Research Project Cover Sheet

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Declaration:
This paper entitled "Assessing the Predictive Capacity of Streamflow Estimations for Modelling Water Security Dynamics in Arid Regions: A Case Study of Kuwait" was submitted in partial fulfilment of the requirements for the unit **CENG30020 Research Project 3** to the School of Civil, Aerospace and Design Engineering, University of Bristol.

I declare that the work in this dissertation was carried out in accordance with the Regulations of the University of Bristol. The research on which this paper is based was carried out under the supervision of **Dr Rafael Rosolem** during the academic year **2023-24**.

The work is entirely my own work and is original, except where indicated by special reference in the text and no part of the paper has been submitted for any other academic award.

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Date: 25th April 2024

ASSESSING THE PREDICTIVE CAPACITY OF STREAMFLOW ESTIMATIONS FOR MODELLING WATER SECURITY DYNAMICS IN ARID REGIONS: A CASE STUDY OF KUWAIT

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ABSTRACT: Kuwait faces significant challenges in water resource management due to its extreme aridity and heavy reliance on non-renewable groundwater and desalination. This study evaluates the water security of the Raudhatain and Umm Al Aysh aquifers, using the Soil and Water Assessment Tool (SWAT) model to simulate groundwater recharge rates. Employing high-resolution spatial data, including Digital Elevation Models (DEM) and satellite imagery, the model was calibrated and validated to assess groundwater flows under various land use and climate scenarios. Streamflow generated from combining surface runoff, lateral flow and baseflow estimations, was used to calibrate the model due to the lack of observed streamflow data in the region. The study estimates the average areal groundwater recharge rates for the Raudhatain watershed to be 6.22 mm/year, and the Raudhatain and Umm Al Aysh freshwater aquifers to be 12.35 mm/year and 13.64 mm/year, respectively. These findings prove the reliability of the streamflow estimations, after deep analysis and comparisons of the results with other studies done on the Raudhatain basin. The findings reveal critical imbalances between groundwater recharge and extraction rates, with recharge rates being significantly less than extraction rates. The simulations in this study indicate that without intervention, the current extraction rates will lead to substantial depletion of the Raudhatain and Umm Al Aysh aquifers by the years 2050 and 2059, respectively. The findings of this paper suggest that the amount of artificial recharge required to ensure the long-term safety of the Raudhatain and Umm Al Aysh freshwater aquifers is 3.0 million m^3 and 1.5 million m^3, respectively, while prioritising the Raudhatain aquifer. This study recommends maximising the utilisation of the sparse rainfall in Kuwait for artificial recharge through sustainable management practices that promote water reuse and recycling. The creation of shallow infiltration ponds in the aquifers known as Chaukas have been proposed to maximise the utilisation of the very little rainfall in Kuwait. By comparing these results with global arid regions, the study provides valuable insights into effective groundwater management strategies that could be adapted to similar environments facing water scarcity.

KEYWORDS: Soil and Water Assessment Tool (SWAT), Raudhatain, Umm Al Aysh, Recharge, Streamflow, Aquifers

STATEMENT OF ORIGINALITY: This paper aims to find how reliable streamflow estimations are for calibrating a Soil and Water Assessment Tool (SWAT) model in arid regions. This paper also proposes sustainable groundwater management recommendations for Kuwait and presents original findings on the estimation of recharge rates for the Raudhatain watershed, and the two freshwater aquifers Raudhatain and Umm Al Aysh.

1. INTRODUCTION

Kuwait, located in the northwestern corner of the Persian Gulf and covering about 18,000 square kilometres, has no freshwater streams and is marked by an arid environment with the lowest renewable water resource index globally due to its sparse and irregular rainfall (Al-Senafy & Abraham, 2004). Hassan, Albanai, & Goudie (2021) show in Figure 1(a), that the water in Kuwait moves from areas with low stream orders and high elevation to areas with high stream orders and low elevations, forming different basins. In the country, the primary natural water sources are the brackish groundwater found in the Kuwait Group and Dammam aquifers, with salinity levels ranging from 4,300 to 10,200 mg/l and 2,500 to 10,000 mg/l, respectively. There are also limited supplies of fresh groundwater in the Raudhatain and Umm Al Aysh aquifers, with salinity between 359 and 1,737 mg/l. Most of Kuwait's groundwater is used for agricultural irrigation, household, use as well as for mixing with distilled water (Al-Ruwaih & Almedeij, 2007).The two freshwater aquifers that can be seen in Figure 1(b), were discovered on May 1960 during a survey conducted by the Parsons Corporation of Los Angles (Parsons Corporation, 1964).

The freshwater extracted from the two freshwater aquifers represents 7% of the potable water and the remaining 93% of potable water comes from desalination of seawater (MEW, 2020). Groundwater depletion and elevated water salinity are two serious environmental issues that have resulted from Kuwait's over-exploitation of the Raudhatain and Umm Al Aysh aquifers (Fadlelmawla et al., 2008; Yihdego and Al-Weshah, 2017). It is becoming progressively harder to replenish these freshwater sources, which are vital for industrial, municipal, and agricultural applications. Kuwait has been depending more and more on desalination and treated wastewater as alternative water sources to deal with the effects of over-extraction and the country's rising water demand (Hamoda, 2001). This strategy seeks to guarantee future water availability while easing pressure on the region's finite freshwater resources. However, if the country does not regulate the groundwater extraction and only focuses on using alternative sources, this could lead to a significant decrease in the water levels which threatens the long-term availability of the freshwater aquifers (Al-Rashed and Al-Senafy, 1998). Additionally, elevated water salinity from over-extraction contributes to public health risks, including potential carcinogenic effects due to bromate contamination in drinking water (Alomirah et al., 2019). It is also important to note that the aquifers have already been seriously affected by the damage caused during the 1991 Gulf War's destruction of oil wells, and the sea water used to control and extinguish the oil fires has directly affected the aquifers (Woldeyohannes and Al-Weshah, 2017).

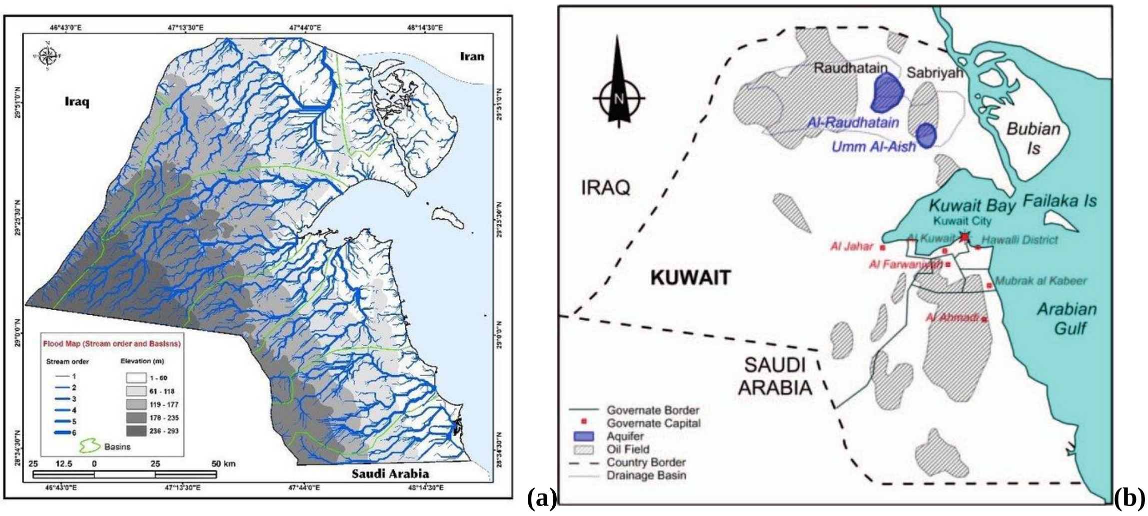


Figure 1: (a) A map of Kuwait showing the elevation and stream orders (Hassan, Albanai & Goudie, 2021) and (b) A map of Kuwait showing the locations of the Raudhatain and Umm Al Aysh aquifers in Kuwait (Woldeyohannes and Al-Weshah, 2017)

