Sustainable Solutions for the Drying Up of Groundwater Wells – A Case Study in a Selected Watershed in Dampe, Sri Lanka

A.C. Dahanayake and R.L.H.L. Rajapakse

ABSTRACT

Groundwater has now become a limited resource due to the adverse impacts of various natural and anthropogenic causes. Due to the increasing population and rapid urbanization, the demand for groundwater has been ever increasing. Consequently, the occurrence of declining groundwater tables and drying up of wells have been reported in different parts of the country. In order to identify adverse impacts and facilitate early decision making, it is necessary to assess and evaluate ungauged small watersheds with simple, easy to apply but quantitative tools. This paper demonstrates the possibility of successfully applying a conceptual, lumped parameter rainfall-runoff model based on water balance approach (The ABCD model) in combination with a basic (Single Basin) HEC-HMS model to identify a comprehensive solution for the drying up of groundwater wells, for Dampe watershed (0.62km2), Sri Lanka. The model was used to carry out a quantitative analysis of groundwater storage and identify the interaction with land use pattern, and it was developed by using gathered and simulated usage and recharge data of the surface and groundwater basins. Several scenarios have been analysed using the ABCD model, in order to identify the groundwater depletion at the present condition, in the future condition (with 50% increase in the impervious area of the catchment) and the proposed solution scenario, which is to increase the pervious area of the catchment. The developed single basin HEC-HMS model has been used in order to determine the peak flow associated with a 10-year re-turn period storm event. Remedial measures to overcome the problem and sustainable methods to preserve water for the future generation are proposed based on the findings of the study.

KEYWORDS: Groundwater depletion, ABCD model, scenario analysis, sustainability

1. Introduction

Groundwater, being the most widely used source of obtaining water in Sri Lanka (Hettiarachchi, 2008), has now become a limited resource due to the adverse impacts of various natural and anthropogenic causes. Due to the increasing population and rapid urbanization, the demand for groundwater has been increasing drastically. In addition, the number of shallow and deep wells extracting groundwater has increased during the last few decades (Panabokke & Perea, 2005). In consequence of unplanned and excessive use of groundwater resources, and due to the absence of means to regulate the usage of groundwater, drying up of wells have occurred (Endersbee, 2006). In Sri Lanka, since most of the groundwater wells were constructed neglecting the appropriate technical norms, drying up of those have been experienced very often, along with a lowering of the groundwater tables in the respective areas (Jayakody, et al., 2006). Since groundwater is a limited resource, sustainable methods of extracting this invaluable resource with proper utilization control and future development plans must be adopted (International Water Management Institute (IWMI), 2005).

2. Methodology

2.1. Study Area

Dampe watershed (0.62 km2) located in the Kesbewa Divisional Secretariat Division of the Colombo district, Sri Lanka (Figure 1) was chosen as the study area. This ungauged watershed consists mainly of residential areas, a few industries, open forest areas, paddy fields and a wetland.

Water for most residential and industrial areas is supplied by the National Water Supply and Drainage Board (NWSDB) and few use dug wells as their main source of water. Water for cultivation of paddy is extracted from the stream and the excess is released back. Main water use sectors included water supply and sanitation, agriculture, irrigation, industries and the environment.

Water related issues were identified by conducting a reconnaissance survey including field interviews

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with community stakeholders in the watershed. After prioritizing the problems, drying up of groundwater wells has come up as the most severe problem in this watershed that requires urgent solutions. This problem has drastically affected the quantity of groundwater, not only affecting the social but also the aquatic and terrestrial environment. The entire catchment was divided into eight sub basins in accordance with the terrain and distribution of stream paths. (Figure 1).

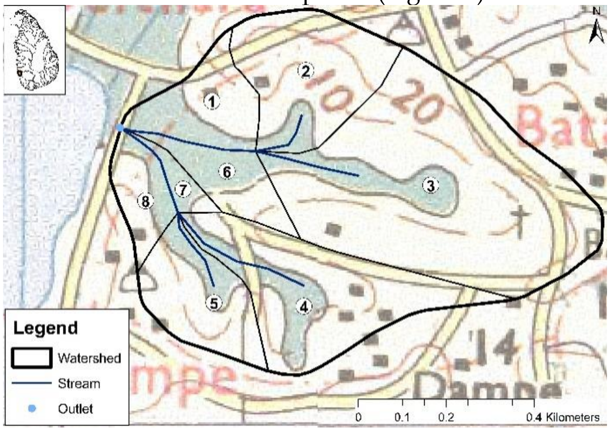

Figure 1: Delineation of Sub-catchments

2.2. Water Balance Concept

Water balance, also known as the water budget, is the application of principle of continuity at any pre-determined time interval, to a control volume. The dynamic water balance of a river basin can thus be expressed as the difference between the inflow and the outflow which is equal to the rate of change of storage, or in other terms, all water stored within the basin.

