

# Assessment and estimation of groundwater recharge for a catchment located in highland tropical climate in central Ethiopia using catchment soil–water balance (SWB) and chloride mass balance (CMB) techniques

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Received: 16 September 2014 / Accepted: 22 January 2015 / Published online: 3 February 2015  
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**Abstract** Two commonly applied groundwater recharge estimation techniques, namely soil–water balance (SWB) and the chloride mass balance (CMB) methods, were applied and compared to quantify and analyse groundwater recharge in the Akaki catchment, located in central Ethiopia. The semi-distributed SWB method estimated natural groundwater recharge at 105 mm/a (10 % of the mean annual areal precipitation, MAAP). The chloride mass balance method applied to the same catchment estimated mean annual groundwater recharge at 273 mm/a (25 % of the MAAP). The SWB recharge value is much less than the recharge estimated by CMB method, highlighting the importance of preferential flow path recharge mechanism which is not captured by the SWB method. In situ permeability measurements undertaken as part of this research and an earlier investigation based on environmental isotopes have demonstrated that the catchment gets recharged both from direct and preferential flow recharge mechanisms which explains the discrepancy between recharge estimated through the two methods. Therefore, SWB model result which only takes into consideration the piston-type flow recharge mechanism should be taken as the minimum possible groundwater recharge for the catchment characterized by fractured aquifers. The mean recharge estimate from the two methods represents the maximum possible recharge estimate for the catchment investigated.

Although calibration of the recharge estimates was not possible, the SWB recharge estimate is found to be highly sensitive to changes in precipitation input. The findings of this research underline the fact that multiple recharge estimation methods are important to understand and capture possible recharge mechanisms and to reach to an acceptable recharge estimate.

**Keywords** Groundwater recharge · Soil–water balance · Chloride mass balance · Preferential flow · Piston-type flow · Ethiopia

## Introduction

Quantification and analysis of groundwater recharge are a prerequisite to all groundwater modelling and management exercises. Groundwater recharge which is defined as the entry of water into the saturated zone together with the associated flow away from the water table within the saturated zone (Freeze and Cherry 1979; Rushton and Ward 1979; Lerner et al. 1990, De Vries and Simmers 2002) remains one of the most challenging parameters to quantify in groundwater studies; given the diverse recharge pathways, sources, mechanism, spatial and temporal variability of the input to its analysis and quantification. However, improved information and knowledge of recharge amount and recharge sources are mandatory to ensure the long-term viability of groundwater resources and evaluate the vulnerability of aquifers to contamination.

Recharge processes can be broadly classified into direct or diffusive recharge through the unsaturated soil zone (Piston-type flow) and bypass recharge processes through fractures, joints, shrinkage cracks, sink holes, etc. (preferential flow recharge). Sources of recharge can be amongst

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others, from direct precipitation, irrigation return flow from irrigated lands, from surface water sources such as rivers and lakes, leakage from water mains and sewers in urban areas. Many studies (Scanlon et al. 2002; Kinzelbach et al. 2002; Lerner et al. 1990) subdivided the techniques of recharge estimation on the basis of three hydrologic sources or zones from which the data are obtained, namely surface water, unsaturated zone and saturated zone. Within each zone, techniques are generally classified into physical, tracer or numerical modelling approaches. A comprehensive review of each method is described in Lerner et al. (1990), Healy and Cook (2002), Scanlon et al. (2002) and Healy (2010). Many researchers (Simmers 1988; Brendenkamp et al. 1995; Sophocleous 1991; Scanlon et al. 2002) advocate the use of multiple recharge estimation methods to reduce uncertainty and increase the reliability of recharge estimates.

Rates of groundwater recharge over large areas of Ethiopia are poorly understood. However, there has been an increased demand for an accurate estimation of the spatial and temporal distribution of groundwater recharge as it is important for many types of hydrological assessments, including those that are related to aquifer replenishment, groundwater flow and contaminant transport modelling, and to understanding the impact of climate change and development in urban, industrial and agricultural regions on groundwater resources. An increasing demand for accurate estimation of groundwater recharge rates for many regions of the country means increasing the need to test and calibrate practical methods of recharge rate quantification.

Two recharge estimation methods, namely the soil–water balance (SWB) and chloride mass balance (CMB) methods, are chosen and applied in the Akaki catchment of central Ethiopia. The two methods are chosen based on the fact that they are tested and most commonly applied techniques, and because of the availability of catchment-specific input data for these methods as part of a three-and-half-year investigation and monitoring of the catchment as part of this research.

Soil–water balance (SWB) methods were first developed by Thornthwaite (1948) and later revised by Thornthwaite and Mather (1955, 1957). These models have since been adopted, reviewed, modified and applied to a number of catchments and hydrological problems (Dune and Leopold 1978; Thomas 1981; Alley 1984, 1985; Xu and Singh 1998). The SWB method calculates groundwater recharge by use of commonly available geographic information system and climatological data. The chloride mass balance (CMB) method, first devised by Eriksson and Khunakasem (1969) uses chloride concentration in rainfall, in the unsaturated zone and in groundwater to calculate a precipitation surplus or

recharge since chloride behaves as a conservative ion (Lerner et al. 1990; Appello and Postma 1993). The CMB method is a preferred method of recharge estimation due to the conservative nature, the relative abundance of chloride in precipitation and its simplicity to analyse (Allison et al. 1984). The application of the CMB method is based on comparison of the chloride concentration in precipitation with the concentration in the soil–water or groundwater. The CMB technique has been applied in recharge investigations recently by many researchers (Allison and Hughes 1978; Cook et al. 1989; Edmunds et al. 1992; Edmunds and Gaye 1994; Ting et al. 1998; Flint et al. 2002). The CMB, when used in the saturated and unsaturated zone, provides not only an estimation of the quantity of groundwater recharge, but also information about the mechanisms of recharge.

