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A Development of a 'ArcSWAT' Surface Runoff Model for Estimating Urban Precipitation Recharge

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A Development of a 'ArcSWAT' Surface Runoff Model for Estimating Urban Precipitation Recharge

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Abstract. Groundwater recharge estimation is a fundamental part of groundwater resources management and may need to be estimated at a variety of spatial and temporal scales. Recharge is variable in time, responding to changes in land use and subsurface infrastructure as well as to climatic changes. Howevera, estimating recharge in urban environments is more complex than rural environments as it has many sources and pathways for recharge. Buildings, roads, land cover permeability, and other surface infrastructure combine with man-made drainage networks to influence recharge. Thus, this study is trying out an existing GIS-based system (ArcSWAT) to model and estimate urban recharge. The unconfined Triassic sandstone aquifer that underlies part of the city of Birmingham, United Kingdom (UK) was used as the study area for this project (occupies around 94.2km^2 area). The results from this study show that SWAT model correlates better with 4RH (RMSE=17.78) as compared to UGif (RMSE=38.89) and 4ReH (RMSE=28.08). This is due to the reason that mains leakage factor has been included in 4RH and SWAT model. In summary, SWAT model produced a satisfactory result of urban precipitation recharge to the previous study that includes mains leakage factor during the modelling process.

1. Introduction

One of the essential parts in groundwater resource management is estimating groundwater recharge and may need to be estimated spatially and temporally. Recharge is usually changeable in time in response to climate, landuse and subsurface infrastructure. [1]. More than 50% of world's population now lives in cities. As urban water demand is huge, many cities are struggling to get enough water. Recharge is a critical determining factor for management of urban water supplies for cities overlying aquifers.

However, estimating recharge in urban environments is more complex than rural environments as there are many sources and pathways for recharge. Buildings, roads, land cover permeability (paved & unpaved), and other surface infrastructure combine with man-made drainage networks to influence recharge [2]. No generally accepted method is available for estimating urban recharge. Since spatial heterogeneity is a signifiacnt feature of urban areas, a GIS approach is attractive.

Thus, this study is trying out an existing GIS-based system, ArcSWAT, that has been used mainly on non-urban areas to estimate urban recharge. The objective of this study is to develop an ArcSWAT surface runoff model to estimate urban direct recharge and compare the output with the results from other recharge models of the same area.

2. Materials and approach

2.1 ArcSWAT ArcGIS extension

The ArcSWAT ArcGIS extension is a graphical user interface for the SWAT model. The ArcSWAT ArcGIS extension requires data on land use, soils, weather, water use, management, surface water, and stream data. This extension can be used to simulate a single watershed or a system of multiple hydrologically-connected watersheds. Each watershed is first divided into sub-basins and then into 'hydrologic response units' (HRUs) based on the land use, slope and soil distributions [3]. SWAT model uses water balance to simulate water routing through the system (Figure 1).

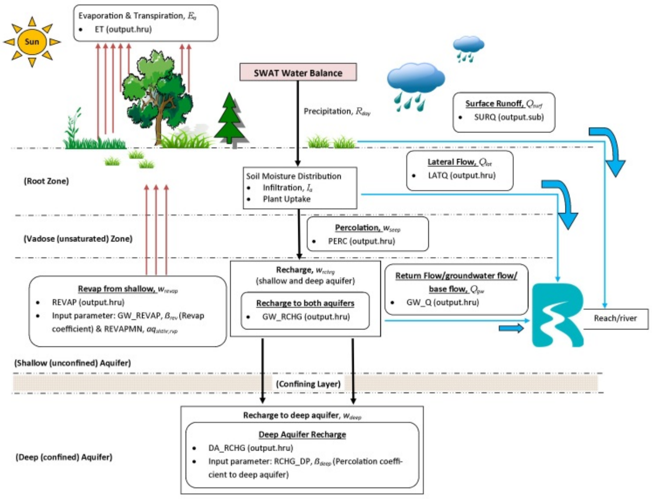

Figure 1. SWAT water routing [4]

2.2 Study Area

The unconfined part of the Triassic sandstone aquifer in Birmingham, United Kingdom (UK) has been chosen to trial ArcSWAT due to data availability. Birmingham broadly represents many long-established industrialised cities in Europe (Figure 2). The sandstone is covered by thin (0-40m) Quaternary deposits comprising clays, sands, and peat. The sandstone dips to the southeast from 0m thickness at its western feather-edge to about 150m at the Birmingham fault. The latter being the roughly northeast/southwest feature on the east of the yellow area of Figure 3. The aquifer continues beyond the Birmingham fault to the southeast, but now confined by Triassic mudstones. The whole of the unconfined region is urbanised. The time period for this study is from 1990 to 1999.

