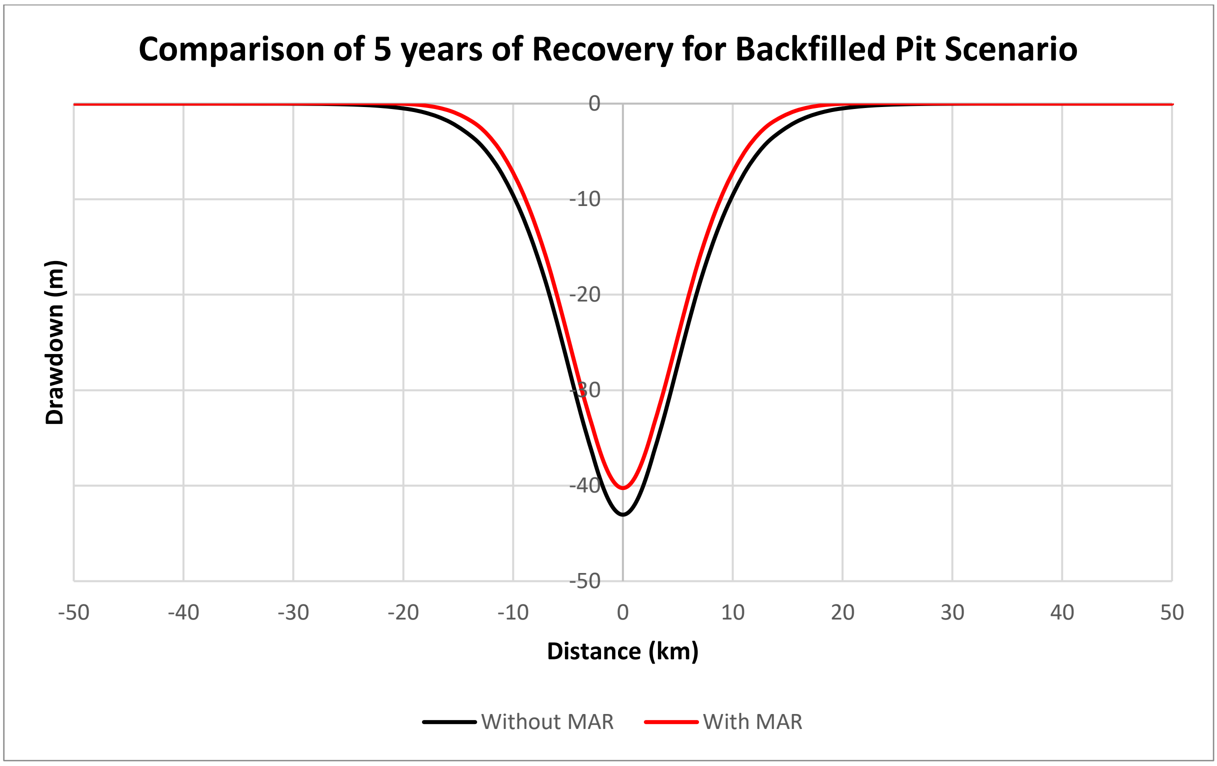
OBS-1
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
Drawdown (m)
Time (day)
Scenario-4 without MAR
Scenario-4 with MAR

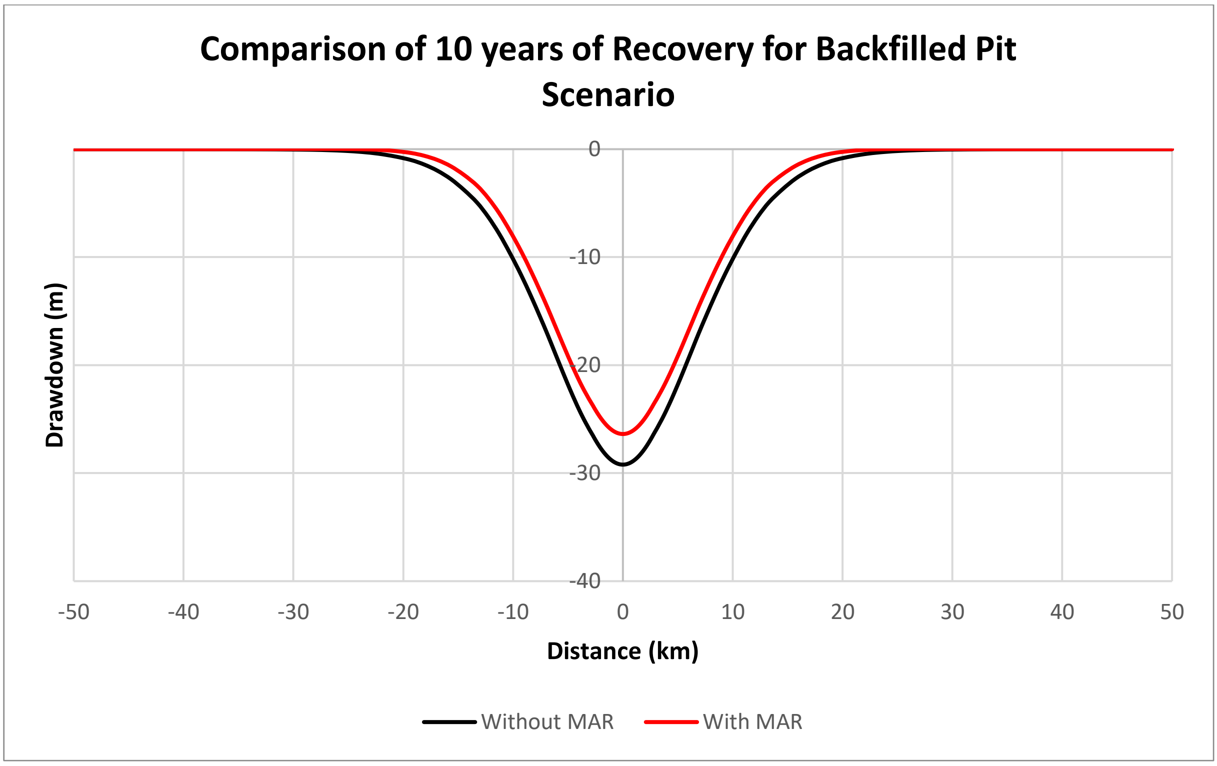


OBS-2
0
7300
14600
21900
29200
36500
0
-10
-20
-30
-40
-50
-60
-70
-80
Drawdown (m)
Time (day)
Scenario-4 without MAR
Scenario-4 with MAR