This research paper presents and discusses the results of groundwater recharge estimated through daily SWB and CMB methods for the Akaki catchment (1,464 km<sup>2</sup> in area) located in central Ethiopia based on site-specific data. This catchment is the major source of water supply for Addis Ababa (the capital of Ethiopia and Africa) from surface water and groundwater sources. The research methods, data and results reported in this paper aimed at contributing towards better understanding of recharge rates, recharge processes and informed management of groundwater resources.

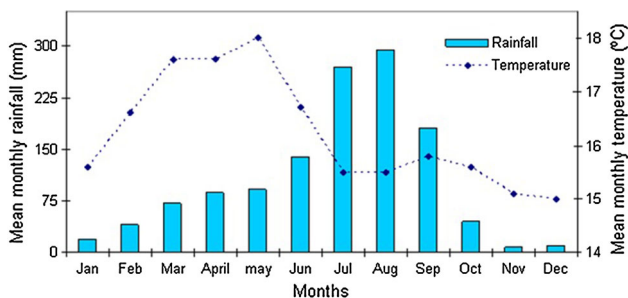
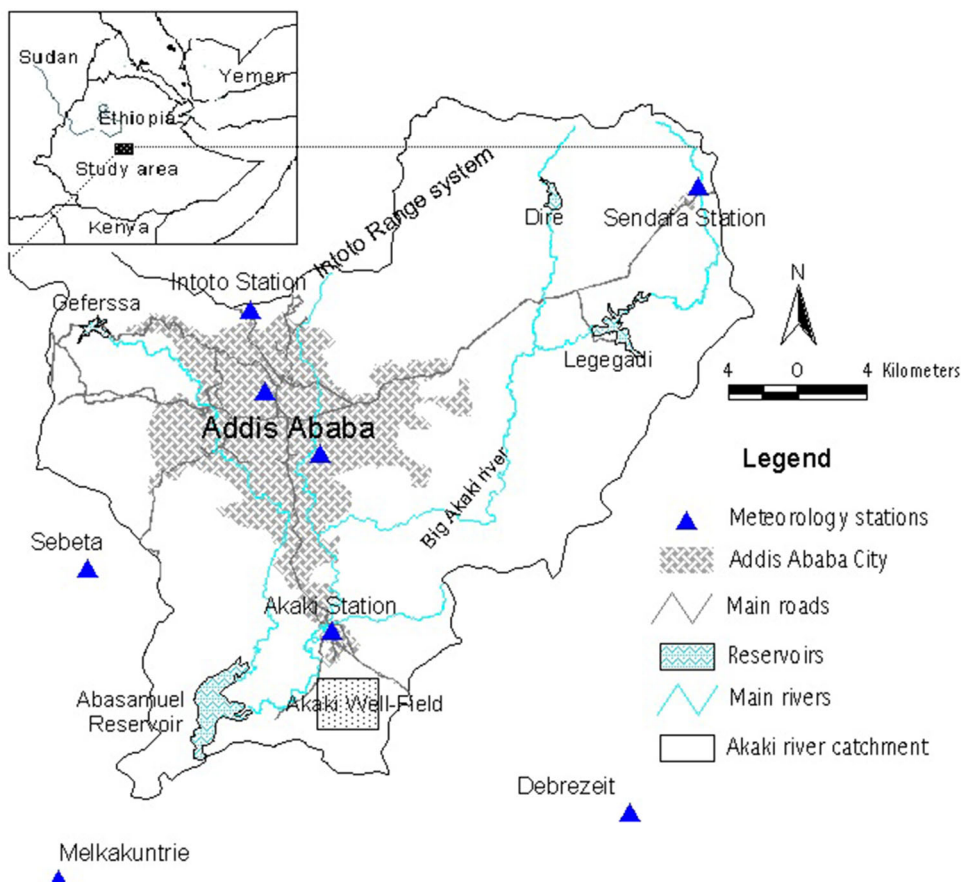
## Description of the study area

### Location and climate

The study catchment is located in central Ethiopia between 8°46′–9°14′N and 38°34′–39°04′E covering a total catchment area of about 1,464 km<sup>2</sup> (Fig. 1). The area is characterized by sub-humid temperate sub-tropical climate with two distinct seasonal weather patterns. The main wet season (monsoon) extends from June to September and contributes about 70 % of the total annual rainfall. A minor rainy season from mid-February to mid-April contributes the remaining moisture to the region. The average annual rainfall measured from the Addis Ababa Observatory is 1,254 mm. The minimum and the maximum annual average temperatures are 9.9 and 24.6 °C, respectively (Fig. 2).

The physiography of the catchment is characterized by very steep slope in the north and west, undulating topography in the central and gentle to flat in the southern part. The elevation ranges from 3,385 m above mean sea level (amsl) at the Wechecha range in the west to 3,270 m amsl along the northern watershed boundary at the Intoto Mountain range, and to 2,040 m amsl in the south downstream of Abasamuel reservoir. Volcanic mountains form

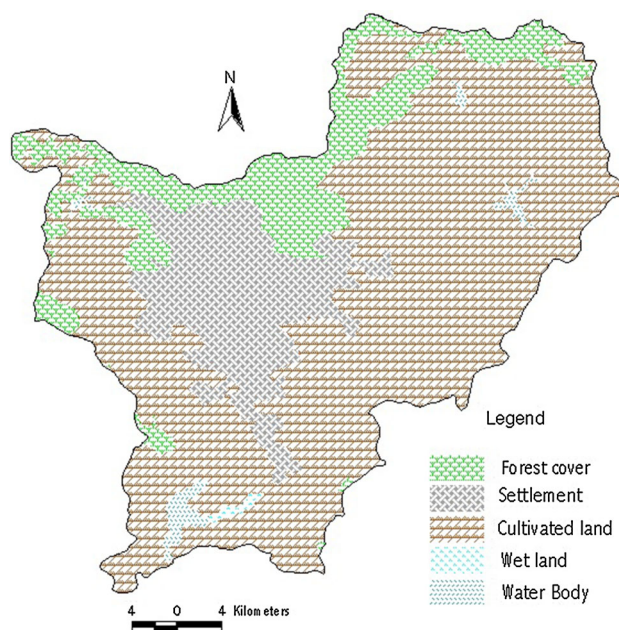
**Fig. 1** Location map of the study area in central Ethiopia