2.3 Research Approach

This study uses the runoff estimation code ArcSWAT, in ArcGIS version 10.2, as a tool to estimate recharge. Data used included: digital terrain model; soil type distribution; landcover distribution; and daily rainfall and potential evapotranspiration (PET). From landuse, soil, and topographic distributions, SWAT defined 367 HRUs and linked these into the 59 'sub-basins' depicted in Figure 3.

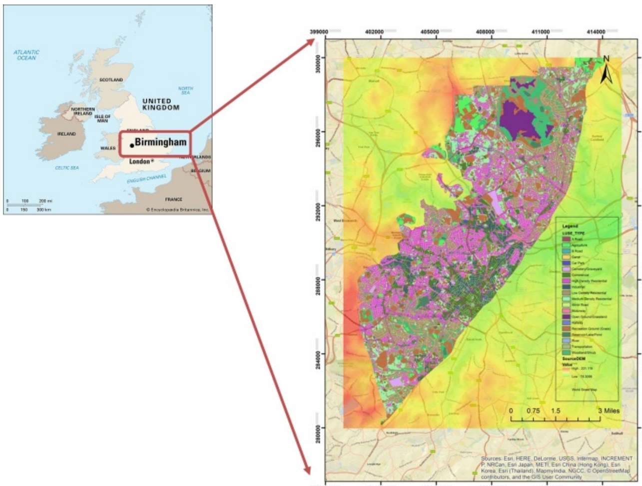

Figure 2. Study area: Unconfined sandstone aquifer in Birmingham, United Kingdom [9]

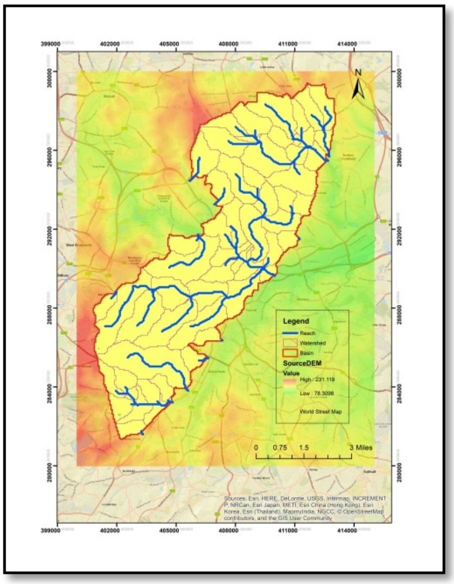

Figure 3. Watershed/catchment, rivers and sub-basins of the study area

2.4 Surface Runoff Model

Very briefly, surface runoff is calculated within SWAT at daily time steps by a modified Soil Conservation Service (SCS) curve number method or the Green & Ampt infiltration method. The curve number (CN), which is a measure of the amount of runoff, is modified in SWAT depending on antecedent soil moisture content as well as landcover[11]. The SCS curve number equation is [5]:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)}$$

where Q_{surf} is the collected runoff or rainfall excess (mm H_2O), R_{day} is the rainfall depth for the day (mm H_2O), I_a is the initial abstractions which include surface storage, interception and infiltration prior to runoff (mm H_2O), and S is the retention parameter (mm H_2O).

The retention parameter varies spatially and temporally in SWAT [11] due soil water content changes in soil, land use, management and slope. The retention parameter is defined as:

$$\mathrm{S} = \left(\frac{1000}{CN} - 10\right)$$

where CN is the curve number of the day. The initial abstraction, I_a, is normally estimated as $0.2S$. Thus, Q_{surf} is:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} - 0.8S\right)}$$

Runoff will only occur when $R_{day} > I_a$.

2.5 Recharge mechanism in SWAT model

The principal aim of SWAT is in calculating the water balance, meanwhile recharge is one of the components. Recharge is estimated through a soil moisture balance in a series of soil layers, taking into account evapotranspiration and runoff, the residue passing downwards as recharge (Figure 1). Potential evapotranspiration values in the present study were estimated using the Penman-Monteith equation.

It was assumed that water leaving the soil zone, the zone subject to evapotranspiration, then reached the water table, i.e. there was no interflow. Flow then occurred through the aquifer eventually to discharge in the 'main channel' in each sub-basin. Clearly this may not be the case in the real system, but the only alternative available is that water is transferred to a deeper aquifer that discharges outside the catchment.

