Assessment of Groundwater Resource Utilization in Wet and Dry Zone Aquifers in Sri Lanka and Quantifying Recharge Losses due to Urbanization and Land-use Change

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ABSTRACT: In Sri Lanka, almost all people have either direct or indirect connection to the groundwater resources. Rapid urbanization, deforestation and land use changes have recently incurred adverse impacts on groundwater recharge, leading to groundwater table decline and drying up of wells. A quantitative analysis of groundwater utilization and recharge loss due to urbanization and subsequent land use change was carried out in this research. Attanagaluoya (Dunamale catchment) and Kirindioyabasin (Thanamalwila catchment) were the study areas selected in wet and dry zones, respectively. The 4-parameter “abcd” monthly water balance model was developed to be compatible with the research objectives based on the gathered and simulated stream flow, groundwater and recharge data and the calibrated and validated model was then used in further analyses and quantitative assessment of recharge loss. The results indicate severe impact on groundwater recharge in dry zone in the future. Further, sustainable groundwater management and proper land use policies to overcome groundwater recharge loss in both wet and dry zones were proposed based on scenario analyses.

1 INTRODUCTION

Groundwater is a valuable resource, often found in close proximity to the final consumers and thus widely used. Further, groundwater is extracted from different types of aquifers in both wet and dry zones for primary human needs, agricultural, commercial and industrial purposes. With rapid population growth and urbanization, buildings, roads, paved areas and areas with other surface infrastructure change the pathways of precipitation runoff and reduce recharge due to impermeable surfaces with different land use. Over-exploitation of groundwater and excessive urbanization cause many adverse effects to the environment and public as well. Drying up of wells, decrease of water quality, and increase in water extraction and utilization costs are among such crucial issues. Urbanization affects both the quantity and quality of groundwater systems. Estimation of recharge losses are necessary to identify remedial actions to be undertaken for sustainable and lasting development and utilization of these invaluable groundwater resources.

2 OBJECTIVES

- To identify groundwater utilization from different aquifers in both wet and dry zones
- To develop a method for quantifying recharge losses due to urbanization and land-use change
- To identify remedial actions to be taken for recharge replenishment of groundwater resources

3 METHODOLOGY

For the purpose of groundwater resource assessment and quantification of recharge losses occurring due to urbanization and land use change, ageneral water balance model was developed for two selected river basins in dry zone(Kirindioya-Thanamalwila catchment) and wet zone (Attanagaluoya-Dunamale catchment), respectively.

3.1 Data Collection

Monthly rainfall data and pan evaporation data were collected for 2005 to 2013 from the following hydro-ecological gauge stations from the Department of Meteorology.

Table 1. River basins data availability

Zone	River basin	Rain gauge station	Evaporation gauge station
Wet zone	Aththangaluoya (Dunamale)	Nittabuwa, Gampaha	Attanagalla
Dry zone	Kirindioya (Thanamalwila)	Thanamalwila, Lunugamwehera	Eraminiyaya

Further, the land use data was collected from the Survey Department for both Attanagaluoya and Kirindioya basins.

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3.2 Study area

3.2.1 *Attanagaluoya basin-Dunamale Catchment*

Attanagaluoya basin with an area extent of 727km^{2}is bounded by Kelani and Mahaoya river basins while the selected Dunamale catchment spreads over 153km^2. The main geological formations in the Attanagaluoya basin are laterite, consolidated sand, alluvium, peat deposits and crystalline basement rocks (Wijesekara&Kudahetty, 2005).

3.2.2 *Kirindioya basin (Thanamalwila catchment)*

Kirindioya basin is situated in the South-East part of the dry zone of Sri Lanka.The main geological formation in the Kirindioya basin is alluvial soil (Panabokke&Perera, 2005). The total area of the selected catchment (Thanamalwila) is 749km^2.