**Fig. 2** Mean monthly rainfall and temperature at the Addis Ababa Observatory

most of the watershed divide. The northern watershed is bounded by the Intoto range, the western by Mount Menagesha and the Wechecha volcanic range, the southwestern by Mount Furi, the southern by mountains of Bilbilo and Guji, the southeastern by the Gara-Bushu hills, and the eastern by the Yerer Mountain. The study catchment is drained by three perennial rivers, namely the Big Akaki, Kebena and the small Akaki Rivers.

The major land uses of the catchment based on Landsat ETM + (December 3, 1999) images and ground truth include agricultural, urban, forest and wetland/reservoir areas accounting 65, 20, 14 and 1 %, respectively (Fig. 3).



**Fig. 3** Land use-land cover map of the study catchment

The urban land use pattern is further divided into residential areas, garden, parks, market, industrial, waste dumping, airports, parking lots, petrol stations, garages,



parks, cemeteries and sporting grounds. Most of the mountains in the north, west and south-western parts of the catchment are covered by forest. The Addis Ababa city represents the settlement area and is located at about the centre of the catchment. The Agricultural land use covers wide but relatively gently sloping areas. The main soil types mapped are alluvial black cotton soil covering the lower reaches of the Akaki River, residual black cotton soils (mainly smectites) and residual lateritic soils developed in the well-drained upstream areas of the catchment (Fig. 4) The main crops grown are wheat, barley and Teff (an indigenous crop).

#### Geological and hydrogeological setting

The study area is covered by Miocene–Pleistocene volcanic succession which is mainly basalts, rhyolites, trachyte, scoria, trachy basalts, ignimbrites and tuff of varying ages and thicknesses. The age of these rocks becomes younger from the Intoto range in the north towards the rift in the south. The volcanic stratigraphy has been established by previous workers (Morton et al. 1979; Mohr and Zanettin 1988; Girmay and Assefa 1989). The rocks have been laid down at different times representing variable lithologies and forming alternating permeable and impermeable units affected by different sets of north–northeast to south–southwest trending faults which are related to the rift extensional tectonics. The rocks also show different degrees of weathering. These faults and degree of weathering

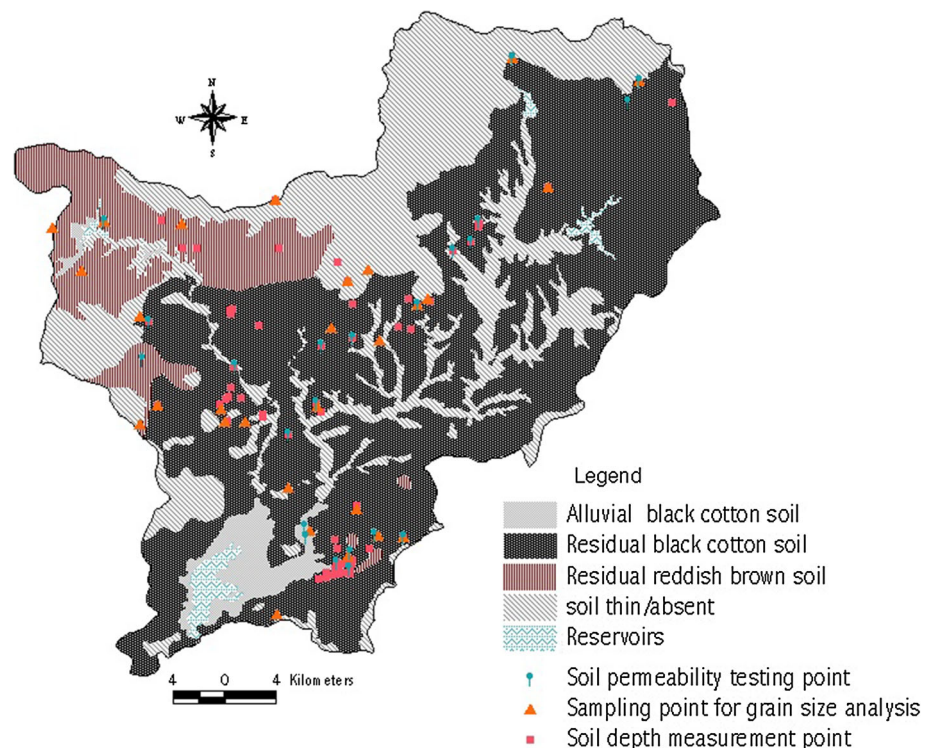
strongly control the occurrence and circulation of groundwater in the region (Demlie 2007; Demlie et al. 2008).

Well logs from boreholes drilled across the study catchment including the Akaki well field indicate that the lithology varies with depth substantially. However, due to high permeability and fracturing, the different water-bearing units are hydraulically interconnected. Pumping test data from various boreholes revealed that the groundwater system behaves as an unconfined to a leaky aquifer system. Scoria and scoriaceous basalt constitutes highly productive aquifers with high primary porosity and permeability. Weathered and fractured basalts, tuff, ignimbrite and pyroclastic materials are productive aquifers with secondary permeability. Basalt with some fractures, vesicles and sparsely spaced joints, ignimbrites and agglomerates form moderately productive aquifers (Demlie and Wohnlich 2006; Demlie 2007; Demlie et al. 2007, 2008). Average transmissivity ( $T$ ) values vary from 4.3 m<sup>2</sup>/d in low yielding areas to as high as 27,648 m<sup>2</sup>/d and average storativities range from  $6.5 \times 10^{-3}$  to  $4.31 \times 10^{-2}$  (AAWSA, BCEOM, SEURECA and Tropics 2000). Groundwater flows, which appears to be controlled by topography and regional structures, from north to south.