1.1 Water Security in Arid Regions

According to the U.S. National Park Service, arid regions are areas which are characterised by extremely dry conditions, receiving less than 250 millimeters of rainfall per year, and having a significantly higher potential evapotranspiration (the amount of water that would evaporate and transpire if sufficient water were available), leading to a deficit in water availability (U.S. National Park Service, 2019). Water scarcity occurs when the demand for freshwater exceeds supply (Kumari et al., 2021). Arid regions are vulnerable to future water scarcity due to the dual pressures of climate change and urban growth (Gober,2010). Within those arid regions, the Gulf Cooperation Council (GCC) of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE) inhabit of one of the most water-scarce regions in the world (Saif, Mezher, and Arafat, 2014). In the past, desalination and non-renewable groundwater have been the main sources of water for GCC nations. Even though desalination is an essential source of freshwater, it has negative environmental effects and high energy costs, which puts additional strain on these oil-rich countries' resources (Al-Saidi and Elagib, 2021). Furthermore, over-extraction brought about by the over-reliance on groundwater, has depleted aquifers and raised soil salinity, both of which have a negative impact on agricultural productivity (Zubari et al., 2017).

Regarding freshwater resources, the world's arid regions today in the GCC are dealing with more challenging issues than they have in the past. For instance, most of Saudi Arabia's freshwater supplies are found in groundwater aquifer systems; only roughly 5% come from desalination facilities, and 10% originate from seasonal runoff (Ouda, 2013). This shows that although Kuwait is mostly dependent on desalination as a source of freshwater, other arid regions are heavily dependent on freshwater from groundwater aquifer systems. Therefore, understanding the water security dynamics in Kuwait’s freshwater aquifers, provides a valuable framework for comparison with other arid regions that are facing similar challenges.

1.2 Modelling Within the Raudhatain Watershed

The Raudhatain and Umm Al Aysh aquifers seen in Figure 1(b) are located within a watershed that is referred to by several studies (Ud Din, Al Dousari and Al Ghadban, 2007; Al-Dousari et al., 2010; Al-Senafy et al., 2013; Milewski et al., 2014) as the Raudhatain watershed. There are many studies conducted on the Raudhatain watershed that estimate the groundwater recharge and many of these studies use the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Williams et al., 2008) to model the watershed and estimate the groundwater recharge. SWAT is one of the most widely used water quality, watershed, and river basin scale models worldwide (Williams et al., 2008) and is proven to be highly flexible in addressing water security problems in arid regions, as shown in the studies made by Ehtiat, Mousavi, and Srinivasan, 2018 and Shao et al., 2019 which focussed on estimating groundwater recharge in arid regions.

Ud Din, Al Dousari and Al Ghadban (2007) assessed the Raudhatain watershed using Surface water physical techniques to have an average recharge rate of 7.8 mm/year during the year 2003. Ud Din, Al Dousari and Al Ghadban (2007) had proposed an addition of recharge wells in the higher order streams to augment the Raudhatain aquifer to utilise more precipitation for reducing pressure on desalination. Al-Dousari et al. (2010) then assessed the same watershed using SWAT modelling, an average recharge rate was estimated to be 12.7 mm/year during the period 1998–2006. Al-Dousari et al. (2010) discussed that their datasets show a good correlation with estimates made from the previous study on the same watershed (Ud Din, Al Dousari, and Al Ghadban, 2007). However, Al-Dousari et al. (2010) believe that these results show only the groundwater potential and that conservative estimates indicate that the annual recharge rates should be slightly higher (13.5 mm/year), and state that additional work is required to refine these estimates.

Al-Senafy et al. (2013) also assessed the same watershed using SWAT modelling, an average recharge rate was estimated to be 4.795 mm/year during the period 2000-2009. Al-Senafy et al. (2013) discussed that this estimate is in good agreement with published recharge estimates in other arid areas. However, Al-Senafy et al. (2013) showed using hydrographs, that the recharge rates at the Raudhatain and Umm Al Aysh depressions (12.5 mm/year) were higher than the watershed and concluded that further investigation on the utilisation of these resources should be made, to determine the volumes that can be recovered from extraction. Milewski et al. (2014) then assessed the same watershed again using SWAT modelling, this time focusing on all the depressions within the watershed. As previously mentioned, some of these depressions include Kuwait's two freshwater aquifers and interestingly, the recharge rates estimated by Milewski et al. (2014) of the entire Raudhatain watershed were the same as the recharge rates as the depressions within the watershed; 33.8 mm/year. This contradicts the findings of Al-Senafy et al. (2013) and show that the recharge rates across the Raudhatain watershed are more uniformly distributed than previously thought.

The study made by Kwarteng et al. (2000) targets the Raudhatain and Umm Al Aysh freshwater aquifers specifically and estimates using the saturated zone water budget equation, that both aquifers have an average areal recharge of 26.7 mm/year during the period 1962-1978. The study found recharge only happened when rainfall exceeded 20 mm/day and that the sustainable recharge rates for the Raudhatain and Umm al Aysh aquifers are estimated to be 0.167 and 0.107 million m^3/month, respectively. Another study made by Alrashidi and Bailey (2020) focuses specifically on the Raudhatain freshwater aquifer, provides an in-depth analysis on estimating long-term groundwater recharge for the aquifer in the future. After testing twelve different recharge rate scenarios using multiple different modelling techniques, the long-term average annual recharge of the aquifer is estimated to be 6.67 mm/year. This study shows the freshwater aquifer is extremely dependent on recharge because if there were to be reduction in recharge the water quantity in the aquifer will be reduced tremendously.