2.3. The ABCD Water Balance Model

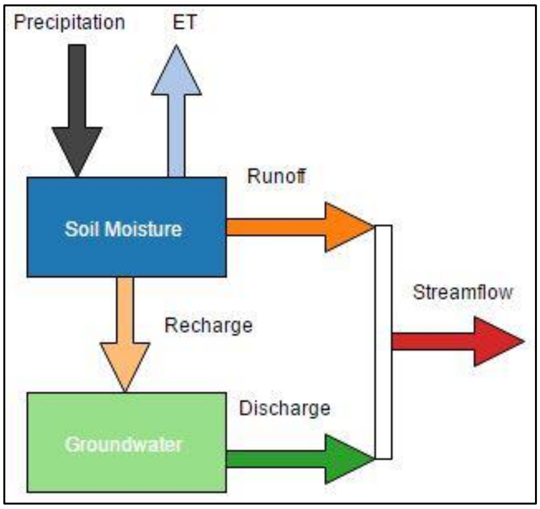

Figure 2: ABCD Water Balance Model

The ABCD water balance model is a simple hydrologic model developed by Thomas (Thomas Jr., 1981) for simulating streamflow in response to precipitation and potential evapotranspiration.

The model is comprised of two storage compartments: soil moisture and groundwater. The soil moisture gains water from precipitation and loses water to evapotranspiration (ET), surface runoff and groundwater recharge. The groundwater compartment gains water from recharge and loses water as discharge. The total streamflow is the sum of surface runoff from the soil moisture and groundwater discharge.

2.3.1. Input Data

The model runs on a daily time step and requires input time series of precipitation, minimum and maximum air temperature, and observed streamflow. The air temperature data are used to compute potential evapotranspiration (PET) from observed air temperature and latitude, using the method described by Shuttleworth (Shuttleworth, 1993).

2.3.2. Model Parameters

The ABCD model has four parameters, a, b, c, and d, each having a specific physical interpretation. The parameter a reflects the propensity of runoff to occur before the soil is fully saturated (Thomas et al., 1983). The parameter b is an upper limit on the sum of actual evapotranspiration and soil moisture storage in a given month. Presumably this parameter depends on the ability of the catchment to hold water within the upper soil horizon. The parameter c is equal to the fraction of streamflow which arises from groundwater discharge in a given month. Over the long term, c is then defined simply as the base flow index (BFI), an index used commonly in studies which develop relationships between drainage basin characteristics and groundwater discharge to a stream channel. The reciprocal of the parameter d is equal to the average groundwater residence time (Al-Lafta, et al., 2013). The upper and lower limits of a, b, c and d were found to be (Martinez & Gupta, 2010);

$0.873 \le a \le 0.999$
$133 \le b \le 922$
$0 \le c \le 1$
$0 \le d \le 1$

2.3.3. Equations Used for the Model

Soil Moisture

$$W_t = S_{t-1}+P_t = S_t+ET_t+GR_t+DR_t \text{ -------------------(1)}$$

$$Y_t = S_t+ET_t = \left(\frac{Wt+b}{2a}\right) - \sqrt{\left(\frac{Wt+b}{2a}\right)^2 - \frac{bWt}{a}} \text{ ---------(2)}$$

$$S_t = Y_t e^{-(\frac{PETt}{b})} \text{ --(3)}$$

$$ET_t = Y_t(1-e^{-(\frac{PETt}{b})}) \text{ ----------------------------------(4)}$$

$$DR_t = (1-c)*(W_t-Y_t) \text{ ---------------------------------(5)}$$

$$GR_t = c*(W_t-Y_t) \text{ --------------------------------------(6)}$$

(Walker, 2014) where;