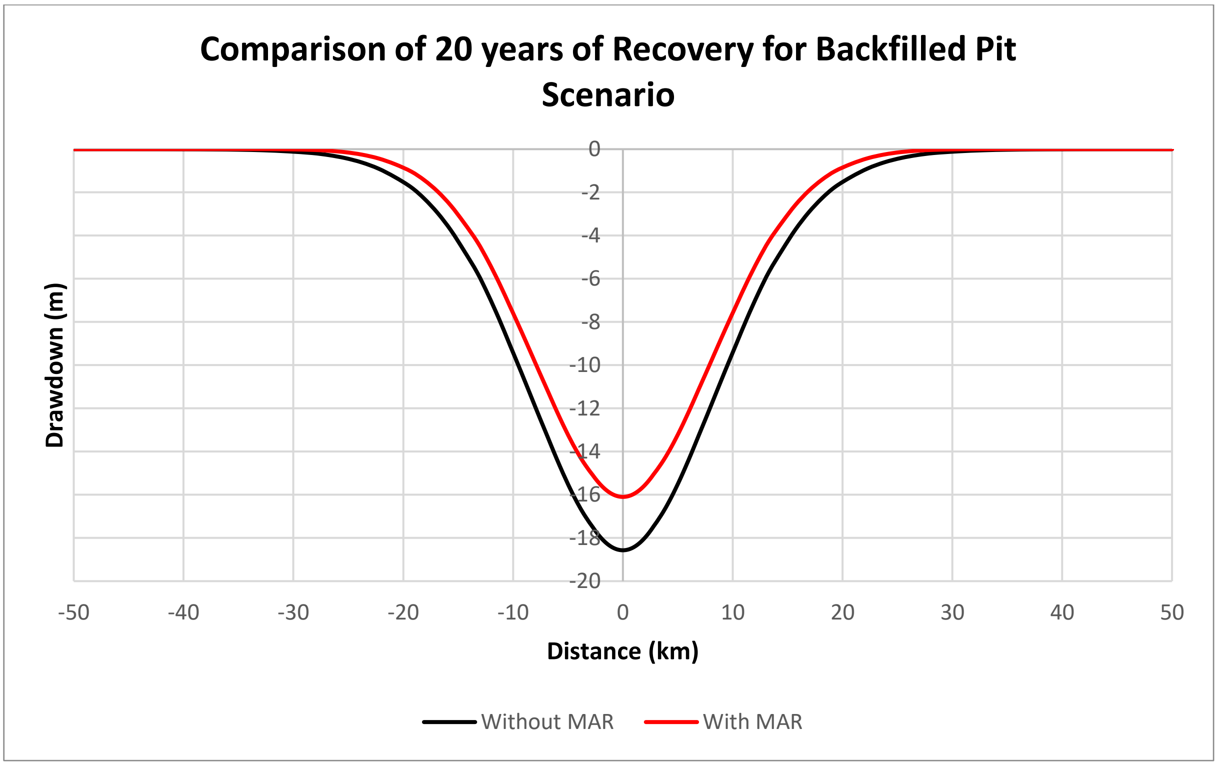

OBS-3
0
7300
14600
21900
29200
36500
0
-5
-10
-15
-20
-25
-30
-35
Drawdown (m)
Time (day)
Scenario-4 without MAR
Scenario-4 with MAr

Appendix-10

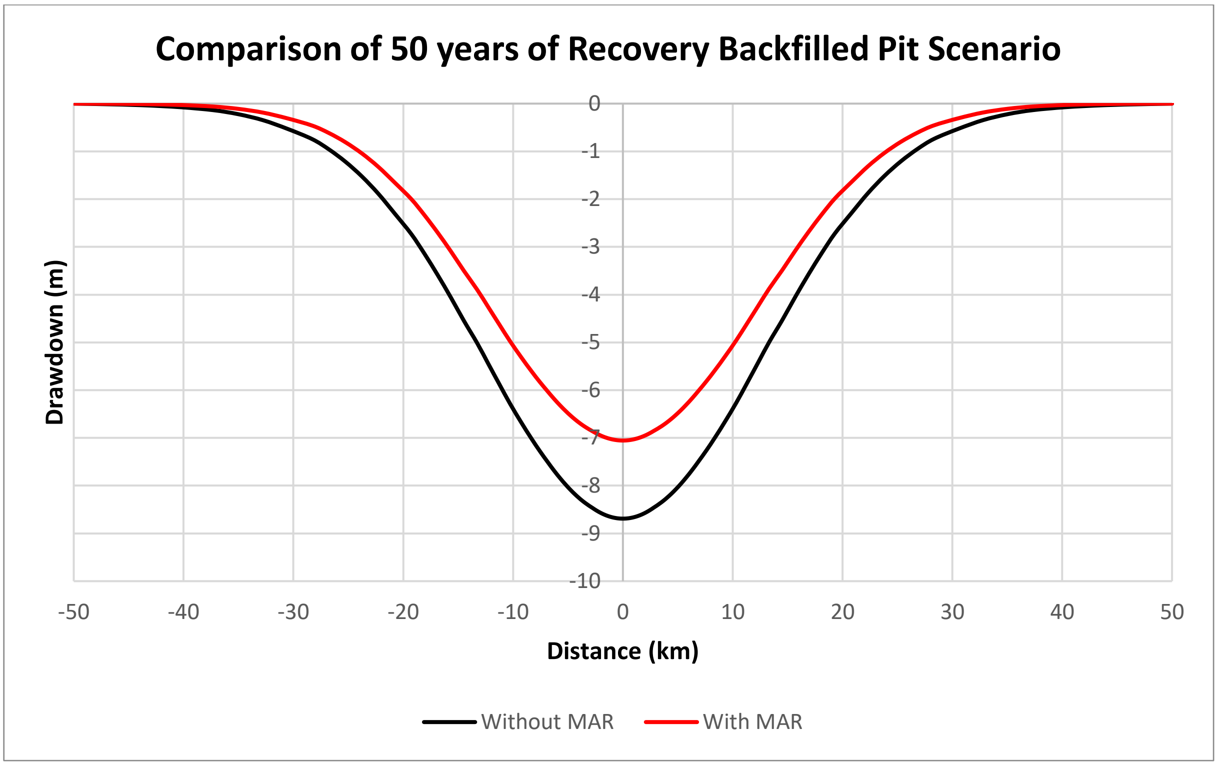

Comparison of 5 years of Recovery for Backfilled Pit Scenario
0
-10
-20
-30
-40
-50
Drawdown (m)
-50
-40
-30
-20
-10
0
10
20
30
40
50
Distance (km)
Without MAR
With MAR