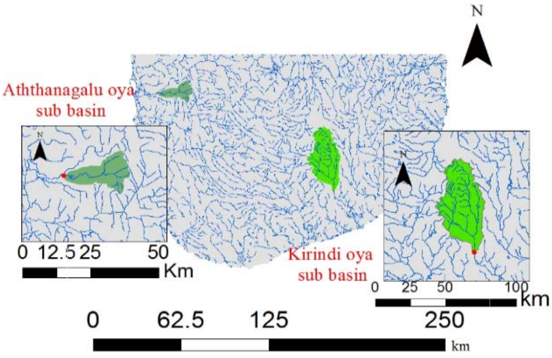

Fig 1. Study area map

3.3 Water balance model

The 'abcd' monthly water balance model which is based on mass balance concept was selected for the analysis. Inflow to the soil moisture is estimated based on the precipitation and the storage loses of water due to evapotranspiration, surface runoff and groundwater recharge. Inflow to the groundwater storage is derived from the water due to recharge and it loses water as groundwater discharge. The total stream flow is the sum of the surface runoff from the soil moisture and groundwater discharge(Harold & Thomas, 1981).

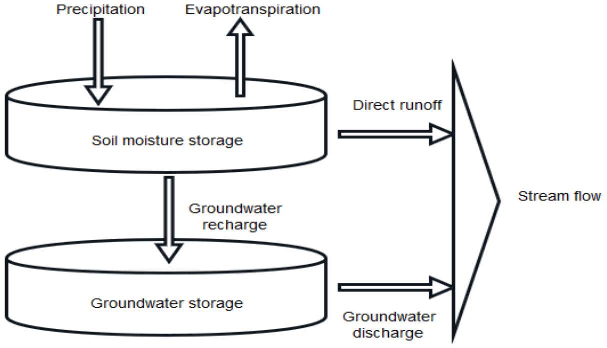

Fig. 2 Conceptual water balance model

3.3.1 *'abcd' water balance model parameters*

- "a"- represents the propensity of runoff to occur before the soil [moisture layer] is fully saturated
- "b" represents the maximum storage capacity of the soil moisture layer
- "c" represents the ratio between groundwater recharge and direct runoff
- "d" represents the reciprocal of the groundwater residence time. The length of time water spends in the groundwater portion of the hydrologiccycle. This is called "residence time" and about 2weeks in average (Freeze & Cherry, 1979).

3.3.2 *'abcd' water balance model equations*

The governing equations of 'abcd' water balance model (Griffen, 2014)can be listed as follows. Available water- W_t ,Precipitation- P , Storage- S, and in all equations, subscript denotes the time.

$$W_t = P_t + S_{t-1} \ldots\ldots\ldots (1)$$

Evapotranspiration (E) opportunity- Y_t

$$Y_t = E_t + S_t \ldots\ldots\ldots (2)$$

It is assumed that available water and evapotranspiration opportunity follow these relationships.

$$Y_t \propto (b - Y_t) \ldots\ldots\ldots (3)$$

$$W_t \propto (b - aY_t) \ldots\ldots\ldots (4)$$

$$Y_t = \frac{W_t + b}{2a} - \sqrt{\left(\frac{W_t + b}{2a}\right)^2 - \frac{W_t * b}{a}} \ldots\ldots\ldots (5)$$

In addition, it is assumed that the rate of loss of soil moisture by evapotranspiration is proportional to the potential evapotranspiration for the current month and proportionality constant is equal to S_t/b.

$$\frac{ds}{dt} = E_t * \frac{S_t}{b} \ldots\ldots\ldots (6)$$

$$E_t = Y_t\left(1 - e^{-\frac{E_t}{b}}\right) \ldots\ldots\ldots (7)$$

Direct runoff, $Q_d = (1 - c) * (W_t - Y_t) \ldots (8)$

Groundwater recharge, $R_t = c * (W_t - Y_t) \ldots (9)$

Groundwater discharge, $Q_g = d * G_t \ldots (10)$

3.3.3 *Water balance model-Mass balance*

Inflow- Outflow = Change in storage

- For the soil moisture storage layer, the mass balance equation is,

$$P_t - (E_t + R_t + Q_d) = S_t - S_{t-1} \ldots\ldots\ldots (11)$$

- For the groundwater storage layer, the mass balance equation is,

$$R_t - Q_g = G_t - G_{t-1} \ldots\ldots\ldots (12)$$

- Stream flow = Direct run off + Groundwater discharge (Base flow)

$$Q = Q_d + Q_g \ldots\ldots\ldots (13)$$

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3.4 Incorporating land use change and urbanization