W_t =Available Soil Water
Y_t =Evapotranspiration Potential
P_t =Precipitation
S_t =Soil Moisture
PET_t =Potential Evapotranspiration
ET_t =Actual Evapotranspiration
DR_t =Direct Runoff
GR_t =Groundwater Recharge

Groundwater

$$G_t+GD_t = G_{t-1}+GR_t \text{ -------------------------------------}(7)$$

$$G_t = \frac{1}{1+d}\left(G_{t-1} + GR_t\right) \text{ ---------------------------------}(8)$$

$$GD_t = dG_t \text{ --}(9)$$

Where;

G_t =Groundwater Storage
GR_t =Groundwater Recharge
GD_t =Groundwater Discharge

2.4. Calibration and Validation of The ABCD Water Balance Model

Due to the unavailability of measured streamflow data in this catchment, a general streamflow data set was used for calculations. Data from 2011 to 2013 was used for calibration and data from 2009 to 2010 were used for validation of the spreadsheet version of the ABCD model. The hydrograph for observed and simulated flows, and the error/optimization coefficients including Pearson product-moment correlation coefficient (R), r-squared value (R2 or RSQ), Root Mean Squared Error (RMSE), Mean Relative Absolute Error (MRAE), and Nash–Sutcliffe model efficiency coefficient (Nash–Sutcliffe Coef.) were used for calibration and validation procedure.

The latitude of Dampe watershed (0.1183 radians) was used in the model computations.

2.5. Scenario Analysis Using the ABCD Water Balance Model

2.5.1. Present Condition

The calibrated and validated model was used to analyse the present condition of the watershed. The flow duration curve for the observed and simulated flows in the calibration and the validation period were drawn, and the 25% and 75% percent probability exceedance flow rates (m^3/s) were calculated.

2.5.2. Groundwater Depletion in the Present Condition

The model with this general data set does not accurately depict the actual situation in the Dampe watershed. Therefore, the rainfall data of the nearest rainfall gauge station - Rathmalana, was applied in the model, and the model parameter (a, b, c and d) values were changed such that the model illustrates the major problem in that watershed – the drying up of groundwater wells. The initial soil moisture storage and the initial groundwater storage were assumed to be 50 inches on 01/01/2009.

2.5.3. Future Condition (with 50% increase in Impermeable area)

The only parameter corresponding to the change in the runoff coefficient of a particular catchment is parameter "a". For the future condition model, the impervious area has been increased by 50%. As a result, the runoff coefficient will change in the future condition.

It could be assumed that there would be less forest cover and less vegetation on the land. Furthermore, most of the land area would now be covered by an impervious material. As a result, the actual evapotranspiration [ETt] will be less. In addition, the St (soil moisture storage) would be less. Therefore, according to the equation (2) the evapotranspiration potential [Yt] would now be less.

Since it is assumed the precipitation values will not be changed in the future, according to equation (1) the Wt (available soil water) will be less.

Therefore, according to the expanded equation (2) the value of parameter "a" will be increased in the future condition.

A sensitivity analysis should be carried out to find the quantitative relationship between a change of the runoff coefficient and the parameter "a". For the purpose aforementioned, the model should be run for several different catchments which have different (known) runoff coefficients. The models should be calibrated and verified using reliable data sets for those respective catchments. Then the behaviour of parameter "a" in those models with the runoff coefficient of the corresponding catchment could be plotted and the associated relationship could be established and used in subsequent modeling. This procedure has not been carried out in this project, and it has been conservatively assumed that 1% increase/decrease in the runoff coefficient results in 10% increase/decrease in the parameter "a".

The area weighted average runoff coefficient for the future condition was found to be increased by 0.096% and according to that the value of parameter "a" had to be increased by 0.96%. Therefore, in the future condition model, all the parameters were kept the same as in the present condition model, but the value of "a" had been increased by 0.96%. This increased value for "a" was applied in the calibration of the future condition model. Then the other parameter values were adjusted such that the error coefficient values give the best result, based on the selected objective function.

The calibrated model parameter values were used as the initial values of the validation period. Then the parameter values were adjusted such that, hydrograph for observed and simulated flows, and the error/optimization coefficients give best results for the validation procedure. The flow duration curve for the observed and stimulated flows in the calibration and the validation period were drawn, and the 25% and 75% percent probability exceedance flow rates (m^3/s) were calculated.