#### Hydro-meteorological data

Daily hydro-meteorological data for the analysis of effective depth of precipitation, evapotranspiration and recharge were obtained from the Ethiopian National Meteorological

**Fig. 4** Map showing soil types, sampling and measurement points in the study area



**Table 1** Relevant meteorological stations considered in this study (data from NMA)

No.	Station name	Altitude (m)	Location (UTM)		Data record period	Mean annual rainfall (mm)
			X	Y		
1	Intoto	2,920	470880	1003826	1983–2002	1,246
2	Sendafa	2,550	503448	1012814	1983–2002	1,117
3	Addis Ababa observatory (AAO)	2,400	471983	997941	1900–2002	1,207
4	Bole observatory (BO)	2,300	475977	993369	1983–2002	1,051
5	Akaki	2,100	476765	980390	1983–2002	991
6	Melkakuntre	2,020	456955	962314	1983–2002	944
7	Debrezeit	1,850	498467	967254	1983–2002	843

Agency (NMA) at seven different meteorological stations located within and in the immediate vicinity of the case study catchment (Table 1; Fig. 1).

The first five stations are located within the Akaki catchment, whereas the remaining two are near but out-side the catchment (Fig. 1). The AAO, Bole and Debrezeit stations have daily data of rainfall, minimum and maximum temperature, wind speed, relative humidity and sunshine duration. Intoto, Sendafa, Akaki and Melkakuntre stations have daily rainfall, and minimum and maximum temperature data. Daily solar radiation data from 1991 to 1998 is available at the Addis Ababa University Geophysical Observatory. Table 2 shows mean monthly meteorological data at the Addis Ababa Observatory.

**Methodology and approach**

Soil permeability testing

A constant-head Guelph Permeameter (Reynolds and Elrick 1986) was used to measure a composite of vertical and horizontal saturated hydraulic conductivity (*K*) at different points in the field (Fig. 4). The instrument measures *K*, soil matric flux potential and soil sorptivity (when the volumetric soil moisture content is known). The hydraulic conductivity and matric flux potential of different soils up to a depth of 75 cm were measured from March to May,

2004 to improve understanding of the spatial variations in permeability and infiltration rates of the soils across the study catchment and support the SWB and CMB methods of recharge estimation.

Soil–water balance (SWB)

The Thornthwaite-type SWB models and variants of it hereafter called the T and T $\alpha$  (Alley 1985) assume that the soil to have a particular soil moisture storage capacity,  $\Phi$ , and a state variable  $S_i$  represents soil moisture storage at the end of the time step *i* (in this case daily time step) applied in this study. In the model, moisture is either added to or subtracted from the soil depending on whether precipitation for the time step,  $P_i$ , is greater than or less than potential evapotranspiration,  $P_{et_i}$ .

Case 1: when  $P_i \geq P_{et_i}$ ,

$$S_i = \min\{(P_i - P_{et_i}) + S_{i-1}, \Phi\} \tag{2}$$

Case 2: when  $P_i < P_{et_i}$ , soil moisture deficits increase and the model of Thornthwaite and Mather (1957) based on the assumption of the relation between loss of soil moisture to evapotranspiration and potential evapotranspiration is given by Alley (1984):

$$\frac{dS}{dt} = \frac{-(P_{et_i} - P_i)}{\Phi} S \tag{3}$$

The analytical solution when,  $P_i < P_{et_i}$ , is:

**Table 2** Mean monthly meteorological data (rainfall in mm, temperature in °C, wind speed in m/s, sunshine duration in hours, and relative humidity in %) at AAO (data from NMA)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<sup>a</sup> Rainfall	17.9	39.5	71.9	86.2	90.7	138.1	269.9	293.9	181.9	44.4	8.1	9.3
Max. temp	23.8	24.9	25.1	24.6	25	23.3	21.1	21	21.8	22.8	23.2	23.3
Min. temp	8.8	10.2	11.7	12.2	12.3	11.4	11.3	11.4	11.3	10.2	8.7	8.3
Wind speed	0.71	0.74	0.8	0.71	0.69	0.45	0.37	0.34	0.46	0.75	0.76	0.73
Sun. hours	8.62	8.11	7.69	6.72	6.79	4.94	3.57	3.47	5.16	8.48	9.01	9.18
R. humidity	42.2	40	43.9	47.6	46.2	59.2	70.9	72	63.2	45.5	41	39.8

<sup>a</sup> Monthly normal rainfall (1973–2002)

**Table 3** Estimated mean monthly reference evapotranspiration (mm) through the FAO Penman–Monteith method

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Intoto	80.4	81.25	97.62	91.86	93.9	75.99	70.29	70.98	76.68	89.72	80.39	77.77	986.8
Sendafa	101	99.04	115.3	106.3	109.1	85.91	77.26	77.78	86.91	108.7	101.6	99.98	1,169
AAO	108.7	107.1	126.3	116.2	118.6	93.55	84.33	85.05	94.49	118	109.6	107	1,269
Bole	110.5	103.6	124.3	115.8	123.4	99.13	86.1	93.21	98.62	118	110.9	108.8	1,292
Akaki	117.1	108.8	128.3	121.4	130.3	105	90.82	98.15	105.3	118.7	120.3	116	1,360

$$S_i = S_i - 1 \exp\left(-(\text{Pet}_i - P_i)/\Phi\right) \quad (4)$$

The soil moisture deficit that develops at the end of the time step  $i$ ,  $D_i$ , is defined as:

$$D_i = \Phi - S_i \quad (5)$$

When precipitation for the time  $i$  exceeds the potential evapotranspiration and the soil moisture storage attains its capacity,  $\Phi$ , the excess water is assumed to contribute to the water surplus:

$$\text{Rgw} = (P_i - \text{Pet}_i) + S_i - 1 - \Phi, \quad S_i = \Phi \quad (6)$$

Otherwise,  $\text{Rgw} = 0$ , where  $\text{Rgw}$  is the addition to water surplus or groundwater recharge.