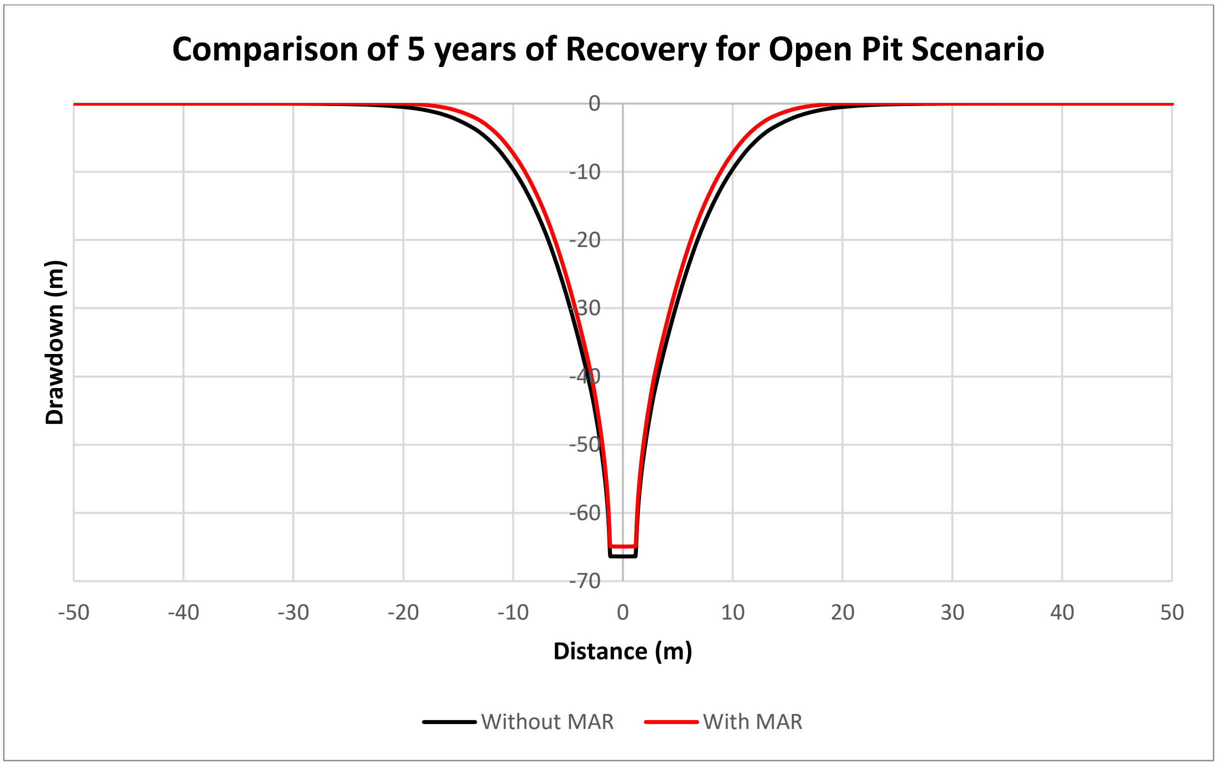
Comparison of 10 years of Recovery for Backfilled Pit Scenario
0
-10
-20
-30
-40
Drawdown (m)
-50
-40
-30
-20
-10
0
10
20
30
40
50
Distance (km)
Without MAR
With MAR



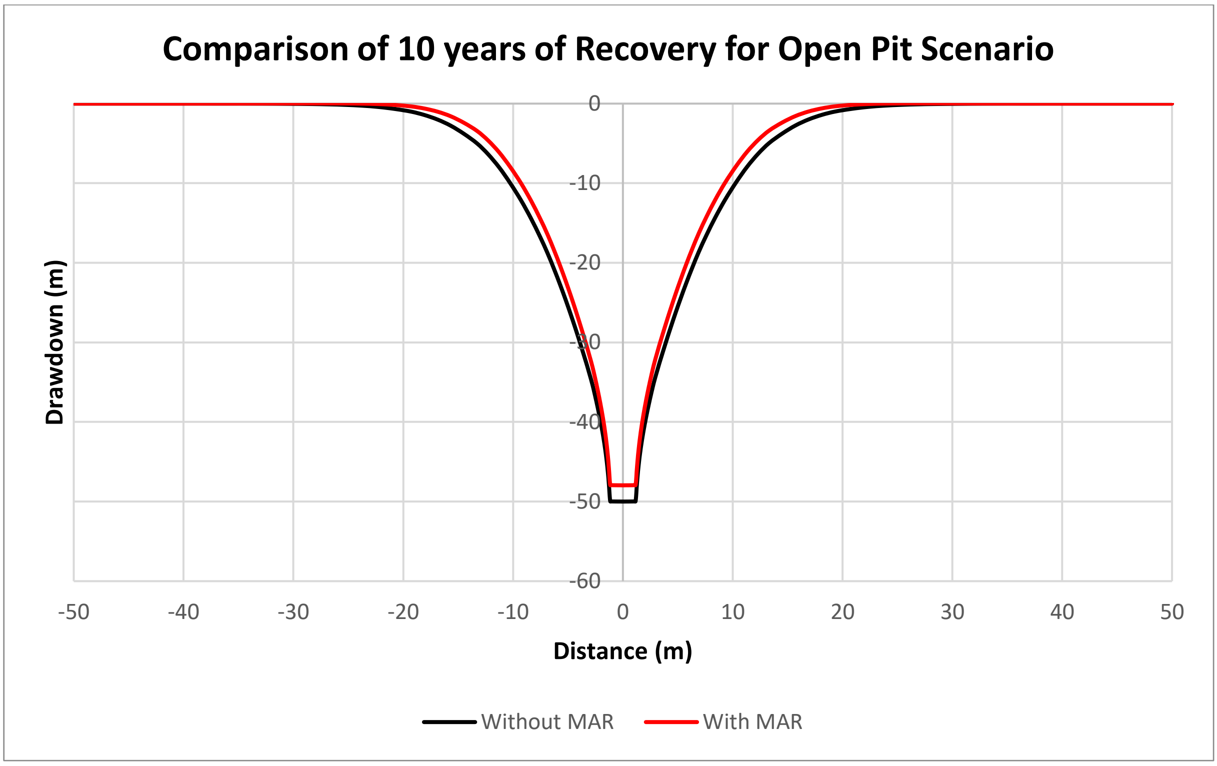
Comparison of 20 years of Recovery for Backfilled Pit Scenario
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
Drawdown (m)
-50
-40
-30
-20
-10
0
10
20
30
40
50
Distance (km)
Without MAR
With MAR