2.5.4 Groundwater Depletion in the Future Condition

The rainfall data of the nearest rainfall gauge station - Rathmalana, was applied in the model, and the model parameter (only b, c and d) values were changed such that the model illustrates the groundwater depletion. In this (groundwater related) future condition model, all the parameters were kept the same as in the (groundwater storage related) present condition model, but the value of "a" was increased by 0.96% (as found earlier under section 2.5.3).

This value for parameter "a" was applied in the calibration of the future condition model used in assessing the possible groundwater depletion. The initial soil moisture storage and the initial groundwater storage were assumed to be 30 inches on the starting date.

2.5.5 Solution Scenario (Impermeable area in the present condition is reduced by 50%)

As a solution to the prevailing problem of groundwater depletion of the catchment, it has been proposed to reduce the impervious area by 50% by using pervious paving materials. It was found that in the solution scenario, the runoff coefficient will be decreased by 0.096%, and hence "a" would be decreased by 0.96%. Therefore, in the solution scenario model, all the parameters were kept the same as in the present condition (groundwater depletion) model, but the value of "a" has been decreased by 0.96%. This reduced value for parameter "a" was applied in the solution scenario model for assessing the impact on the groundwater storage under the future scenario.

The other parameter values (b, c and d) values were also kept unchanged such that the model illustrates the future conditions that would lead to the drying up of groundwater wells. The initial soil moisture storage and the initial groundwater storage were assumed to be 50 inches on 01/01/2009.

2.6. A Basic (Single Basin) HEC-HMS Model for the Dampe Watershed

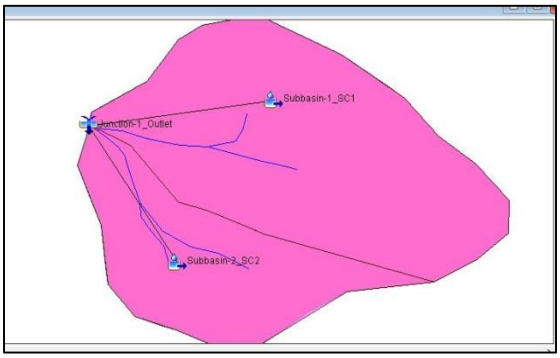

Figure 3: The HEC-HMS Basin Model

A single basin HEC-HMS model for the data of the Dampe watershed was prepared, in order to determine the peak flow associated with a 10-year return period storm event. For simplification, the entire catchment was divided into two sub basins in accordance with the terrain and distribution of stream paths. Two basin models were created to represent current situation of the basin and future situation of the basin with the increase of impermeable area by 50%. (Figure 3).

The SCS CN (Curve Number method of the Soil Conservation Service, USA) method was used as the loss method. Curve numbers and imperious areas were calculated according to the land use of the catchment. The SCS unit hydrograph method is used as the transform method. Lag times (TL) and time of concentration (TC) for each sub catchment were calculated using Irrigation Department guidelines (Ponrajah, 1984). Since the watershed is located in a flat terrain, at any point the average gradient of the stream is taken to be less than 1%. The base flow was not modelled using this HEC-HMS model due to relatively short model duration. For the meteorological model, the precipitation was input as "specified hydrograph" and the rainfall event was estimated using the alternate block method. Evaporation has been input as monthly averages and the values have been obtained for the Colombo station (Ponrajah, 1984). The simulation time interval was selected as one minute. First, the model for the present condition was simulated and then the future condition model with the 50% increase in the impervious area was analysed.

3. Results

3.1. Present Condition

The values of the four parameters a, b, c and d, before and after calibration and validation, are tabulated in Table 1.

Table 1: Parameter Values before and after Calibration and Validation

Parameter	**Before Calibration**	**After Calibration**	**After Validation**
a	0.95	0.88	0.93
b	133.0	139.6	133.0
c	0.341	0.555	0.446
d	0.045	0.00001	0.00001

The associated error coefficients are tabulated in Table 2.

Table 2: Error Coefficients

Error Coef.	**For Calibration**	**For Validation**
Pearson	0.929	0.948
RSQ	0.863	0.900
RMSE	0.024	0.023
Nash	0.863	0.895
MAPE	0.193	0.418

The streamflow hydrographs for calibration and validation periods of the present condition model are shown in Figures 4 and 5, respectively. The flow duration curves for the calibration period and the validation period are shown in Figures 6 and 7, respectively.