The recharge on a given day is calculated using:

$$w_{rchrg,i}=(1-exp[-1/\delta_{gw}])\cdot w_{seep}+exp[-1/\delta_{gw}]\cdot w_{rchrg,i-1}$$

where $w_{rchrg,i}$ is the amount of recharge entering the aquifers on day i, δ_{gw} is the delay time or drainage time of the overlying geological units (days), w_{seep} is the total amount of water that exits the bottom of the soil profile on day i (mm H_2O), and $w_{rchrg,i-1}$ is the amount of recharge that enters the aquifer on day i-1(mm H_2O).

3. Results

The predicted SWAT model recharge to the study area was compared with the results from three previous modelling studies (Figure 4).

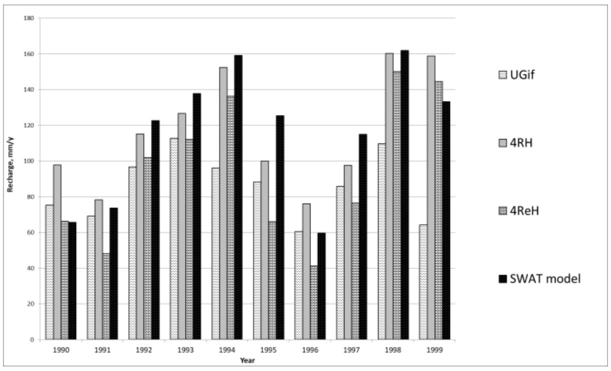

Figure 4. Comparisons of recharge estimations by three different modelling studies.

UGif 1 is a bespoke ArcView GIS based model that was developed for estimating recharge and pollutant fluxes in urban areas [9]. With this model, using land use and geological maps together with attribute tables covering meteorological data, infrastructure characteristics, chemical characteristics, and reaction constraints, surface water runoff, groundwater recharge and chemical fluxes in recharge waters were calculated.

4RH and 4ReH result from the code 4R (Rainfall, Runoff and Recharge Routing) [10] applied during the development of a regional groundwater flow model [12]. 4R estimates recharge for rural and urban areas using a soil moisture balance approach, simulating runoff, and undertaking calculations across a gridded region. It is intended to produce recharge data for regional groundwater flow models. 4RH represents recharge for historic runoff-recharge 4R model; 4ReH represents recharge for early historic runoff-recharge 4R model.

The highest average calculated recharge rate for 1990-1999 was 116 mm/y (4RH) with mains leakage. UGif recharge rates were estimated to be the lowest at 86 mm/y on average excluding leakage from water supply pipes. The SWAT model estimated the average recharge rate to be 115 mm/y meanwhile 4ReH has estimated the recharge rate as 94 mm/y. Both SWAT model and 4RH include mains leakage in recharge estimation meanwhile UGif and 4ReH exclude the mains leakage factor.

Figures 5 to 7 plot the correlation of recharge for each models (UGif, 4RH and 4 ReH) against the SWAT model. The results show that SWAT model has strong positive relationship between 4RH (R^2=0.75) and 4ReH (R^2=0.77). However, UGif (R^2= 0.54) gives a moderate positive relationship with SWAT model. The Root Mean Square of Error (RMSE) among the recharge models are presented in Table 1. A low value of RMSE indicates a better fitting model. The results show that 4RH with mains leakage factor has the lowest RMSE (17.78) than other models. Meanwhile UGif and 4ReH without mains leakage factor gives RMSE values of 38.89 and 28.08 respectively.