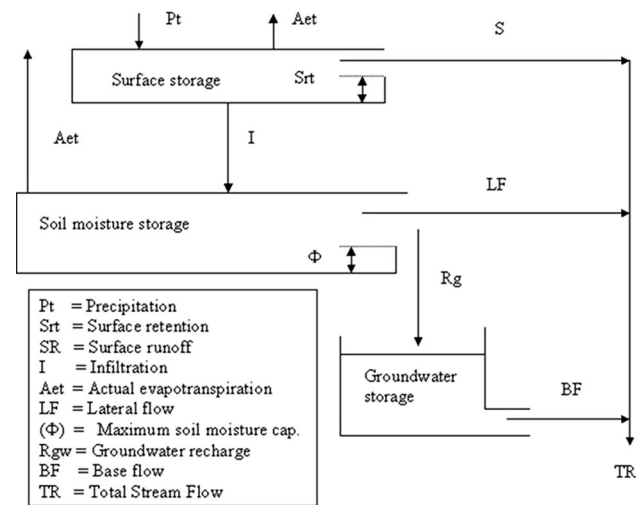
Stream flow and groundwater recharge are assumed to drive from the water surplus. Since partitioning the surplus into stream flow and groundwater storage is difficult in the above T model, a modified version of it, by assuming that some fraction,  $\alpha$ , of the precipitation for the time step (usually a day or month) is direct runoff, has been applied and the model has been referred to as  $T\alpha$  model (Alley 1984) and applied in this work, in which case the  $\text{Rgw}$  is routed into groundwater recharge or storage.

#### Evapotranspiration computation

Evapotranspiration is a collective term by which water in the liquid or solid phase becomes atmospheric water vapour. It includes both evaporation from open water bodies and from land, and transpiration by vegetation. Evapotranspiration is a physical process which is affected by solar radiation, temperature, wind speed, atmospheric pressure, water vapour capacity of the air and supply of moisture at the evaporating surface and is probably one of the most difficult to quantify amongst the many phases of the hydrologic cycle. An attempt is made in the following section to estimate evapotranspiration for the study catchment which will be input to the SWB model.

#### Reference crop evapotranspiration (ET<sub>o</sub>)

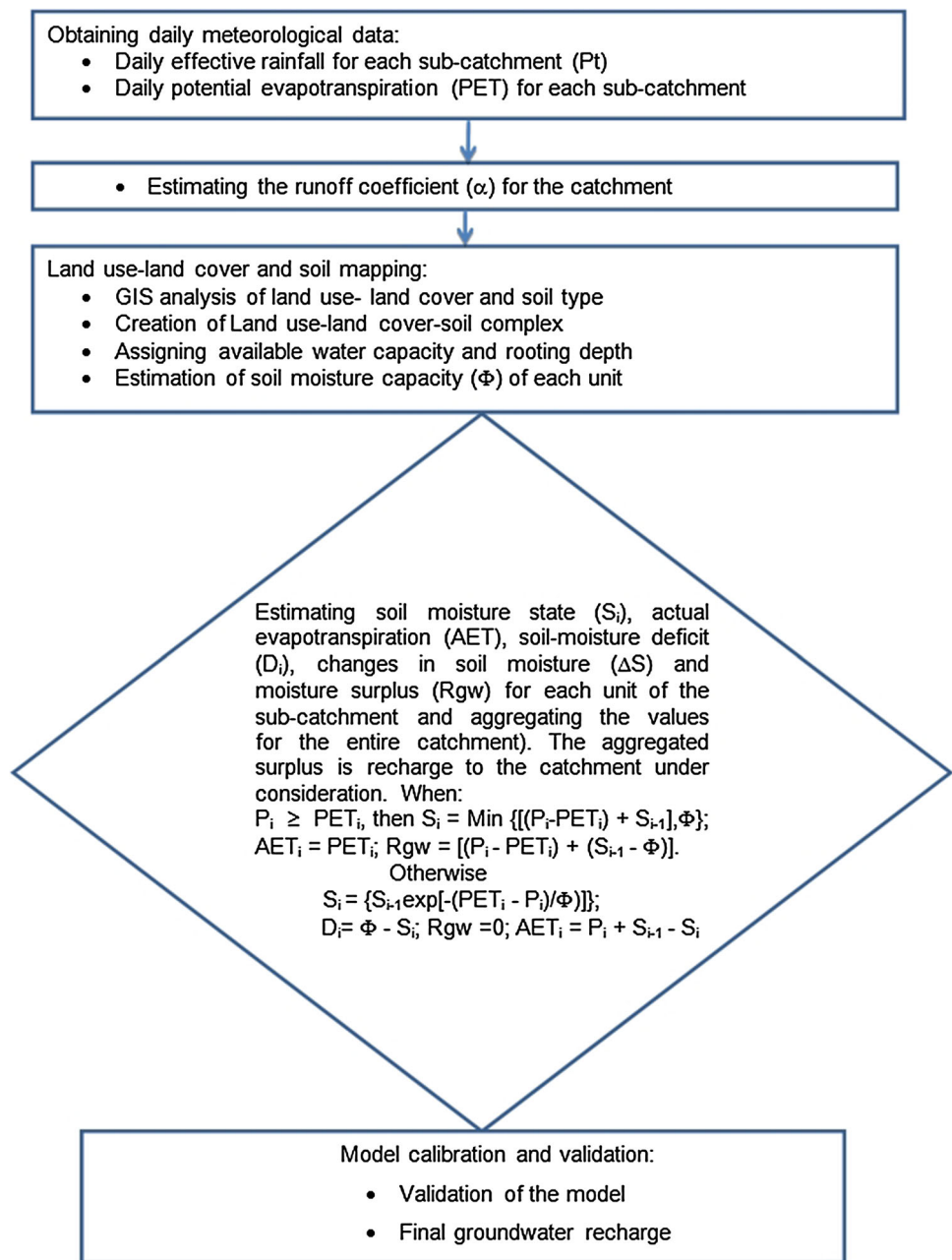
Evapotranspiration rate from a reference surface not short of water is known as reference (crop) evaporation (Allen