For the 2011-2013 (calibration) period both low flows and high flows are over estimated. For the 2009-2010 (validation) period the low flows are under estimated and the high flows are over estimated.

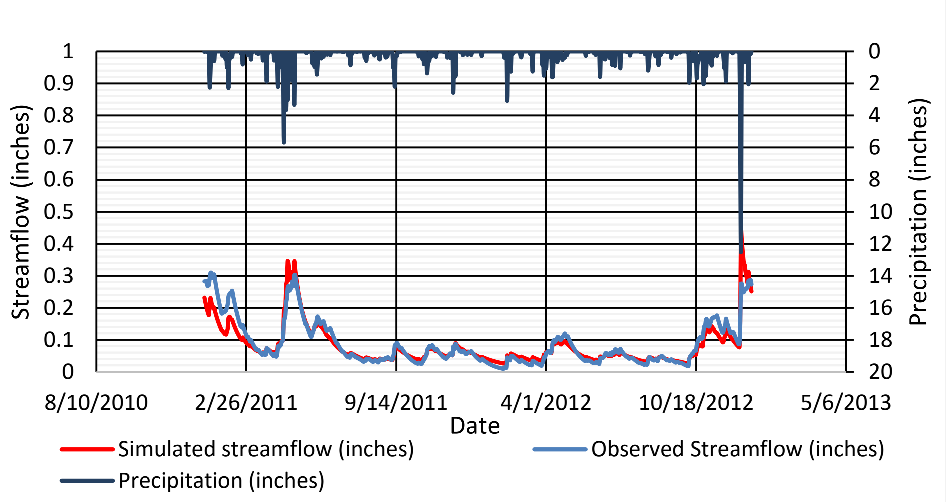

Figure 4: Hydrograph for Calibration