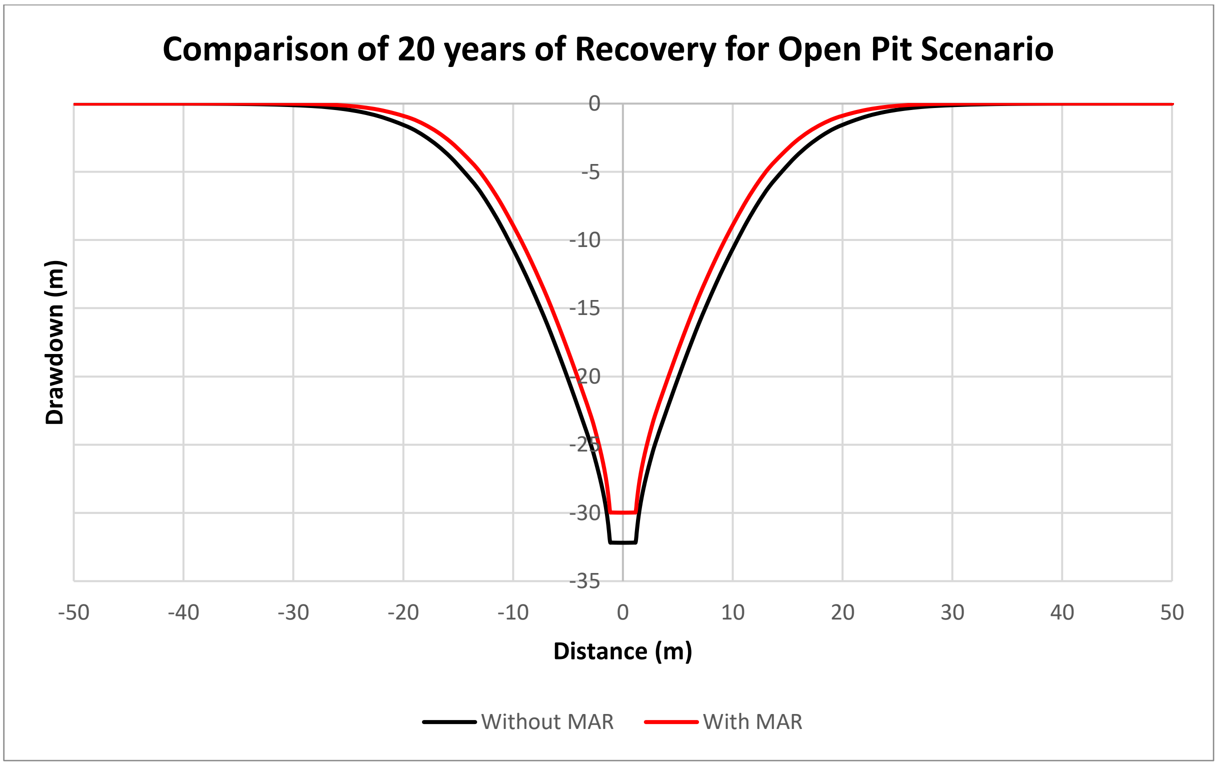


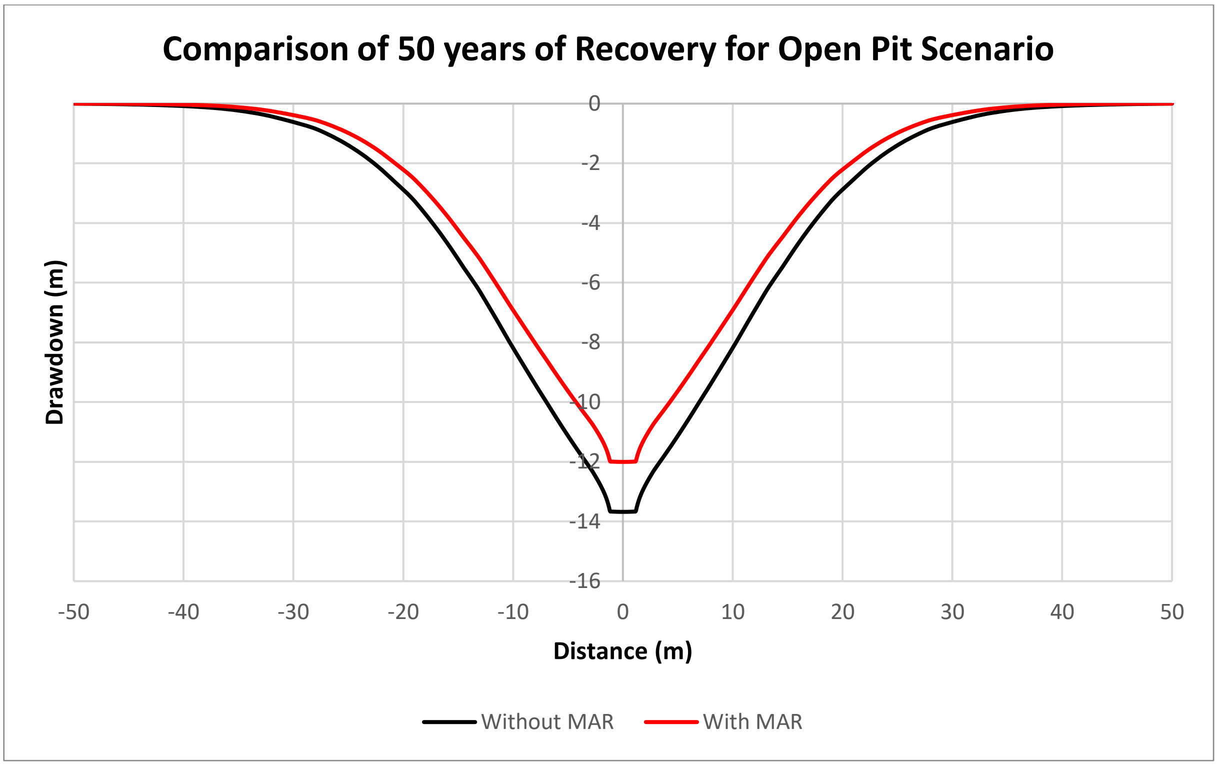
Comparison of 50 years of Recovery Backfilled Pit Scenario
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Drawdown (m)
-50
-40
-30
-20
-10
0
10
20
30
40
50
Distance (km)
Without MAR
With MAR