To quantify recharge losses due to urbanization and land-use change, runoff coefficient (*C*) was incorporated to the model. Basically, the runoff coefficient is a function of land use pattern and land use patterns vary with time mainly due to urbanization. The river basin boundary was obtained from geographical information system (GIS) maps. Then the land use map was superimposed on it and the percentage land use areas were obtained.

According to rational formula, direct runoff value, *Q* is equal to *CiA*(Subramanya, 2006). Then the fraction of (1-*C*) *iA* value should be equal to the groundwater recharge quantity.

$$\text{Model "c"} = \frac{\text{Groundwater recharge}}{Direct\ runoff} \ldots\ldots (14)$$

$$\text{Model "c"} = \frac{(1-C)iA*x\%}{(CiA)} \ldots\ldots (15)$$

$$\text{Model "c"} = \frac{(1-C)*x\%}{C} \ldots\ldots (16)$$

The "*x*" is the portion of total infiltrated water quantity and the value of "*x*" was determined during the model calibration process.

4 ANALYSIS

Annual deforestation rate and annual population growth rate were obtained from literature and forecasted forest cover and population values for 20 years to the future and 20 years to the past, considering the base years as 2009-2013. Land use change andurbanization impact were incorporated to the model by changing runoff coefficient according to land use change. Further, water usage was applied to the model by considering the population growth and per capita water usage during a particular given time period. Annual deforestation rates (Sri Lanka Forest information and data, 2016)used in the model were;

- 1990-2000 = 1.20%
- 2000-2005= 1.17%
- 2005-2010= 1.00%

And thus, the future deforestation rate is assumed as 0.8% in average. Similarly, the following estimates were made for population growth rates in each district, as follows.

- Annual mean population growth rate- Gamphaha district (1981-2012) = 1.68%
- Annual mean population growth rate- Monaragala district (1981-2012) = 1.66%

(Source: Department of Census and Statistics- Sri Lanka, 2015)

4.1 Attanagaluoya basin

The streamflow measured at Dunamale gauging station was used for model calibration and the parameters used and simulation results are shown in Table 2, and Figs. 3 and 4 below.

Table 2. Model parameters

Model parameters	Model calibration(2005-2009)	Model validation(2009-2013)
a	0.95	0.95
b	375	375
c	0.103	0.103
d	0.46	0.46
Coefficient of determination R^2	0.8866	0.8236
Nash coefficient E	0.79	0.77