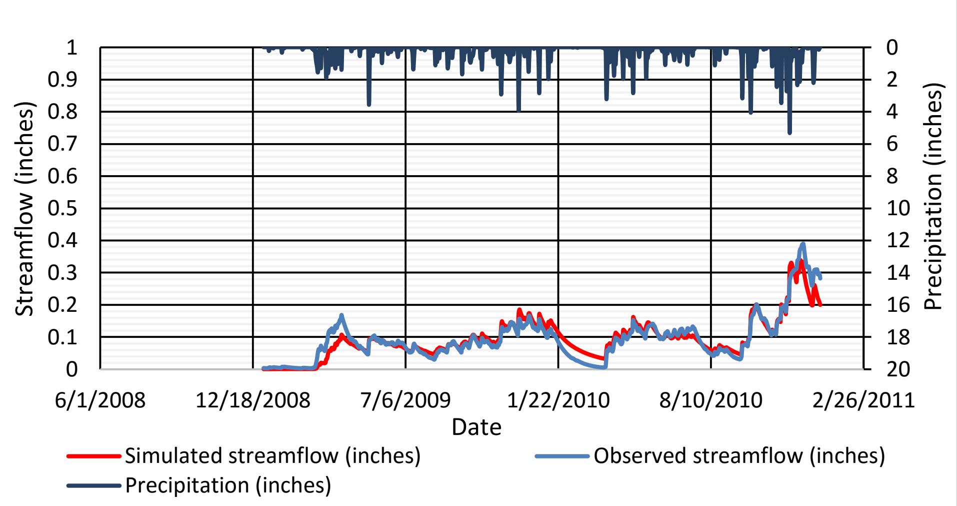

Figure 5: Hydrograph for Validation

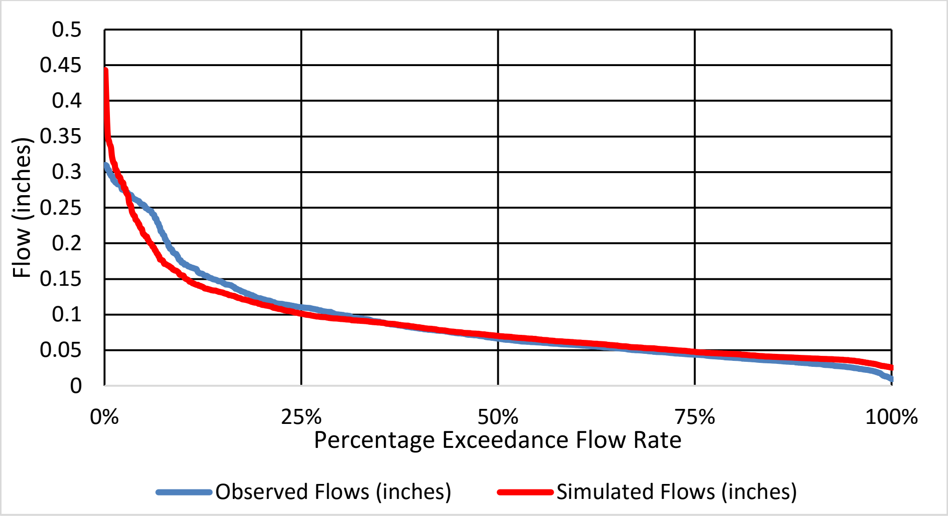

Figure 6: Flow Duration Curve for Calibration Period (2011 - 2013)

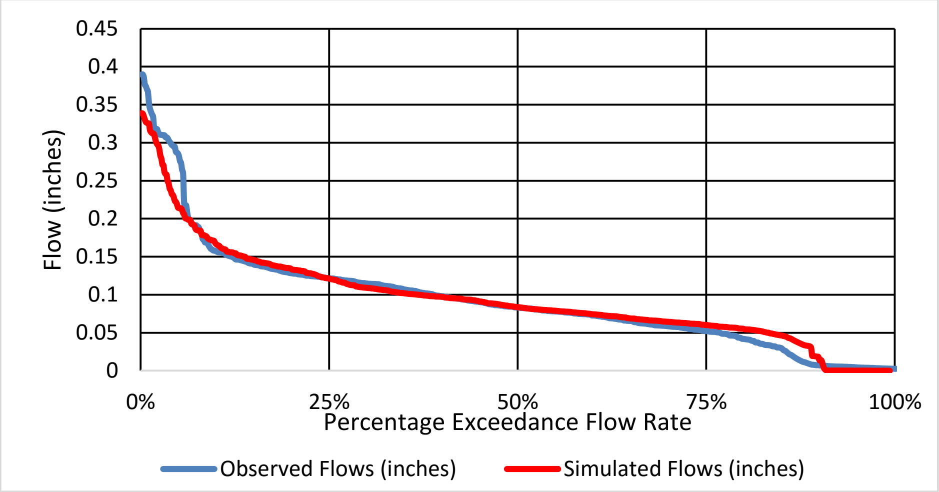

Figure 7: Flow Duration Curve for Validation Period (2009 - 2010)