Table 1: Summary of recharge estimates for studies on the Raudhatain basin

Reference	Basin Type	Timescale	Estimation method	Average areal recharge (mm/year)
Kwarteng et al. (2000)	Raudhatain aquifer	17 years (1962–1978)	Saturated zone-water budget equation	26.70
Ud Din, Al Dousari and Al Ghadban (2007)	Raudhatain watershed	1 year (2003)	Surface water-physical techniques	7.80
Al-Dousari et al. (2010)	Raudhatain watershed	9 years (1998–2006)	Soil and Water Assessment Tool (SWAT)	12.70
Al-Senafy et al., (2013)	Raudhatain watershed	10 years (2000–2009)	Soil and Water Assessment Tool (SWAT)	4.90
Milewski et al. (2014)	Raudhatain aquifer	12 years (1998–2009)	Soil and Water Assessment Tool (SWAT)	33.90
Alrashidi and Bailey (2020)	Raudhatain aquifer	100 years (2020-2120)	3D density-dependent groundwater flow model	6.67

1.3 Objectives

The primary objective of this study is to assess the accuracy and reliability of streamflow estimations for the calibration of a SWAT model. As well as estimate the groundwater recharge rates for Kuwait's freshwater aquifers and propose sustainable management practices to ensure the long-term availability of the freshwater aquifers. The following research questions will be the focus of this paper:

- How accurate and reliable are streamflow estimations for the calibration of a SWAT model?
- How do the simulated recharge rates of the Raudhatain and Umm Al Aysh freshwater aquifers correlate with the current extraction rates?
- What are the sustainable management practices that Kuwait should consider in order to ensure the long-term availability of the freshwater aquifers?

To address these questions, the study will rely on the Soil and Water Assessment Tool (SWAT) to simulate the recharge rates of the Raudhatain watershed and use the studies in Table 1 for the comparison and analysis of results.

2. STUDY SITE AND DATA

The Raudhatain watershed seen in Figure 2 was located after using a Digital Elevation Model (DEM) with a spatial resolution of 30 meters, generated by the Shuttle Radar Topography Mission (SRTM) satellite from the United States Geological Survey (USGS) (US Geological Survey, 2021).

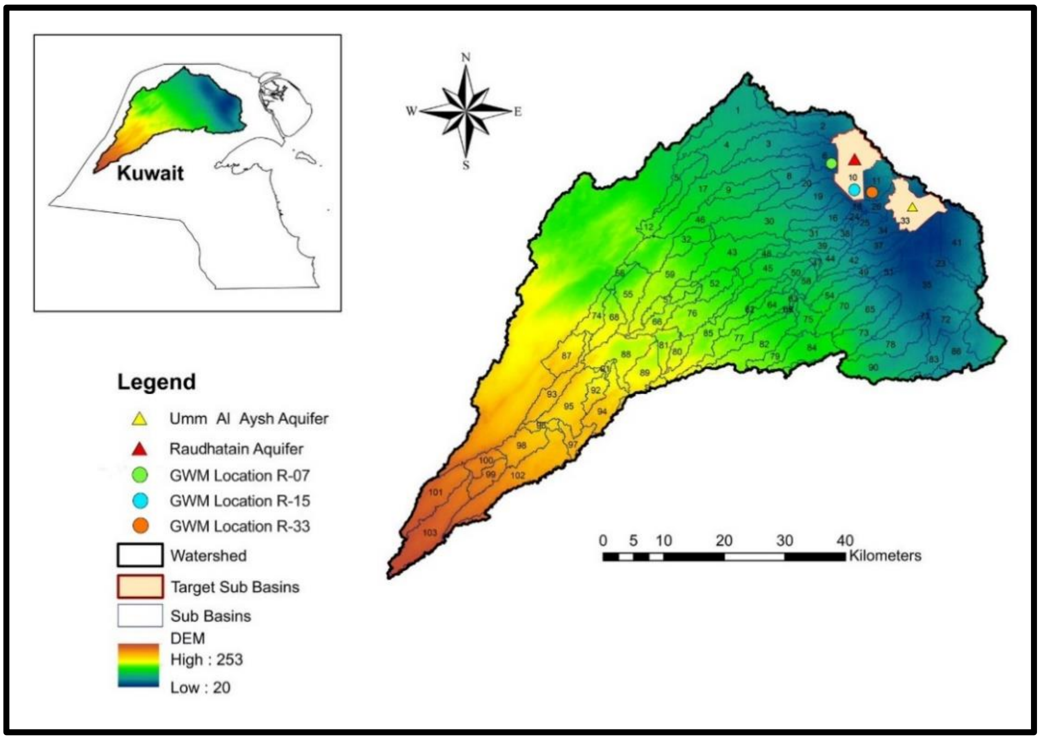


Figure 2: A Digital Elevation Model (DEM) of the Raudhatain watershed with all the delineated sub-basins and chosen sub-basins of aquifers with the Groundwater Monitoring (GWM) locations

The DEM was able to define the watershed boundary and delineate all the major sub-basins within the watershed. The watershed has a total area of 3694.4 km^2 and the target sub basins were selected according to the global coordinates of the centre of the Raudhatain and umm Al Aysh aquifers, (46.67^o Longitude, 29.90^o Latitude) and (47.78^o Longitude, 29.80^o Latitude), respectively. After the centre of the aquifers were located within the watershed, the sub basins that are located around the centre of each aquifer were combined to match the total area of each aquifer, 40.5 km^2 and 33 km^2, respectively. The Environmental Monitoring Information System of Kuwait (eMISK)'s GIS system (Environment Public Authority, n.d.) initiated by the Environment Public Authority (EPA) of Kuwait, was used to collect the geographic data (centre locations and area) of the freshwater aquifers and the groundwater levels. The Raudhatain watershed has many groundwater monitoring (GWM) locations and for the collection of the observed groundwater levels data, GWM locations R-07, R-15, R-33 were chosen because they are around the watershed outlet, where the Digital Elevation Model (DEM) value is the lowest and the stream order is the highest (see Figure 1(a)).

2.1 Data Selection and Processing

The World Weather for Data Service (W3S) was used to obtain precipitation and temperature data due to its format compatibility with the SWAT model. It aggregates data from various sources, including the Integrated Multi-satellite Retrievals for GPM (IMERG) (NASA, 2020) for precipitation data, and the Climate Prediction Center of the Physical Sciences Laboratory (CPC, 2020) for temperature data. The daily relative humidity, wind speed, solar net radiation data was obtained from the Kuwait Meteorological Center and then supplemented with additional data in the missing areas from the ERA5 reanalysis (ECMWF, 2020) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The extraction rates of the freshwater aquifers were obtained from Kuwait's Ministry of Electricity and Water and Renewable Energy (MEW, 2020). The Land Use/Land Cover (LULC) map utilised in this study was derived from Sentinel-2 imagery, providing a high resolution of 10 meters. The Food and Agriculture Organization (FAO, 2022) was sourced to obtain the soil map. All datasets were processed and reprojected to Universal Transverse Mercator (UTM), Zone 38 and 39.

3. METHODS

As mentioned previously, there are no specific estimations of recharge for the Umm Al Aysh aquifer and there are estimations of the Raudhatain aquifer (Alrashidi and Bailey, 2020; Kwarteng et al., 2000; Milewski et al., 2014) using different modelling approaches. However, there are studies that estimate the recharge in the entire watershed using the SWAT model (Al-Dousari et al., 2010; Al-Senafy et al., 2013). Therefore, to accurately estimate the recharge rates separately in both aquifers, the recharge rate of the entire watershed will be estimated first and compared to studies that estimated the recharge rate in the entire watershed. After the results are shown to be similar, then the separate recharge rate simulations of the freshwater aquifers will be extracted from the model (Sub-basins 10 and 33) and compared to the extraction rates. The methodology of this study can be seen in the flowchart below in Figure 3.