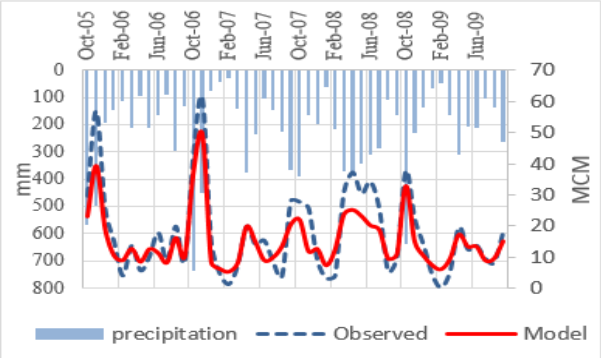

Fig. 3 Time series for simulated stream flow

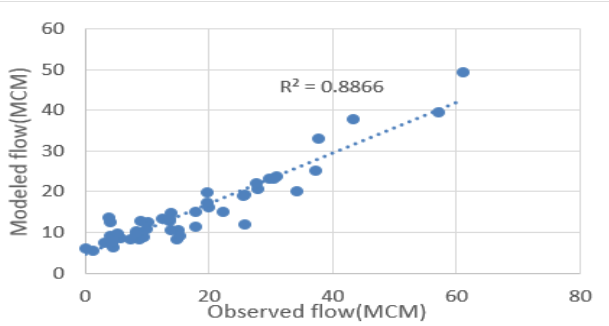

Fig. 4 Regression line- Model calibration stage

Table 3. Land use and runoff coefficients

Land use	Present % (2009-2013)	Past % (1989-1993)	Future % (2029-2033)
Coconut (C)	27.44	33.16	23.52
Forest - Unclassified (F)	0.020	0.024	0.017
Grassland	1.24	1.49	1.06
Homesteads/Garden (G)	37.28	24.32	46.23
Other (roads/ paved areas)	0.15	0.09	0.15
Paddy-abandoned	15.63	18.89	13.40
Quarry	0.004	0.000	0.000
Rubber	15.61	18.86	13.38
Scrub land	2.62	3.16	2.24
Weighted runoff coefficient	0.45	0.44	0.46

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4.2 Kirindioya basin

For Kirindioya basin, the stream flow measured at Thanamalwilagauging station was used for calibration and validation of the water balance model.

Table 4. Model parameters

Model parameters	Model calibration	Model validation
a	0.95	0.95
b	550	550
c	0.4623	0.4623
d	0.46	0.46
Coefficient of determination R^2	0.7681	0.7423
Nash coefficient E	0.7032	0.7398

In order to quantify groundwater recharge, recharge losses due to urbanization and land use change in past and future conditions, the validated 'abcd' water balance model was used. Land use change and urbanization impact were applied to the model by changing runoff coefficient according to land use change (Table 4 & 5).

Table 5. Land use and runoff coefficients

Land use	Present % (2009-2013)	Past % (1989-1993)	Future % (2029-2033)
Chena	22.795	24.73	20.60
Forest - Unclassified (F)	28.755	31.19	25.99
Grassland	0.863	0.94	0.78
Homesteads/Garden (G)	16.064	9.45	10.84
Other	0.102	0.06	0.14
Paddy-abandoned	4.824	5.23	6.51
Rock (RK)	1.642	1.34	1.74
Scrub land	24.954	27.07	22.55
Weighted runoff coeff..	0.4165	0.4202	0.4357

4.3 Introduction of rainwater harvesting method for dry zone

Rainwater harvesting can be introduced as one of the solutions for groundwater recharge loss. It is assumed that in future condition, the rainwater harvested from roof areas can be used for certain daily needs the remainder of harvested rainwater will contribute to the groundwater replenishment.

- Homestead garden area in future condition (2029-2033) = 20.43%
- Roof area (assume 50%) =20.43*0.50% = 10.21%

Future condition cumulative groundwater recharge without rain water harvesting = 42,379 Mm^3

Future condition cumulative groundwater recharge with rain water harvesting = 52,125Mm^3

% Groundwater recharge increase

$$=\frac{52125-42379}{42379} = 23\%$$

Table 6. Groundwater recharge loss (%)

Description	Base condition	Variation in groundwater Recharge-Dry zone	Variation in groundwater Recharge-Wet zone
present condition (2009-2013)	Past	3.23% decrease	3.37% decrease
Future condition (2029-2033)	Present	5.72 % decrease	3.2 % decrease

The model results show a significant future impact in dry zone (Table 6) and introduction of rainwater harvesting was shown to have a marked benefit in terms of improving groundwater recharge by 23%.

5 CONCLUSION

The 'abcd' water balance model was calibrated and validated for both wet and dry zone selected catchments with satisfactory values of R^2 and Nash coefficients. Therefore, predictions on groundwater recharge loss due to urbanization and land use change could be achieved for possible alternative water uses and management options.

It can be concluded that resulted land use change due to rapid population growth and urbanization caused decrease in the groundwater recharge and it severely affects the dry zone in the future. Rainwater harvesting can be implemented in order to increase groundwater recharge up to 23%, as shown. Further, it is necessary to implement sustainable groundwater management and proper land use policies to overcome groundwater recharge loss, conserving this invaluable resource.

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