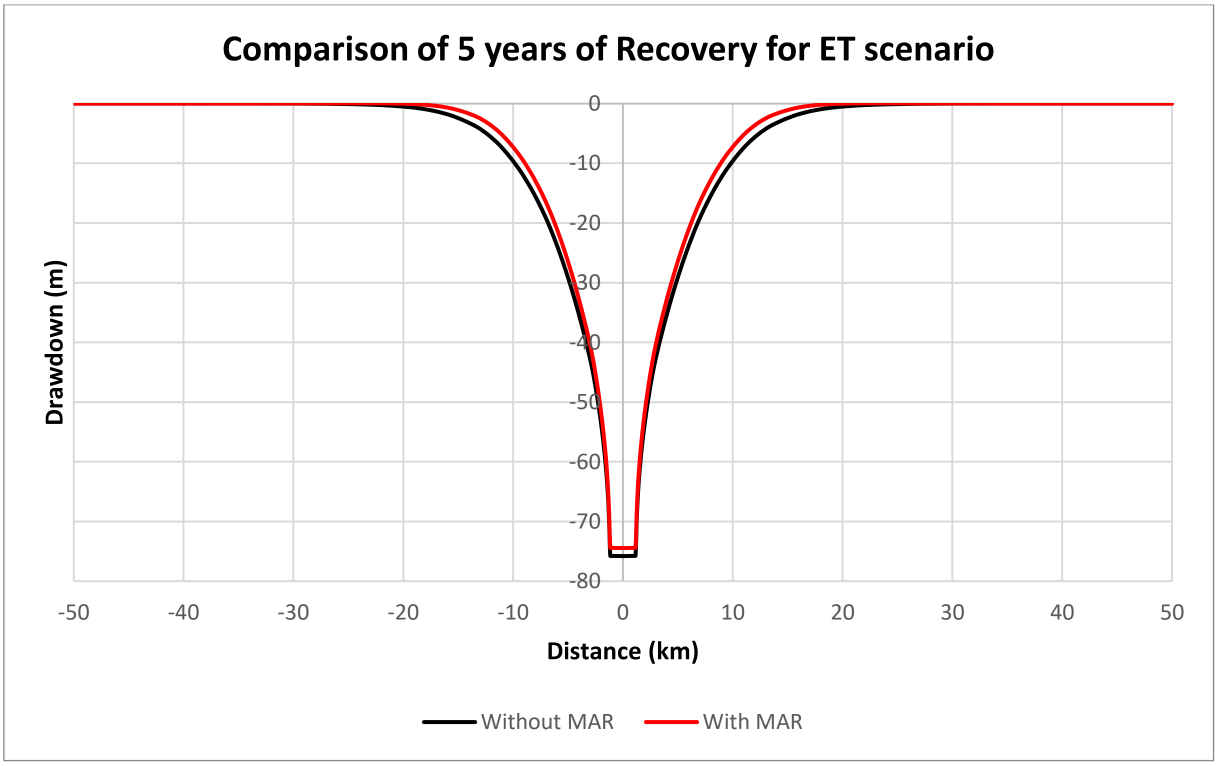
Comparison of 5 years of Recovery for Open Pit Scenario
0
-10
-20
-30
-40
-50
-60
-70
Drawdown (m)
-50
-40
-30
-20
-10
0
10
20
30
40
50
Distance (m)
Without MAR
With MAR


Comparison of 10 years of Recovery for Open Pit Scenario
0
-10
-20
-30
-40
-50
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
Drawdown (m)
Distance (m)
Without MAR
With MAR

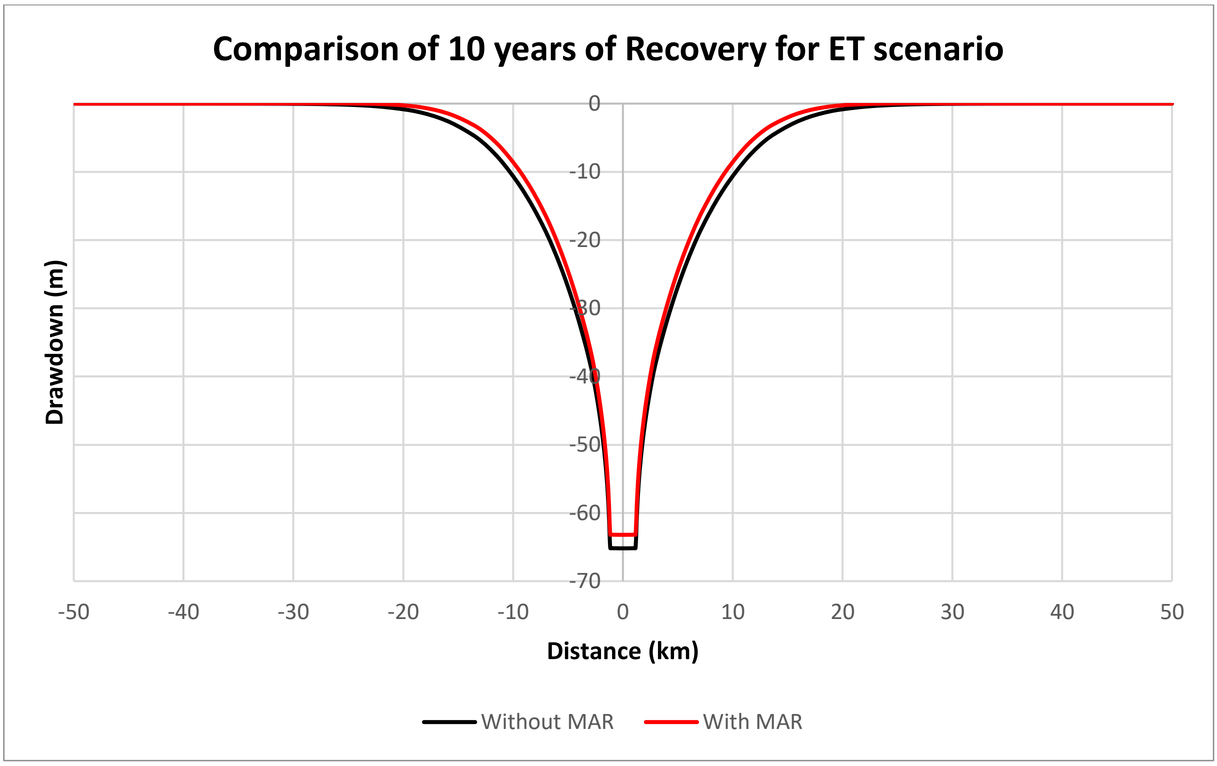

Comparison of 20 years of Recovery for Open Pit Scenario
0
-5
-10
-15
-20
-25
-30
-35
-50
-40
-30
-20
-10
0
10
20
30
40
50
Drawdown (m)
Distance (m)
Without MAR
With MAR