**Fig. 5** Conceptual catchment water balance model of groundwater recharge (modified after Chidley 1981)

et al. 1998). Allen et al. (1998) define the reference surface as a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23. This reference surface resembles an extensive surface of green, well-watered grass of uniform height actively growing and completely shading the ground. Allen et al. (1998) introduced the ETo concept to study the evaporative power of the atmosphere at a specific location and time of the year independent of crop characteristics and soil factors. Since obtaining accurate measurement of field data is both expensive and difficult, ETo is computed readily from weather data. Studies undertaken by American Society of Civil Engineers and a Consortium of European research institutes to evaluate the performance of different evapotranspiration estimation techniques indicated that the FAO Penman–Monteith method of reference evapotranspiration computation has superior accuracy and has consistent performance in both arid and humid climates. The method has been applied and compared and contrasted with other methods extensively (Allen 1999, 2000; Eitzinger et al. 2002; Allen et al. 2005; Temesgen et al. 2005; Er-Raki et al. 2006, 2007, 2010; Kite and Droogers 2000; Lui and Luo 2010; Hosseini et al. 2013, Valipour 2014a, b, c) and it is recommended as a standard

**Fig. 6** Flow chart of a semi-distributed modified  $T\alpha$ -type catchment soil–water balance model used in this study



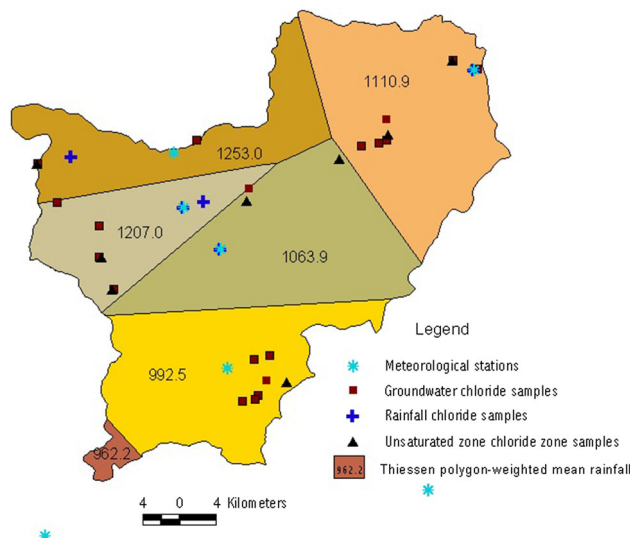
method in evapotranspiration estimation (Allen et al. 1998). The reference crop evapotranspiration is similar to the concept of potential evapotranspiration introduced by Thornthwaite (1948) and will be used in that context. Reference crop evapotranspiration of the study catchment was estimated on a daily basis using the FAO Penman–Monteith approach, and the actual evapotranspiration for each crop or vegetation type or bare soil was derived from the reference evapotranspiration using the appropriate

corresponding crop coefficient. The FAO Penman–Monteith equation of  $E_{To}$  is given by:

$$E_{To} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 U_2)} \quad (7)$$

where  $E_{To}$  = reference evapotranspiration [mm/d],  $R_n$  = net radiation at the crop surface [ $MJ/m^2d$ ],  $G$  = soil heat flux density [ $MJ/m^2d$ ],  $T$  = mean daily air temperature at 2 m height [ $^{\circ}C$ ],  $U_2$  = wind speed at 2 m height





**Fig. 7** Map showing Thiessen polygons for the weather stations, rainfall and groundwater chloride measurement points

[m/s],  $e_s$  = saturation vapour pressure [kPa],  $e_a$  = actual vapour pressure [kPa],  $e_s - e_a$  = saturation vapour pressure deficit [kPa],  $\Delta$  = slope vapour pressure curve [kPa/°C],  $\gamma$  = psychrometric constant [kPa/°C].

The derivation of each of the parameters in Eq. 7 is described in detail in the FAO guide for computing crop water requirements (Allen et al. 1998). The results of mean monthly reference evapotranspiration values for the study catchment aggregated from daily computation for each meteorological station using available meteorological data are presented in Table 3. The value of crop reference evapotranspiration increases from north to south towards the rift proper following the decrease in altitude and increase in temperature. The value of actual evapotranspiration is computed from the potential (reference) evapotranspiration through a semi-distributed catchment SWB modelling approach for a soil–vegetation complex mapped for the area.

#### Input data pre-processing and modelling

The conceptual model used in the catchment SWB modelling of direct groundwater recharge is illustrated in Fig. 5. Daily effective precipitation ( $P$ ) estimated through the Thiessen polygon weighting method (Fig. 7) is used. Potential evapotranspiration for each Thiessen polygons representing a sub-catchment was estimated using available daily meteorological data according to the FAO Penman–Monteith approach. Land use–land cover and soil maps were processed and analysed in a desk-top ArcView/ArcGIS environment to develop a land use–land cover–soil complex. For each vegetation–soil unit, rooting depth, and available water capacity and consequently the maximum water holding capacity of the root zone ( $\Phi$ ) were assigned from published data (Thorntwaite and Mather

1957; Dune and Leopold 1978; Shaw 1994). Runoff coefficient ( $\alpha$ ) which is the ratio of direct runoff to mean precipitation is calculated from stream flow data separated into direct runoff and baseflow and is 0.24. The effective precipitation minus direct runoff is input to the model so that the model calculates a surplus which represents potential groundwater recharge. All daily input data were put into a spread sheet program and automatically iterated to output  $A_{et}$ ,  $\Delta S$ ,  $S_i$ , and  $R_{gw}$  in a daily time step for each sub-region or catchment represented by its own land cover–soil complex. The daily values are aggregated later into monthly and annual values. Figure 6 illustrates a flow chart of the modelling process.