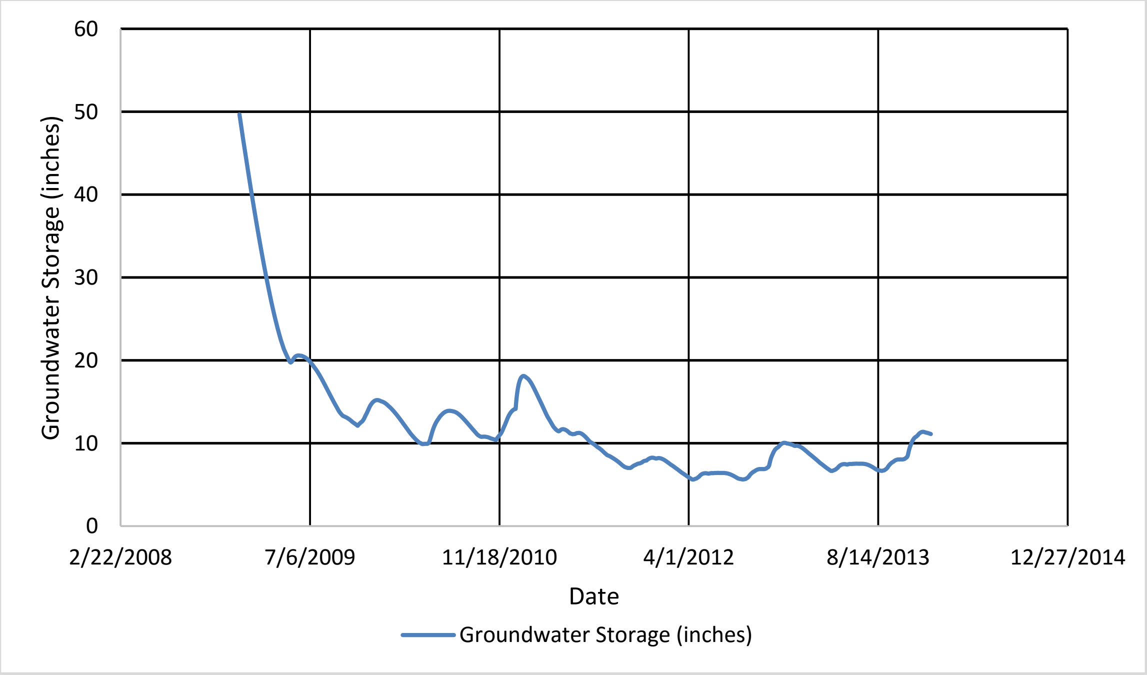

Figure 8: Variation of Groundwater Storage with Time

3.2. Groundwater Depletion in the Present Condition

The model parameter values for calibration and validation of the groundwater depletion in present condition model are listed in Table 3. The variation of groundwater storage with time in this groundwater depletion present condition model is shown in Fig. 8. Based on the results, the average value of groundwater storage was found to be 12.16 inches.

Table 3: Model Parameter Values for Calibration and Validation

Parameter	**Calibration**	**Validation**
a	0.888	0.875
b	140	600
c	0.356	0.346
d	0.01	0.01

3.3. Future Condition (Impermeable area is increased by 50%)

The values of the four parameters a, b, c and d, before and after calibration and validation, are tabulated in Table 4.

Table 4: Model Parameter Values for Calibration and Validation

Parameter	**After Calibration**	**After Validation**
a	0.888	0.927
b	139.6	133.0
c	0.555	0.445
d	0.00001	0.00001

The associated error coefficients are tabulated in Table 5.

Table 5: Error Coefficients

Error Coef.	**For Calibration**	**For Validation**
Pearson	0.927	0.949
RSQ	0.859	0.900
RMSE	0.024	0.023
Nash	0.857	0.895
MAPE	0.198	0.418

From the flow duration curves for the future condition model, for the 2011-2013 (calibration) period, both low flows and high flows are over estimated. For the 2009-2010 (validation) period, the low flows are under estimated and the high flows are over estimated.

3.4. Groundwater Depletion in the Future Condition

The model parameter values for calibration and validation of the groundwater depletion in future condition model are listed in Table 6. For this scenario, the average value of groundwater storage was found to be 10.67 inches.

Table 6: Model Parameter Values for Calibration and Validation

Parameters	**Calibration**	**Validation**
a	0.897	0.875
b	140	600
c	0.356	0.346
d	0.01	0.01

3.5. Solution Scenario (Impermeable area in the present condition reduced by 50%)

The model parameter values for calibration and validation of the groundwater depletion in future condition model are listed in Table 7. For this particular scenario, the average value of groundwater storage was found to be 12.21 inches. By considering the average values of groundwater storage in the Present, Future and Solution scenarios, it is evident that by applying the conditions of the Solution scenario, the groundwater storage could be significantly increased.

Table 7: Model Parameter Values for Calibration and Validation

Parameters	**Calibration**	**Validation**
a	0.872	0.875
b	140	600
c	0.356	0.346
d	0.01	0.01

3.6. HEC-HMS Model Results

From the results of the HEC-HMS model analysis, it was found that, the peak discharge for the total catchment in the present and future conditions are, 11.7m^3/s and 19.9 m^3/s, respectively.

4. Discussion

It is evident from the results of the ABCD model simulations that the groundwater storage varies with peaks and troughs over the time, depending on the recharge and losses. In some periods of the year, the groundwater storage depletes due to the amount of precipitation received in the basin, extraction from the wells, as well as the other losses from the groundwater storage. The increase in the groundwater storage or replenishment in some other periods of the year can also be explained similarly.

Furthermore, an insight into the rate of depletion of groundwater could be deduced by considering the average values of groundwater storage for the three scenarios that have been analysed. The average value of groundwater storage in the Present (groundwater depletion) model, Future (groundwater depletion) model and the Solution scenario model are, 12.16 inches, 10.67 inches and 12.21 inches, respectively. Therefore, the groundwater storage values will further decrease in the future. On the other hand, by increasing the pervious area (decreasing the impervious area), the rate of groundwater depletion could be reduced.