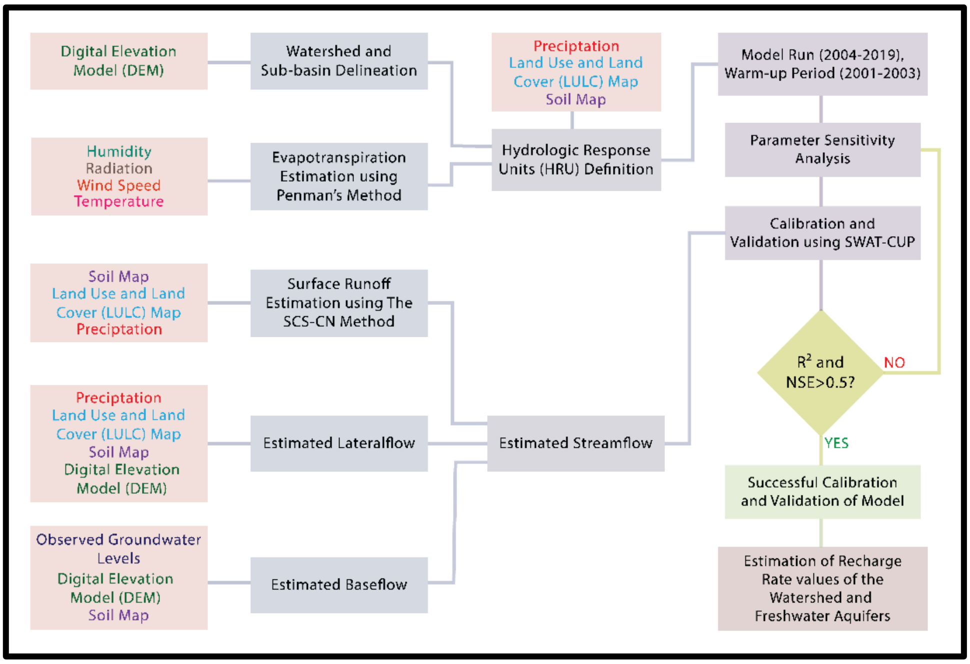


Figure 3: A flowchart showing the procedures of the methodology for this study

Once all the data is processed into the SWAT model, the model uses the water balance equation seen in Equation 1 to calculate the movement and availability of water within the watershed. These calculations allow the model to simulate how water interacts with the environment under varying land use and management conditions. Within those simulations, the model will estimate groundwater recharge in the entire watershed and the Raudhatain and Umm al Aysh aquifer. The warmup period will be 15% of the period of the available data (2001-2019), and the remaining period will be split into thirds, two thirds of the period will be for calibration (2004-2015) and the last third will be used for validation (2016-2019) as inspired by Arnold et al. (2012) in their comprehensive discussion on the calibration and validation periods on the SWAT model. To ensure the accuracy of the model, the model will be calibrated and validated using streamflow estimations because streamflow data is non-existent in the study area as stated by Milewski et al. (2014) in their study.

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \quad 1.$$

Where, SW_t is the soil water content at time t (mm), SW_0 is the initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), Q_{gw} is the amount of return flow on day i (mm).

3.1 The Estimation of Flow used for Calibration

The estimated flow used for the calibration of the SWAT model in this study is obtained by combining the calculated estimates of the 3 components of flow. The flow in SWAT is split into 3 components: surface runoff, lateral flow and baseflow (Neitsch et al., 2009), this can be seen in equation 2.

$$Q = Q_{surf} + Q_{lat} + Q_{gw} \quad 2.$$

Where, Q is the total water flow (mm/day), Q_{surf} is the surface rainfall excess (mm), Q_{lat} is the lateral flow (mm/day), Q_{gw} is the groundwater flow to the main channel (mm H_2O/day).

Many hydrological models have been created to estimate surface runoff and The Soil Conservation Service Curve Number (SCS-CN) method (USDA NRCS, 2004) is the simplest and most well-documented method, as stated by Soulis (2021) which found that after more than 60 years of modification and improvement attempts, the original formulation of the method is still mostly used. The SCS-CN method is widely used because of its suitable applicability to ungauged watersheds and because it requires only one parameter (Curve Number or CN), which is determined by soil group, surface condition and antecedent moisture condition (AMC) (Ponce and Hawkins, 1996). Since the Raudhatain watershed has infiltration rates as high as 9m/day due to the soil groups within the region (Parsons Corporation, 1964; Kwarteng et al., 2000), the SCS-CN method is shown to be the perfect approach for estimating surface runoff in the region. Equation 2 describes the SCS-CN method used in this study to estimate surface runoff in further detail.

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{R_{day} + 0.8S},\ R_{day} > 0.2S \text{ (a)} \qquad S = 25.4\left(\frac{1000}{CN} - 10\right) \text{ (b)} \quad 3.$$

Where, Q_{surf} is the surface rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), S is the retention parameter (mm), CN is the curve number.

The lateral flow seen in equation 4(a), is obtained using the DEM, LULC, soil map and precipitation data in the SWAT model. The baseflow seen in equation 4(b), is obtained using the DEM, soil map and groundwater levels. The groundwater levels are monthly observed datasets obtained in 3 GWM locations within the watershed. Further detail can be found in chapter 2 of the SWAT theoretical documentation (Neitsch et al., 2009).

$$Q_{lat} = 0.024\left(\frac{2SW_{ly,excess}K_{sat}slp}{\varphi_d L_{hill}}\right) \text{ (a)} \qquad Q_{gw} = \frac{8000K_{sat}}{{L_{gw}}^2} h_{wtbl} \text{ (b)} \quad 4.$$

Where, Q_{lat} is the lateral flow (mm/day), $SW_{ly,excess}$ represents the volume of water in the soil that exceeds the soil's capacity to hold water against gravity (mm) and is derived from precipitation data as well as the soil map, K_{sat} is the soil's permeability when fully saturated (mm/h) and is obtained the soil map, slp is the slope of the landscape and is determined from the DEM, φ_d is the drainable porosity which shows the proportion of the soil volume from which water can drain under gravity and is obtained from the soil map, L_{hill} is the length of the hill slope (m) which is the potential lateral flow discharge area and is derived from the DEM, Q_{gw} is the groundwater flow to the main channel (mm H_2O/day), L_{gw} is the distance from the ridge to the main channel within a sub-basin (m) and is derived from the DEM, h_{wtbl} is the water table height (m) and is obtained from the GWM locations.

3.2 Evapotranspiration Estimation

For the estimation of evapotranspiration, the Food and Agriculture Organization (FAO) derived an equation known as the Penman-Monteith equation, which can be seen in equation 5, that estimates net evapotranspiration (ET) from meteorological data (Djaman et al., 2018). The Penman-Monteith equation provides reliable estimates of evapotranspiration after being effectively applied and validated in arid regions (Hua et al., 2020). A study made by Lemeur and Zhang, 1990 tested three evapotranspiration methods in arid regions, they found that the Penman-Monteith equation is the most effective method due to its sensitivity to specific parameters that are crucial in arid regions. The equation has also been shown to perform well even with limited climatic data. (Djaman et al., 2018).

$$ET_0 = \frac{0.408\Delta(R_n - G_0) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad 5.$$

Where, ET_0 is the reference evapotranspiration (mm day^{-1}), Δ is the slope of the saturation vapour pressure curve at the air temperature (kPa °C^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2}day^{-1}), G_0 is the soil heat flux density (MJ m^{-2}day^{-1}), γ is the Psychrometric constant (kPa °C^{-1}), T is the mean daily temperature ($°C$), u_2 is the wind speed (ms^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure.