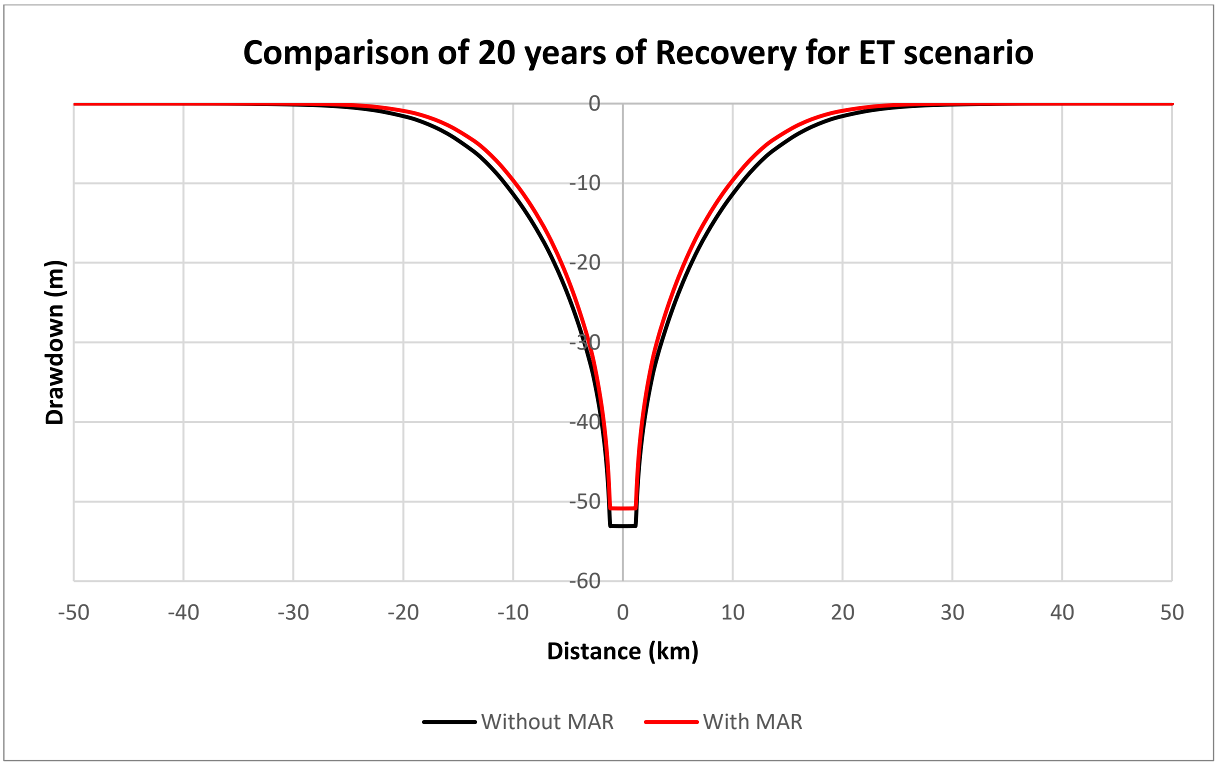
Comparison of 50 years of Recovery for Open Pit Scenario
Drawdown (m)
0
-2
-4
-6
-8
-10
-12
-14
-16
-50
-40
-30
-20
-10
0
10
20
30
40
50
Distance (m)
Without MAR
With MAR



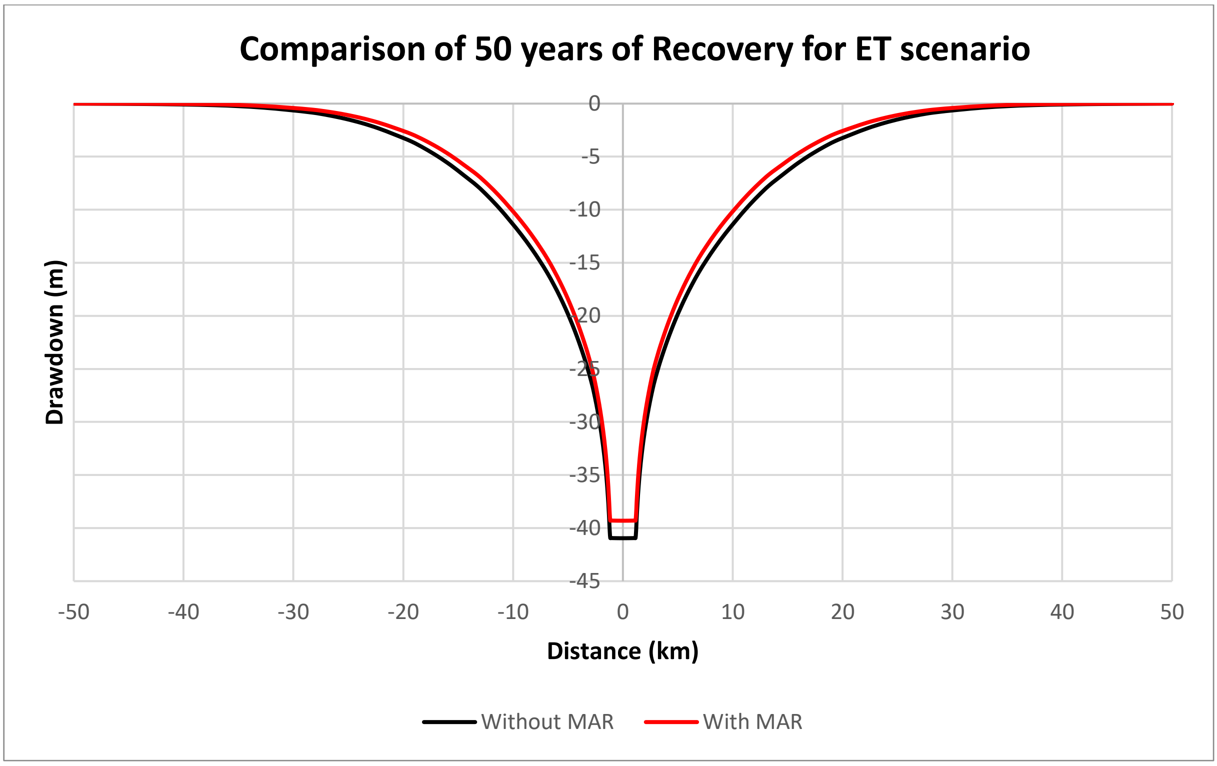
Comparison of 5 years of Recovery for ET scenario
Drawdown (m)
0
-10
-20
-30
-40
-50
-60
-70
-80
-50
-40
-30
-20
-10
0
10
20
30
40
50
Distance (km)
Without MAR
With MAR