There can be numerous reasons for this decreasing trend (with time) that has been observed. Due to the increasing population with time, the water usage values will also increase. If pipe borne water is not made available, growing population masses will dig more wells in order to satisfy their water needs. The extraction rates from the existing wells may also increase due to the changes in utilization patterns. This might lead to a further decrease in the groundwater storage with time, aggravating the consequences.

Moreover, rapid urbanization will lead to continued removal the forest cover, transfer in them into urban areas, in order to facilitate and cater for the increasing demand due to escalating human needs. A decrease in the forest cover with subsequent increase in the urban area will lead to an increased runoff coefficient value, resulting in augmented runoff generation causing aggravated adverse impacts in the basin.

5. Conclusions and Recommendations

Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment. Since water sustains life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems. Effective management links land and water uses across the whole of a catchment area or groundwater aquifer.

This project mainly focused on the studying of the catchment characteristics on the recent depletion of groundwater as observed in several aquifer basins in Sri Lanka. The better awareness of depletion-recharge characteristics and role of aquifer characteristics in governing well behaviour is expected to be extremely useful in proposing sustainable new methods of preserving invaluable groundwater resources for future generations. Catchment characteristics directly and indirectly affecting the groundwater recharge pattern of the basin should be well recognized for deriving remedial measures and continuing further studies on drying up of wells. In this study, runoff coefficient was considered as a major catchment characteristic affecting this phenomenon.

Several feasible recommendations for enhancing sustainable groundwater usage in Sri Lanka have been discussed below. The policymakers and water managers should be provided with reliable information in a usable form, enabling early decision making. An island-wide assessment of groundwater resources is needed to identify where pump irrigation should be encouraged and where the danger zones are located. For areas that can be further developed, researchers must calculate all the key elements of the hydrological cycle, including recharge rates, to determine how much water can be extracted, how fast and by how many pumps (safe yield). The groundwater and surface water resources (especially tank cascade systems) should be managed jointly in the hard rock areas, which constitute a large part of the dry zone. All wells should be registered, to monitor trends in groundwater development and use. The coastal aquifers should be monitored vigilantly, as there is a danger of seawater intrusion. Monitoring and addressing agrochemical pollution of aquifers and soil salinization should be done, particularly in areas where groundwater is used for drinking and where there is not enough rainfall to flush out salts and other contaminants. The growth of the groundwater economy in areas where groundwater is renewable, and base management strategies on existing groundwater-use patterns and socio-economic conditions, must be encouraged. It should be ensured that the groundwater development activities of different government agencies and NGOs are coordinated by an apex body. The public awareness of aquifer capacities and vulnerability to pollution should be increased, especially in danger zones.

Several approaches for sustainable groundwater management plans could be adopted. One of them is the direct approaches, which include creating appropriate rules and regulatory mechanisms that can be applied to groundwater management. This includes imposing groundwater regulations and implementing limits on extraction. Another approach is based on the indirect approaches, which include; supplying agricultural subsidies, energy pricing food procurement policies, rural employment policies, agricultural trade and tariff policies, etc. The other approach type is the technical approaches, which include supply management methods such as managed aquifer recharge and rain water harvesting, as well as demand management techniques such as artificial recharge. The final approach is the awareness and education based approach, which includes community participation.

Further changes in the climate can be expected in the future. These changes may occur due mainly to the impacts on the nature caused by anthropogenic activities. As a result, we can expect a reduction in the precipitation in future in some parts of the world, including India in the South Asian groin. This reduction of rainfall will affect the groundwater storage in a drastic amount. In order to get an idea about the impact of the climate change on the groundwater storage, and the future condition model could be modified by using the precipitation values reduced by a certain percent amount.

The remedial measures that can be adopted to reduce the reduction in the groundwater storage could be further investigated. Rainwater harvesting has come up as one of the solutions for this problem. Therefore, the effect of rain water harvesting on the groundwater storage could be studied in detail.

It can be concluded that it is necessary to implement remedial actions to preserve the groundwater to our future generations. By implementing suitable measures to overcome the groundwater problems that have been encountered and managing the utilization of groundwater in a sustainable manner, satisfactory changes that would contribute to the preservation of this valuable resource in a more pragmatic way, could be expected.

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