3.3 Groundwater Recharge Estimation

Groundwater resources are recharged by water percolating downward and then flowing through the vadose zone to replenish aquifers. The water table and the hydraulic characteristics of the prevailing geologic formations in the vadose zone, determine the amount of recharge (Neitsch et al., 2009). The land phase is vertically divided into four different control volumes in SWAT: surface, root zone, shallow aquifer, and deep aquifer (Neitsch et al., 2009). SWAT defines groundwater recharge as the downward water volume that reaches the water table of the shallow aquifer and/or deep aquifer, as shown by Ehtiat, Mousavi, and Srinivasan, 2018. Venetis (1969) proposed an exponential function to estimate daily groundwater recharge. This function seen in equation 6, has been used in this study because it captures the variability in recharge rates due to changes in precipitation, evapotranspiration, soil characteristics, and land use patterns more accurately than linear models, as stated by Jyrkama and Sykes (2007) in their comprehensive review of groundwater recharge models.

$$W_{rchrg,i} = \left\{W_{seep}\left(1 - exp\left[\frac{-1}{\delta_{gw}}\right]\right) + W_{rchrg,i-1}exp\left[\frac{-1}{\delta_{gw}}\right]\right\} \quad 6.$$

Where, $W_{rchrg,i}$ is the amount of recharge entering the aquifers on day i (mm), W_{seep} is the total amount of water exiting the bottom of the soil on day i (mm), δ_{gw} is the delay time or drainage time of the overlaying geologic formations (days) and $W_{rchrg,i-1}$ is the amount of recharge entering the aquifers on day $i - 1$ (mm).

3.4 Calibration and Validation Analysis

The parameters listed in Table 1 were chosen for this study because they cover a wide range of variables that have a major impact on groundwater recharge rates in arid areas. This study leverages insights from Gee and Hillel (1988), who critically reviewed various estimation methods, highlighting that understanding the dynamics of vegetation and soil properties, such as hydraulic conductivity, is crucial for accurately modelling groundwater recharge in arid areas. The selection of the parameters related to flow (e.g. r_SOL_AWC(..).sol, r_SOL_NO3(..).chm, r_SOL_K(..).sol) and infiltration (e.g. r_SOL_AWC(..).sol, r_SOL_NO3(..).chm, r_SOL_K(..).sol), were inspired by the study of Milewski et al. (2014) on the Raudhatain basin.

Table 2: Table of chosen parameters with their descriptions

Parameter Name	Parameter Description
r_SOL_AWC(..).sol	Available water capacity of the soil layer (%)
r__CH_N1.sub	Manning's n value for tributary channel
r__DEWPT(..).wgn	Dew point temperature, which can influence evapotranspiration (°C)
r_SOL_NO3(..).chm	Nitrate concentration in the soil layer (mg/L)
r_CH_N2.rte	Manning's n value for the main channel
r_EPCO.bsn	Plant water uptake compensation factor
r_SOL_K(..).sol	Saturated hydraulic conductivity of the soil layer (m/day)
r_ESCO.hru	Soil evaporation compensation factor
r_CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (m/day)
r__CN2.mgt	Initial SCS runoff curve number for moisture condition II
r_USLE_K(..).sol	Soil erodibility factor for the Universal Soil Loss Equation (ton/ha)
r_FLOWMIN.mgt	Minimum channel flow for baseflow (m³/s)
v__GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to begin (m)
v__GW_DELAY.gw	Groundwater delay time, the time between when water enters the aquifer and when it exits (days)
v__ALPHA_BF.gw	Baseflow alpha factor, which affects the response of groundwater flow to recharge
r__CH_K1.sub	Effective hydraulic conductivity in tributary channel alluvium (m/day)

The Coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE), as shown in Equation 7, are frequently used to assess model performance (Moriasi et al., 2007). Both performance metrics were used to evaluate the model's performance in this study, and for successful calibration and validation, these metrics must score higher than 0.5 (Moriasi et al., 2007). The observed variable is the estimated streamflow, and the simulated variable is the simulated streamflow.

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - S_i)(S_i - \bar{S})}{(\sum_{i=1}^{n}(O_i - \bar{O})^2)^{0.5}(\sum_{i=1}^{n}(S_i - \bar{S})^2)^{0.5}}\right]^2 \text{(a)} \qquad NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \text{(b)} \qquad 7.$$

Where, R^2 is the coefficient of determinations, NSE is the Nash-Sutcliffe efficiency, O_i is observed variable, S_i is simulated variable, $\bar{O}$ is mean of observed variable, $\bar{S}$ is mean of simulated variable, n is number of observations under consideration.

4. RESULTS

4.1 Parameter Selection and Sensitivity Analysis

The parameters are ranked on a scale of 1-16 from most sensitive to least sensitive. The sensitivity is determined by two statistical measures: the t-statistic and the P-value. Green (1977) showed in their analysis of multivariate methods that the t-statistic indicates the strength and direction of the parameter's influence, therefore the high absolute values suggest a stronger influence. Meanwhile, the P-value measures the statistical significance of this influence, with lower values indicating a higher likelihood that the parameter's effect is meaningful and not due to random variation. Table 3 below provides a comprehensive overview of the parameters analysed by showing their fitted values, sensitivity ranking, and statistical significance.

Table 3: Table of parameter values and rankings based on sensitivity analysis

Ranking	Parameter Name	Fitted Value	Minimum Value	Maximum Value	P-Value	t-stat
1	r_SOL_AWC(..).sol	0.78	0	1	0.0000	-9.4378
2	r__CH_N1.sub	9.87	0.01	30	0.0000	6.6589
3	r__DEWPT(..).wgn	21.24	-50	25	0.0254	-2.2987
4	r_SOL_NO3(..).chm	89.71	0	100	0.1103	-1.4962
5	r_CH_N2.rte	0.09	-0.01	0.3	0.1302	1.3418
6	r_EPCO.bsn	0.99	0	1	0.2005	-1.1984
7	r_SOL_K(..).sol	1988	0	2000	0.2907	-1.0089
8	r_ESCO.hru	0.99	0	1	0.3109	1.0023
9	r_CH_K2.rte	399	-0.01	400	0.3204	-0.9987
10	r__CN2.mgt	96.37	35	98	0.3406	-0.0976
11	r_USLE_K(..).sol	0.64	0	0.65	0.5201	0.7012
12	r_FLOWMIN.mgt	77.96	0	100	0.5304	-0.6698
13	v__GWQMN.gw	4992.02	0	5000	0.5802	0.5023
14	v__GW_DELAY.gw	497.7	0	500	0.6205	-0.3997
15	v__ALPHA_BF.gw	0.99	0	1	0.6607	0.3496
16	r__CH_K1.sub	289.65	0	300	0.6067	0.3014

When calibrating the model, the available water capacity of the soil layer unsurprisingly was the most sensitive parameter. This corelates with the findings of Kwartenget al., 2000 when they found that the region has very high infiltration. The parameter value selection was inspired by the methodology of Milewski et al. (2014), the parameters related to infiltration (e.g. r_SOL_AWC(..).sol, r_SOL_NO3(..).chm, r_SOL_K(..).sol) were increased and the parameters related to flow (e.g. r__CH_N1.sub, r_CH_N2.rte, r_CH_K2.rte) were reduced to eliminate runoff at the GWM locations (Watershed outlet). However, because of the different methodology, additional parameter adjustments were needed to align with the combination of baseflow, lateral flow and surface runoff as streamflow. The parameter which affects how quickly the aquifer contributes to stream baseflow (v__ALPHA_BF.gw) was increased and the parameter that represents the delay in groundwater's contribution to streamflow (v__GW_DELAY.gw) was increased. The parameter that represents the minimum amount of flow in channels (r_FLOWMIN.mgt) was increased because of the affect it had on streamflow dynamics. The parameter that represents the threshold depth of water in the shallow aquifer for return flow to begin (v__GWQMN.gw) was increased because of the groundwater's contribution to surface flow. These adjustments to the parameters derived the simulated streamflow, which the estimated streamflow was calibrated against, allowing for an accurate representation of both extreme drought and occasional wet periods.