Table1: Comparison of model fit

Model	RMSE	Mains leakage factor
UGif	38.89	No
4RH	17.78	Yes
4ReH	28.08	No

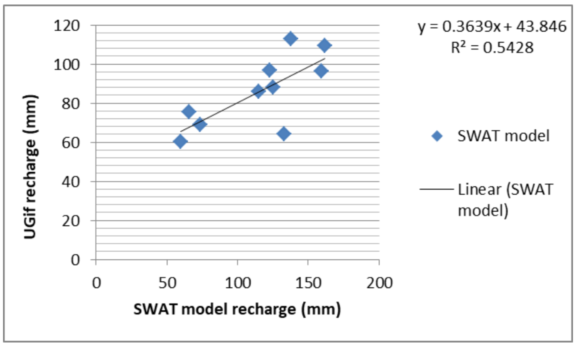

Figure 5. Correlation between SWAT model and UGif

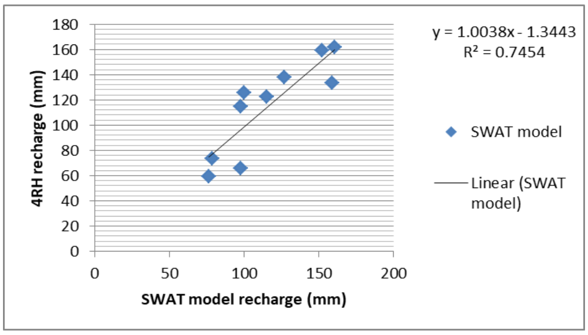

Figure 6. Correlation between SWAT model and 4RH

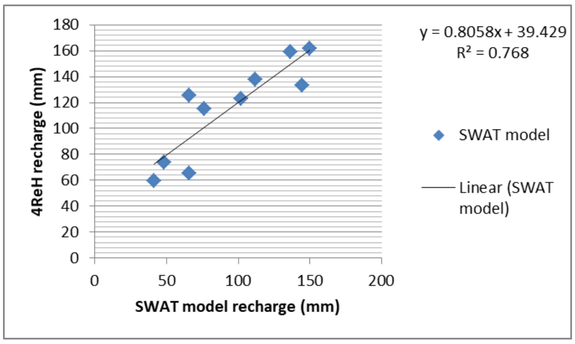

Figure 7. Correlation between SWAT model and 4ReH

4. Discussion and conclusions

Urban direct recharge, i.e. that including mains leakage (SWAT model), has been estimated using ArcSWAT ArcGIS extension, indicating that a surface water runoff model can be utilised to estimate recharge in an urban setting. The results are broadly similar to the total recharge predicted by previous models of the area, but with significant differences in some cases such as mains leakage factor.

Detailed information on groundwater recharge in space and time provide basic data for management of urban aquifers. One of the questions in this case remains: is the differences between the recharge estimates significant in terms of groundwater resources? Therefore, a future additional research would be suggested in order to understand the remaining case.

Acknowledgements

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References

[1] Lerner D N 2002 Identifying and quantifying urban recharge: A review. *Hydrogeology Journal*, **10**(1), 143–152. https://doi.org/10.1007/s10040-001-0177-1

[2] Scanlon B R, Healy R W and Cook P G 2002 Choosing Appropriate Techniques For Quantifying Groundwater Recharge *Hydrogeology Journal* **10**(1) 18–39.

[3] Winchell M, Srinivasan R, *Luzio M D, and Arnold J 2013 ArcSWAT interface for SWAT2012: User's guide* (Texas: Blackland Research and Extension Center Texas Agrilife Research)

[4] Arnold J G, Kiniry J R, Srinivasan R, 2012 Soil and Water Assessment Tool - Input/Output Documentation Version 2012 **TR-439** 1-30

[5] SCS 1972 *Soil Conservation Service Engineering Division: Hydrology In National Engineering Handbook* **4**

[6] Arnold J G, Allen P M and Bernhardt G 1993 A comprehensive surface-groundwater flow model. *Journal of Hydrology* **142** (1–4) 47–69. doi:10.1016/0022-1694(93)90004-S

[7] Zhou P, Huang J, Pontius R G, et al. 2016 New insight into the correlations between land use and water quality in a coastal watershed of China: Does point source pollution weaken it? *Science of the Total Environment* **543** 591–600. doi:10.1016/j.scitotenv.2015.11.063.

[8] Arnold J G and Allen P M 1999 Automated methods for estimating baseflow and groundwater recharge from streamflow records *Journal of the American Water Resources Association* **35** (2) 411–424. doi:10.1111/j.1752-1688.1999.tb03599.x

[9] Thomas A 2001 A *Geographic Information System methodology for modelling urban groundwater recharge and pollution* (United Kingdom: University of Birmingham Press)

[10] Entec UK Limited 2006 *Routing of Rainfall to Runoff and Recharge (4R)* (England:

[11] Neitsch S L, Arnold J G, Kiniry J R, et al. 2009 Soil and Water Assessment Tool Theoretical Documentation Version 2009 (TR 406)

[12] Daily P J J, McBride A, Rivett M, Buss S R, Davis J, Rahman A 2014. *Numerical Model Report: Birmingham Permo-Triassic Sandstone Aquifer Investigation* (Birmingham: Environment Agency by ESI Ltd.)