#### Chloride mass balance (CMB)

For the chloride mass balance method, untreated groundwater samples for chloride analysis were taken from non-urban area of the catchment directly from shallow dug wells and boreholes (Fig. 7). In the case of previously inactive wells, samples were taken after 10 min of pumping. Three-year rainfall composite samples (Summer 2003 to Summer 2005) were collected at five different meteorological stations within the study catchment (Table 6). These hydrochemical samples were analysed for chloride content in the Laboratory of Applied Geology at the Ruhr-University of Bochum using an ICS-1000 Ion Chromatograph. It is assumed that the rainfall chloride concentrations closely reflect the total annual deposition for the continental Ethiopian highlands with negligible atmospheric dust and relatively far from the coast.

An environmental mass balance of the chloride ion, assuming chloride to be a conservative tracer and no source of chloride ion in the soil zone or groundwater other than precipitation, was applied at a number of sites within the non-urban area of the study catchment. This allowed the computation of total recharge (including preferential flow recharge through fractures, fissures and joints) through the following relations:

$$P * Cl_p = R * Cl_{gw} \quad (8)$$

where  $P$  is the mean annual areal effective precipitation in mm,  $R$  is total recharge (mm),  $Cl_p$  is the mean chloride concentration in precipitation (mg/l) and  $Cl_{gw}$  is the chloride concentration in groundwater (mg/l).

## Results and discussion

Results of in situ saturated hydraulic conductivity measurements of soils in the stud catchment

The results of the Guelph Permeameter measurements (Table 4) indicated a strong vertical and horizontal



**Table 4** In situ-measured saturated hydraulic conductivity and matric flux potential of soils in the Akaki catchment

ID. No.	Location		Depth (cm)	Soil type	K (m/s)	Matric flux potential (cm <sup>2</sup> /s)
	X	Y				
1	479192	994163	48	a	-8.40E-06	1.16E-02
2	486897	1000807	23	c	4.56E-06	4.95E-03
3	486897	1000807	56	c	5.68E-06	-2.40E-04
4	478958	976412	68	c	4.80E-06	-2.77E-03
5	479006	977682	45	a	2.33E-05	4.80E-03
6	479006	977682	75	a	0	0
7	475646	978777	56	b	2.52E-06	3.11E-03
8	475646	978777	75	b	1.72E-06	2.52E-03
9	460114	1003075	30	c	9.71E-06	-1.05E-03
10	460114	1003075	70	c	-1.48E-05	1.62E-02
11	470123	991973	70	c	1.77E-05	-7.17E-03
12	476373	989112	70	a	6.67E-07	6.79E-04
13	463540	995390	26	a	1.18E-06	4.64E-03
14	463040	992413	20	c	5.88E-06	1.17E-03
15	463040	992413	64	c	-8.02E-06	3.50E-02
16	501239	1013935	25	-	5.42E-05	-5.51E-03
17	501239	1013935	60	-	0	0
18	503786	10122004	30	a	2.87E-04	-1.64E-02
19	503786	10122004	70	a	2.40E-06	-1.39E-03
20	480856	978969	25	a	H	Not calculated
21	480856	978969	46	a	-1.52E-06	3.92E-03
22	483166	978840	40	a	3.39E-06	5.64E-03
23	483166	978840	70	-	0	0
24	491529	1015653	24	a	6.64E-05	-2.53E-02
25	488275	1001525	30	a	1.09E-05	2.383
26	484184	996663	39	a	1.34E-05	-7.77E-03
27	488004	976870	28	a	7.20E-06	-4.16E-03
28	474278	986749	30	a	H	Not calculated
29	474278	986749	70	a	H	Not calculated
30	475516	979579	32	b	8.89E-06	-1.34E-03
31	476817	993549	28	a	1.04E-05	-5.26E-03
32	488858	1003086	23	a	0	0
33	488858	1003086	46	a	0	0
34	494317	1005766	36	a	H	Not calculated

- others, H high hydraulic conductivity

<sup>a</sup> Residual black cotton soil

<sup>b</sup> Alluvial black cotton soil

<sup>c</sup> Residual lateritic soil

heterogeneity of the soils. The negative values of K in Table 4 are indications of this heterogeneity due to the presence of hydraulic discontinuities or the presence of rodent and root holes which not only supports the vertical heterogeneity within the soils but also enhances the permeability and preferential flow. In some locations, due to the wide and deep cracks developed over the black cotton soils, the permeability of the soil formation was much more than the water supplied from the Permeameter reservoir, demonstrating the importance of preferential flow paths in the studied catchment.

Impermeability of a vast area of the catchment covered by black cotton soils reported by AAWSA, BCEOM, SEURECA and Tropics (2000) is found to not correct.

Comparison of average measured hydraulic conductivity for the three types of soils mapped in the catchment, namely residual black cotton soils ( $3.84 \times 10^{-5}$  m/s), alluvial black cotton soils ( $4.38 \times 10^{-6}$  m/s) and residual lateritic soils ( $3.19 \times 10^{-6}$  m/s), indicates that the residual black cotton clay soils have relatively higher permeability, especially when dry (Table 4).