4.2 Calibration and Validation of the SWAT Model

The flow estimates from section 3.1 were used to calibrate the model by aligning it with the simulated flow derived from the sensitivity analysis as shown in Figure 4. There are many zero flow values, which is unsurprising due to the region being very arid and for the integrity of this model, the zero values were included to ensure that the model can accurately predict both dry and wet conditions. Excluding zero flows could lead to a model that overpredicts flows, which would not be representative of the actual hydrological conditions in an arid environment. The warmup period (2001-2003) is not included in the calibration and validation, so that the initial condition biases do not affect the assessment of the model's performance.

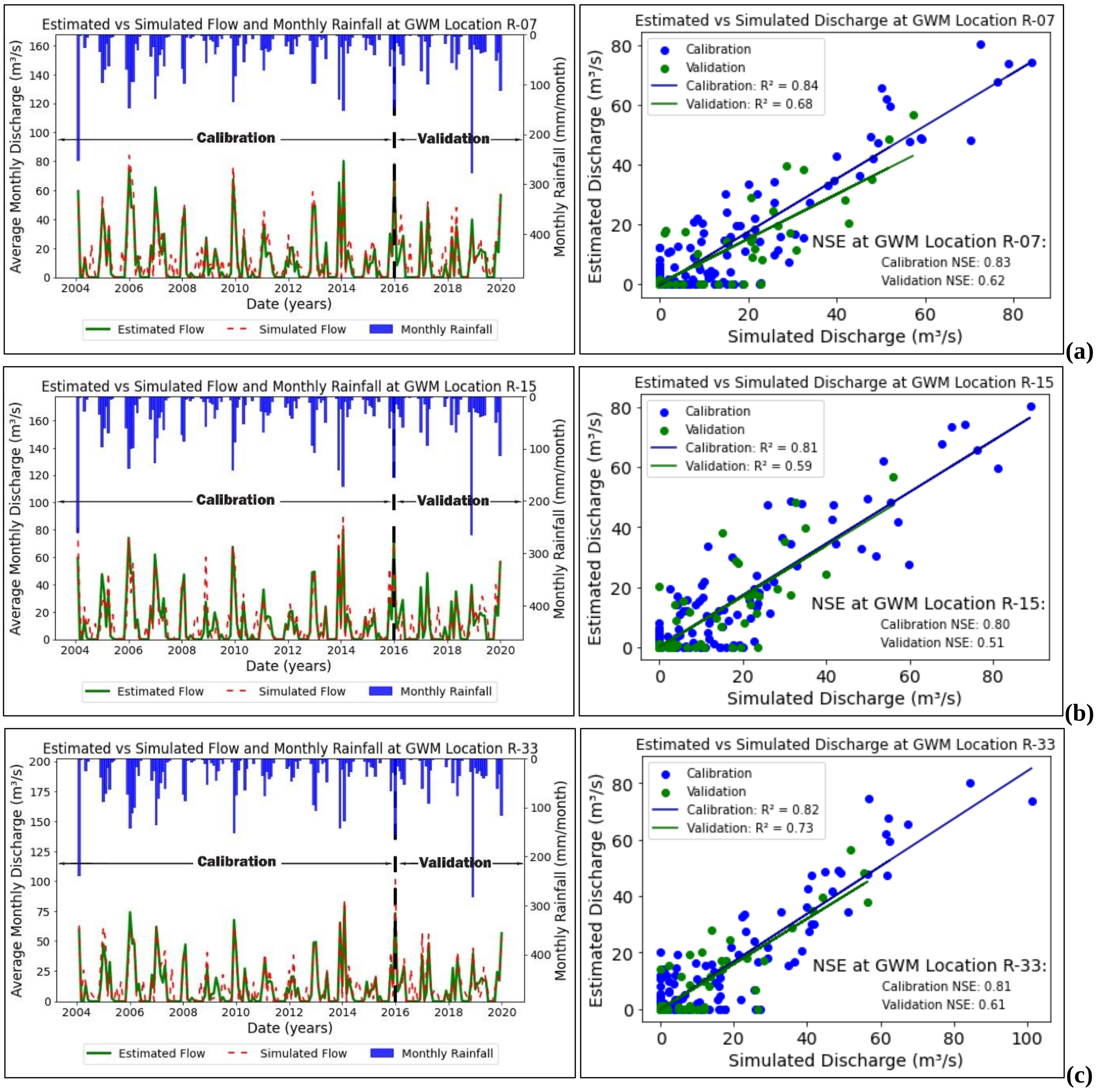


Figure 4: Graphs showing the results of the calibration and validation of the SWAT model by plotting the estimated vs simulated discharge and rainfall for (a) GWM Location R-07 and (b) GWM Location R-15 and (c) GWM Location R-33

When examining the plots of the estimated vs simulated flow and rainfall, there seems to be many similarities across all three GWM locations, which is not surprising since they are very close to each other. All the locations had increased rainfall during the winter season and very low/inexistent rainfall during the summer periods showing a seasonal trend in the region. It is also shown that there is a highly noticeable trend in high rainfall during the peak flows. The results of the model assessment were at least 0.8 for the R^2 and NSE during the calibration phase and above 0.5 for the validation phase, representing the successful calibration of a model (Moriasi et al., 2007).

However, not all the locations performed as good, GWM locations R-07 and R-33 showed fantastic results in both the calibration and validation period, whereas the GWM location R-15 had good results during the calibration period but just about acceptable results during the validation period. GWM location R-15 was in a freshwater aquifer and suggested that local aquifer dynamics might influence surface water measurements and should be integrated into the model's parameters.

4.3 Watershed Recharge Rates

Before estimating the recharge rates of the Raudhatain and Umm Al Aysh freshwater aquifers, it is essential to first model and understand the recharge rate of the entire watershed. This modelling involves a detailed water balance analysis (Table 4) to determine how precipitation is distributed throughout the watershed. Understanding this distribution is critical because it directly affects how much rainfall percolates down to recharge the aquifers versus how much is lost to runoff or evaporation. Additionally, comparing the modelled recharge rates against those derived from other studies ensures the reliability of the model.