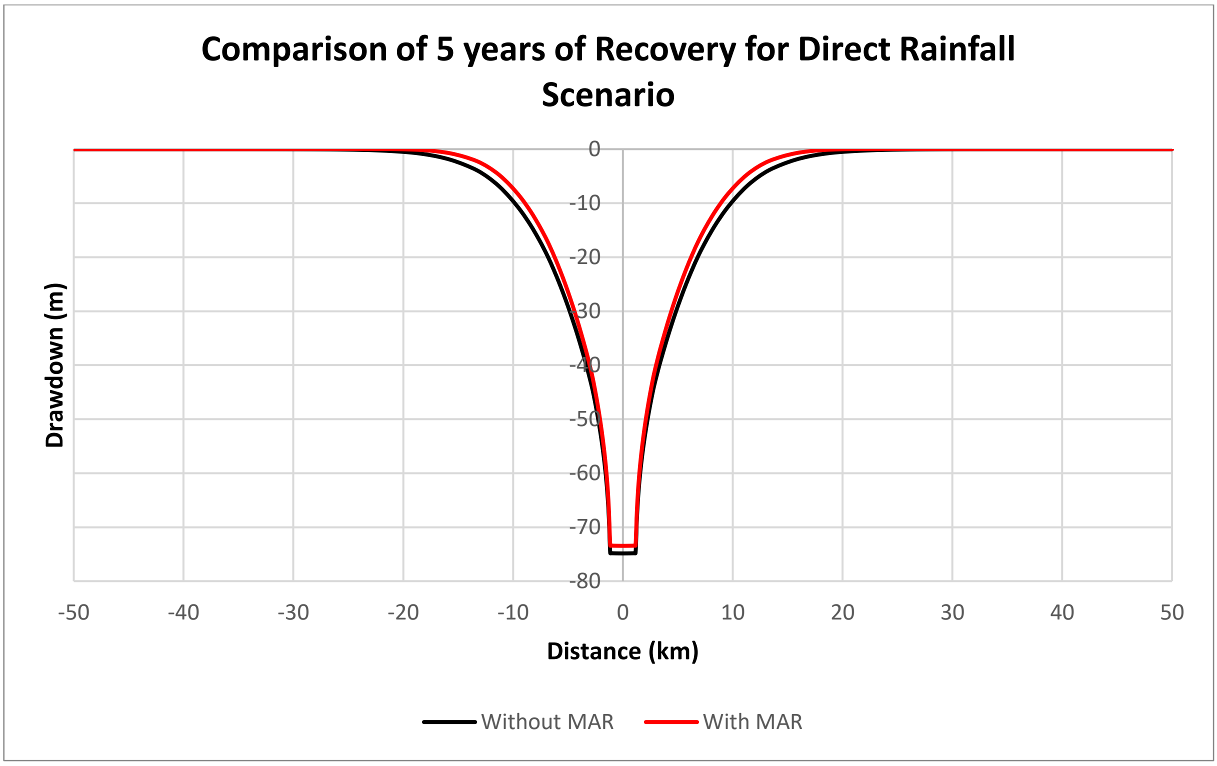
Comparison of 10 years of Recovery for ETscenario
Drawdown (m)
0
-10
-20
-30
-40
-50
-60
-70
-50
-40
-30
-20
-10
0
10
20
30
40
50
Distance (km)
Without MAR
With MAR



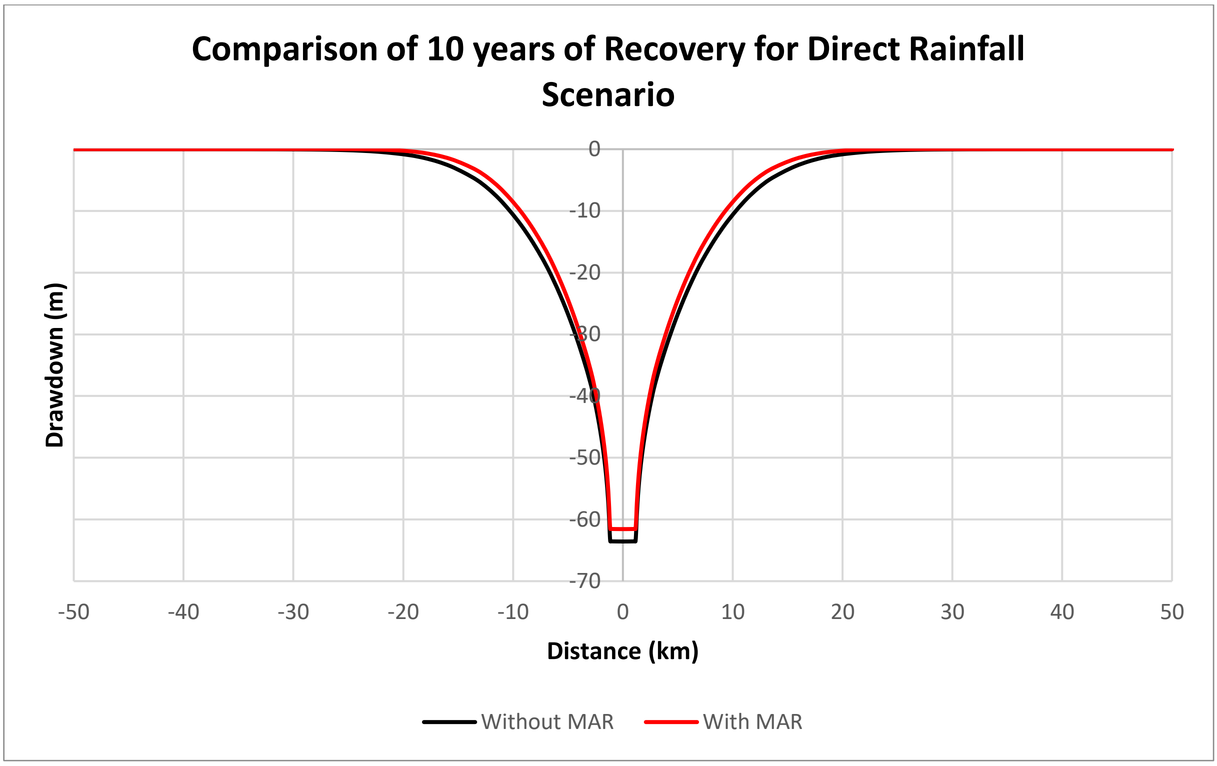
Comparison of 20 years of Recovery for ET scenario
Drawdown (m)
0
-10
-20
-30
-40
-50
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
Distance (km)
Without MAR
With MAR

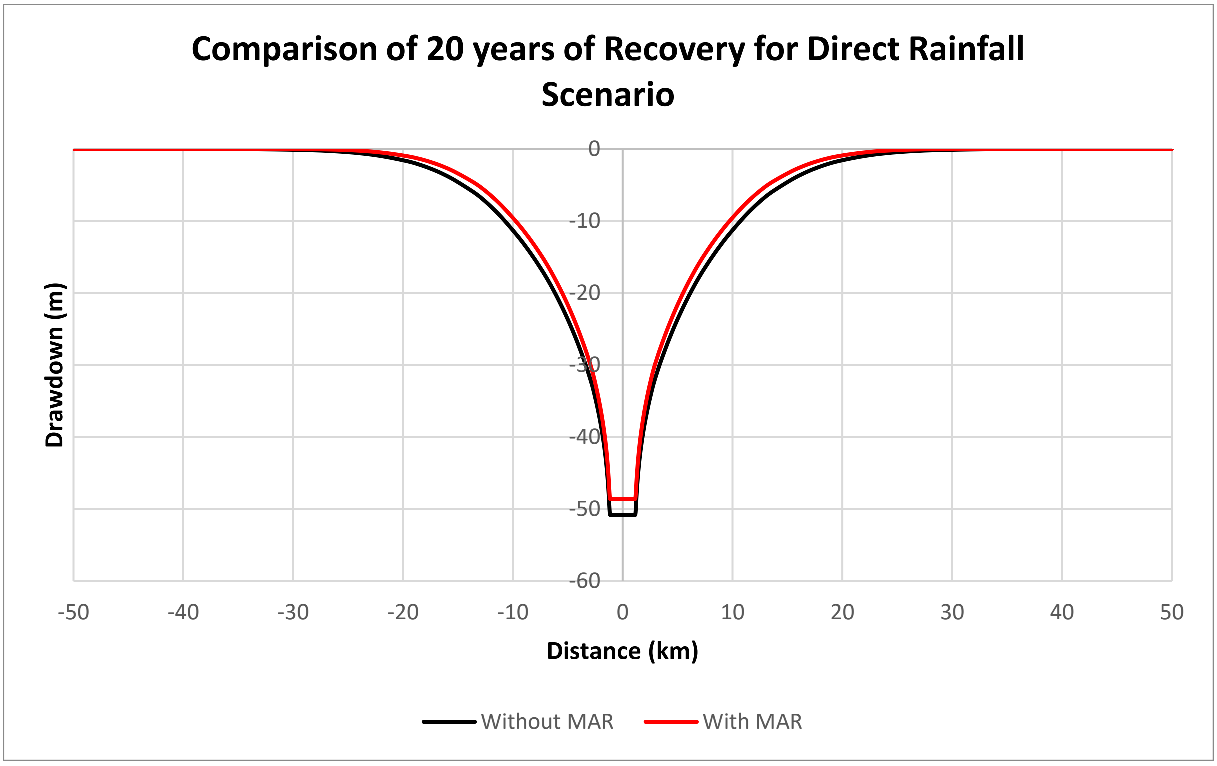


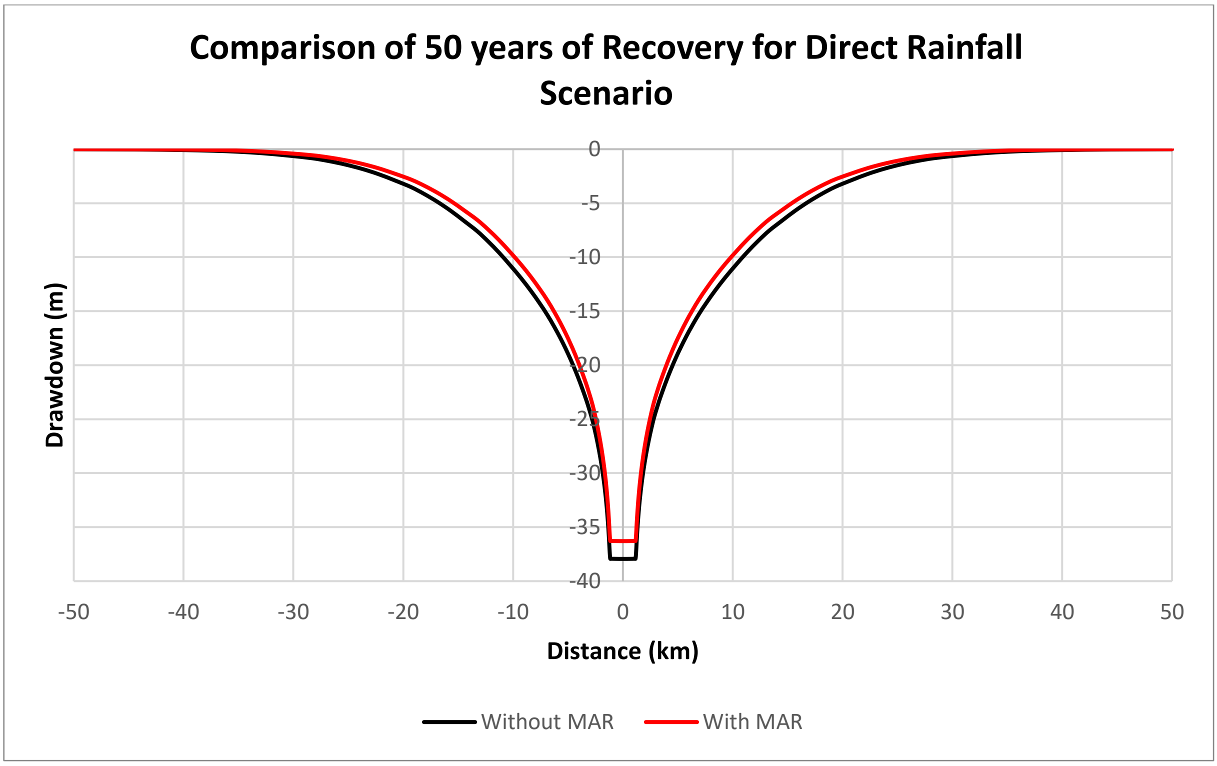
Comparison of 50 years of Recovery for ET scenario
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-40
-30
-20
-10
0
10
20
30
40
50
Drawdown (m)
Distance (km)
Without MAR
With MAR



Comparison of 5 years of Recovery for Direct Rainfall Scenario
0
-10
-20
-30
-40
-50
-60
-70
-80
-50
-40
-30
-20
-10
0
10
20
30
40
50
Drawdown (m)
Distance (km)
Without MAR
With MAR


Comparison of 10 years of Recovery for Direct Rainfall Scenario
0
-10
-20
-30
-40
-50
-60
-70
-50
-40
-30
-20
-10
0
10
20
30
40
50
Drawdown (m)
Distance (km)
Without MAR
With MAR


Comparison of 20 years of Recovery for Direct Rainfall Scenario
0
-10
-20
-30
-40
-50
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
Drawdown (m)
Distance (km)
Without MAR
With MAR



Comparison of 50 years of Recovery for Direct Rainfall Scenario
Drawdown (m)
0
-5
-10
-15
-20
-25
-30
-35
-40
-50
-40
-30
-20
-10
0
10
20
30
40
50
Distance (km)
Without MAR
With MAR