Table 4: A Table showing the total and annual distribution of the precipitation in the entire watershed

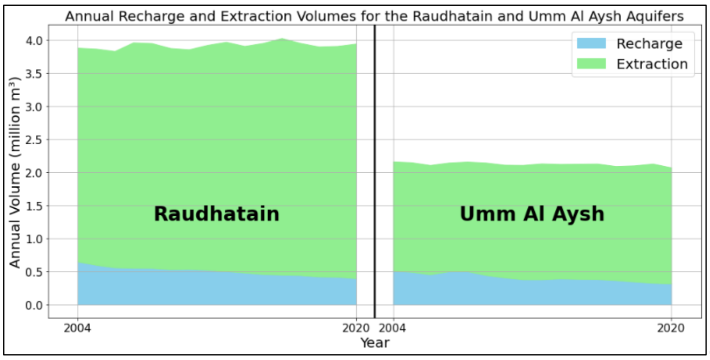
	Annual (x10^{6}m^3/year)	% of precipitation	Total of 2004-2019 (x10^{6}m^3)
Area (km)	3696.40	-	-
Precipitation	387.00	-	6192.00
Surface Runoff	81.00	21.00	1300.00
Transmission Losses	6.00	1.50	93.00
Initial Losses	277.00	71.50	4427.00
Aquifer recharge	23.00	6.00	112.5.00
Average areal recharge (mm/year)	**6.22**		

The water distribution within the watershed shown in Table 4, reveals a significant challenge in groundwater management. Only 6% of the total annual precipitation contributes to aquifer recharge, while a significant 71.5% is lost to initial losses such as soil absorption and evaporation. This highlights the limited natural replenishment of the aquifers and emphasises the need of strategic interventions to enhance water capture and minimise losses.

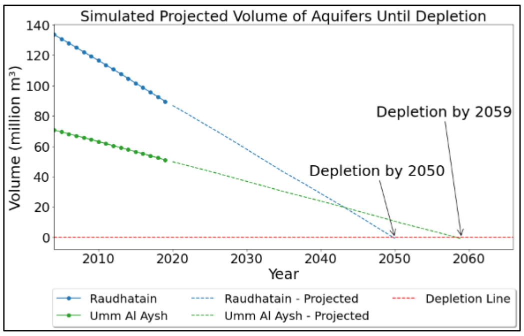
After comparing the average areal recharge value (6.22 mm/year) with other studies (Table1) done on the Raudhatain watershed, the SWAT calibration technique done in this study appears to be a viable approach for arid regions that lack streamflow data. Al-Dousari et al. (2010) and Al-Senafy et al., (2013) estimated the average areal recharge to be 12.7 mm/year for the duration 1998-2006 and 4.9 mm/year for the duration 2000-2009, respectively. Al-Dousari et al. (2010) used only surface runoff estimated from the SCS-CN (USDA NRCS, 2004) method instead of streamflow to calibrate the model in their study, whereas in this study complete streamflow was used to calibrate the model by combining surface runoff, lateral flow and baseflow estimations. However, Al-Senafy et al., (2013) calibrated their SWAT model using field-measured infiltration rates.

4.4 Water Security of the Freshwater Aquifers

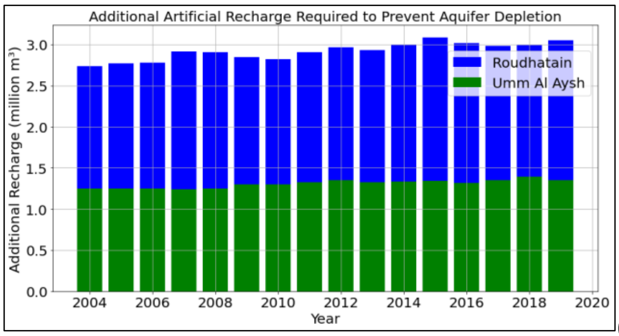
The recharge volumes during the simulation period for the Raudhatain (sub-basin 10) and Umm Al Aysh (sub-basin 33) were extracted from the SWAT model and compared to the extraction rates (MEW, 2020) of each aquifer, as shown in Figure 5(a). The annual differences of the aquifer changes (Recharge - Extraction) were combined and added to the total volumes of water in the aquifers estimated by the Parsons Corporation (Parsons Corporation, 1964). Using the gradient of the simulated aquifer volume changes line from 2004-2020, the projections of the aquifer volumes were predicted until the depletion of each aquifer, as shown in Figure 5(b). Figure 5(c) shows the artificial recharge required of each aquifer during the simulation period, this was done by finding the annual differences of the aquifer changes (Recharge - Extraction).



(a)



(b)



(c)

Figure 5: (a) A graph showing a comparison of the simulated annual recharge and extraction volumes for the Raudhatain and Umm Al Aysh aquifers during the simulation period and (b) The simulated projected volume of aquifers until depletion and (c) The estimated required additional artificial recharge required to prevent aquifer depletion

The graph seen in Figure 5(a) shows a massive imbalance between extraction and recharge, the average recharge to extraction ratio percentage for the Raudhatain and Umm Al Aysh aquifers are 14.79% and 24.05%, respectively. The average areal recharge of the Raudhatain and Umm Al Aysh aquifers is 12.35 mm/year and 13.64 mm/year, and the average areal recharge of the Raudhatain aquifer can be compared with other studies done on the aquifer which are shown in Table 1. The studies which estimated the average areal recharge of the Raudhatain aquifer (Milewski et al., 2014; Kwarteng et al., 2000) show that the areal recharge of the Raudhatain aquifer is higher than the Raudhatain watershed (Ud Din, Al Dousari and Al Ghadban, 2007; Al-Dousari et al., 2010; Al-Senafy et al., 2013), which is also proven to be the case in this study. This could be because the depression areas in the Raudhatain watershed have higher infiltration rates as suggested by Milewski et al., 2014. The study made by Alrashidi and Bailey (2020) on the Raudhatain aquifer which estimated the futuristic average areal recharge for the aquifer to be 6.67 mm/year during 2020-2120, is approximately half the value of this study.

The low recharge to extraction ratio indicates that the Raudhatain aquifer is particularly vulnerable to overexploitation and depletion. If these trends occurred from 2004 without any interventions, then the Raudhatain aquifer is expected to be depleted by the year 2050, whereas the Umm Al Aysh aquifer is expected to be depleted by 2059, as seen in Figure 5(b). The depletion of these aquifers would not only limit the availability of freshwater for domestic and agricultural use, but also elevate the water salinity in the remaining groundwater resources which contributes to several public health risks such as potential carcinogenic effects due to bromate contamination in drinking water (Alomirah et al., 2019).

The graph seen in Figure 5(c) shows the amount of additional artificial recharge required to prevent aquifer depletion, these can serve as a critical benchmark for policy-makers to set targets for artificial recharge projects. The amount of artificial recharge required to ensure the long-term safety of the Raudhatain and Umm Al Aysh freshwater aquifers is 3.0 million m^3 and 1.5 million m^3, respectively, while prioritising the Raudhatain aquifer. Sustainable recommendations should focus on maximising the utilisation of the sparse rainfall in Kuwait for artificial recharge through sustainable management practices that promote water reuse and recycling.

5. DISCUSSION

Streamflow estimations were found to be successful for calibrating a SWAT model in the Raudhatain watershed where observed streamflow data is unavailable due to the aridity of the climate. This success comes from the flexibility of the SWAT model, which allows for innovative techniques of integrating various data types to provide accurate estimations of missing data. The SWAT theoretical documentation (Neitsch et al., 2009) showed that streamflow in SWAT is split into 3 components: surface runoff, lateral flow and baseflow. The missing observed streamflow data was replaced with estimations seen in section 3.1 of this study to calibrate the SWAT model and the performance of the model was assessed using the Coefficient of determination (R^2) and Nash-Sutcliffe (NSE). The parameterisation process was inspired by the methodology of the study by Milewski et al. (2014) on the Raudhatain basin, were the parameters related to infiltration (e.g. r_SOL_AWC(..).sol, r_SOL_NO3(..).chm, r_SOL_K(..).sol) were increased and the parameters related to flow (e.g. r__CH_N1.sub, r_CH_N2.rte, r_CH_K2.rte) were reduced to eliminate runoff at the GWM locations (Watershed outlet). The results of the model assessment were at least 0.8 for the R^2 and NSE during the calibration phase and above 0.5 for the validation phase, representing the successful calibration of a model (Moriasi et al., 2007).

The estimated average areal groundwater recharge rates in this study of the Raudhatain watershed (6.22 mm/year), and the Raudhatain (12.35 mm/year) and Umm Al Aysh (13.64 mm/year) freshwater aquifers, prove the reliability of the streamflow estimations, after analysing and comparing the results with other studies done on the Raudhatain basin seen in Table 1. The SWAT modelling studies on the Raudhatain watershed by Al-Dousari et al. (2010) and Al-Senafy et al., (2013) show similar results to this study, they estimated the average areal groundwater recharge rates of the Raudhatain watershed to be 12.70 mm/year and 4.90 mm/year, respectively. Additionally, Al-Senafy et al., (2013) showed using hydrographs, that the recharge rates at the Raudhatain and Umm Al Aysh depressions (12.5 mm/year) were higher than the watershed, proving that the aquifer depressions yield more recharge than the entire watershed and is the case in this study.

On the other hand, the accuracy of the streamflow estimations in SWAT depends on the quality and resolution of the input data rather than the outputs and findings of the study, because the streamflow estimations are a product of the input data used in this study. The integration of high-resolution input data such as the Digital Elevation Model (DEM), land use data, and soil characteristics, directly influence the precision of the runoff and flow paths simulated by SWAT. The accuracy of these estimations depends on how well these inputs represent the actual conditions within the watershed. The parameterisation feature of the SWAT model which allows the adjustment of the parameters that contribute to streamflow, enabled the model to be finely tuned to reflect the specific hydrological behaviours observed in arid regions. This study showed that the streamflow estimations can be accurate enough to be used for the calibration of a SWAT model in arid regions, where observed streamflow data is unavailable. However, this methodology should not be seen as universally applicable without adjustments for local conditions and specific watershed characteristics.

5.1 Sustainable Management Recommendations

The results of this study indicate that there is a massive imbalance between extraction and recharge in the Raudhatain and Umm Al Aysh freshwater aquifers. The simulated recharge in this study was compared to the extraction rates obtained from Kuwait's Ministry of Electricity and Water and Renewable Energy (MEW, 2020) and the average recharge to extraction ratio percentage for the Raudhatain and Umm Al Aysh aquifers are 14.79% and 24.05%, respectively. If these trends occurred from 2004 without any interventions, then the Raudhatain aquifer is expected to be depleted by the year 2050, whereas the Umm Al Aysh aquifer is expected to be depleted by 2059. The water securities of these aquifers are dangerously at risk if current management practices are not revised, and sustainable measures are not implemented.

The current management practices for artificial recharge which involves the injection of water into both carbonate and clastic aquifers (Mukhopadhyay, Székely, and Senay, 1994), need to be revised to enhance the effectiveness and sustainability of water resource utilisation in Kuwait's arid environment. The findings of this paper suggest that the amount of artificial recharge required to ensure the long-term safety of the Raudhatain and Umm Al Aysh freshwater aquifers is 3.0 million m^3 and 1.5 million m^3, respectively, while prioritising the Raudhatain aquifer. This study recommends maximising the utilisation of the sparse rainfall in Kuwait for artificial recharge through sustainable management practices that promote water reuse and recycling.

Instead of adding more recharge wells in the freshwater aquifers as proposed by Ud Din, Al Dousari and Al Ghadban (2007), the creation of shallow infiltration ponds in the aquifers known as Chaukas, is a better approach for enhancing groundwater recharge, as proven to be effective for arid regions by the Yadav et al. (2021) study. This proposal ensures that water collected during rare rainfall events is effectively captured and gradually released into the aquifers, thus enabling better infiltration and minimal surface runoff. This approach not only maximises the use of natural precipitation, but also helps in maintaining higher groundwater levels over time. Using such infiltration techniques can prevent the exposure of the aquifers to pollutants that might be present in surface water. Additionally, this management recommendation aims to promote sustainability, water reuse and recycling, and cleaner recharge sources.

5.2 Limitations of the study

This study relied on comparing the recharge rates simulated, to other studies done on the region to justify the reliability of the methodology, due to the missing observed streamflow data to validate the streamflow estimations. This reliance is valuable for contextual validation but introduces potential biases or errors if those comparative studies themselves are based on assumptions or data that may not be entirely accurate or up to date. This limits the ability to accurately gauge the model's predictive reliability and could potentially lead to overconfidence in the simulated results.

6. CONCLUSION

This paper presents findings on the groundwater management challenges in Kuwait using streamflow estimations for the calibration of a SWAT model to estimate the groundwater recharge in the Raudhatain basin, during the (2004-2019) period. The recharge rate estimations of the Raudhatain watershed (6.22 mm/year) prove the reliability and accuracy of the streamflow estimations used to calibrate the model, after making several comparisons to other studies done on the watershed. However, this methodology should not be seen as universally applicable without adjustments for local conditions and specific watershed characteristics because the accuracy of the streamflow estimations are determined by the quality of the input data used, and how well these inputs represent the actual conditions within the watershed.

The recharge rates of the Raudhatain and Umm Al Aysh aquifers were estimated to be 12.35 mm/year and 13.64 mm/year, respectively, highlighting a significant imbalance between extraction and recharge rates in these freshwater aquifers. Additionally, if the current trends continue without any interventions, the Raudhatain aquifer is projected to be depleted by 2050, whereas the Umm Al Aysh aquifer is expected to be depleted by 2059. The findings of this paper suggest that the amount of artificial recharge required to ensure the long-term safety of the Raudhatain and Umm Al Aysh freshwater aquifers is 3.0 million m^3 and 1.5 million m^3, respectively, while prioritising the Raudhatain aquifer. This study proposes the creation of shallow infiltration ponds in the aquifers known as Chaukas as a sustainable management recommendation, instead of drilling more recharge wells in the aquifers. This proposal aims to maximise the use of natural precipitation and promote sustainability, water reuse and recycling, and cleaner recharge sources.

6.1 Recommendations for further work

For further advancement in this research, future studies should aim to implement advanced monitoring and modelling techniques to provide more accurate and real-time data on aquifer levels and quality. This could include enhancing the model's spatial resolution or incorporating more detailed local data, such as soil moisture or aquifer depth changes, to improve the prediction accuracy of streamflow estimations.

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