Results and comparison of groundwater recharge estimation from the SWB and CMB methods

The results of the semi-distributed SWB recharge modeling for the study catchment are presented in Table 5 and its spatial distribution is illustrated in Fig. 8. The total

**Table 5** Semi-distributed SWB rainfall recharge estimated for the study area per sub-catchment

Sub-catchment no.	Sub-catchment area (m <sup>2</sup> )	Recharge (mm)	Area weighted recharge (mm)
1	163,981,978.8	0	0
2	86,920,292.9	11	0.65
3	3,849,110.8	22.5	0.06
4	48,154,602.3	23.8	0.78
5	468.5	30.9	0
6	4,526,677.2	44.3	0.14
7	85,921,916.3	51.4	3.02
8	7,352,118.1	53.4	0.27
9	56,202,736.2	55.9	2.15
10	3,964,508.3	67.4	0.18
11	15,571,696.4	80.3	0.85
12	1,638,682.6	94.4	0.11
13	561,571.5	104.4	0.04
14	58,736,934.5	107.1	4.3
15	283,641,054.3	114.6	22.21
16	16,306,831.7	126	1.4
17	172,043,181	131.8	15.49
18	9,425,302.9	140.2	0.9
19	553,684.4	148.9	0.06
20	59,586,489.7	149.2	6.07
21	306,884,026.7	173.6	36.4
22	34,841,480.3	181.3	4.32
23	42,984,733.3	203	5.96
Total mean annual recharge (mm) = 105.4			
Total catchment area (km <sup>2</sup> ) = 1,463.7			
Recharge contributing area (km <sup>2</sup> ) = 1,299.7			
Mean annual areal precipitation (mm) = 1,102.7			

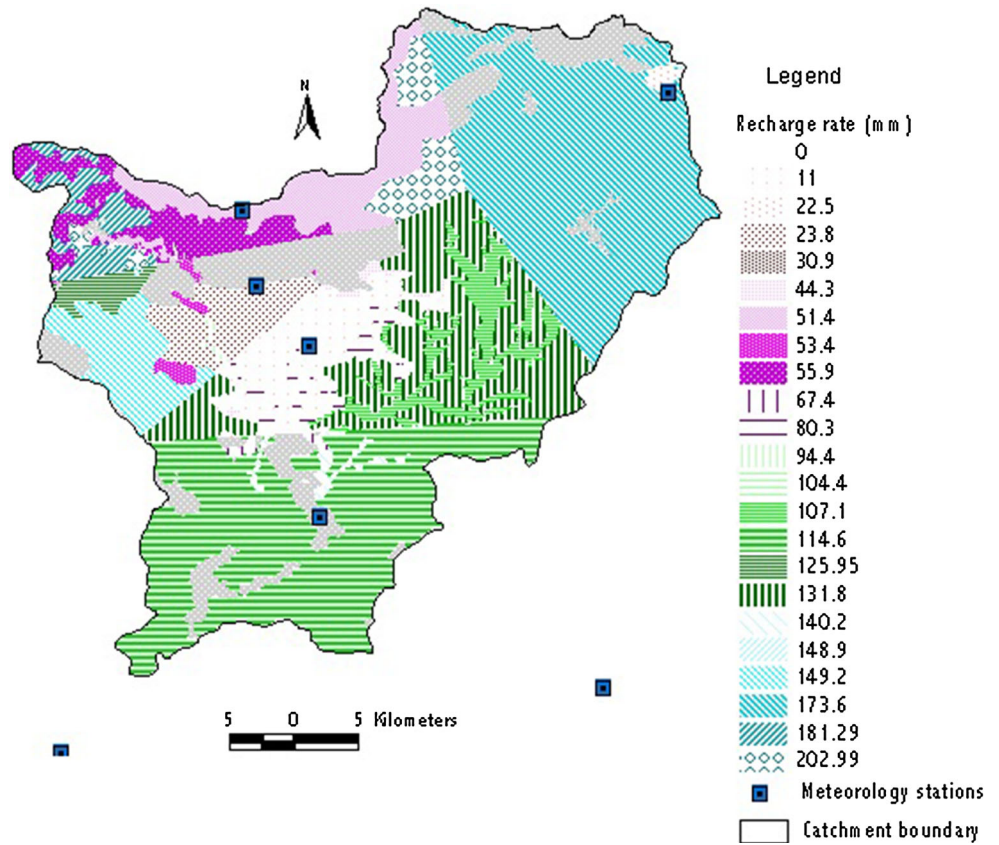
weighted mean annual direct recharge for the catchment under investigation aggregated from daily modelling results is 105.4 mm which about 10 % of the mean annual areal precipitation for the catchment. This amount is equivalent to a total volume of about 137 million cubic meters (mcm) per year or 4,344 l/s taking into account only areas that contribute to recharge.

Many studies show that urbanization results in land surface impermeabilization and reduces the direct infiltration of excess rainfall, and hence accelerates direct runoff. This surface impermeabilization includes construction of roofs and paved areas such as major highways, minor roads, parking lots, industrial areas, and airport aprons. Since this fraction of impervious surfaces (due to urbanization) within an urban catchment does not contribute to groundwater replenishment, it is deducted from the total urban catchment contributing to recharge. Examples of the proportion of impervious surfaces for some cities around the world are 30 % for the city of Hamburg, Germany (Paluska et al. 1988); 20–40 % for Baltimore, USA; and 20–30 % of the districts of

Columbia, USA. Arai (1990) cited in Foster et al. (1993) estimated a groundwater recharge reduction of 25–45 % for two districts of Tokyo as a result of 60 years of progressive urbanization. For the city of Addis Ababa, in which informal settlements are progressively consolidated into an urban centre, about 25 % of the city is assumed to be impervious surface which does not directly contribute to the direct natural recharge. Similarly, Lerner et al. (1990) suggests 75 % of natural recharge for urban areas with rainfall greater than 1,000 mm/year which is the case for the study catchment.

From field geologic and hydrogeologic mapping, soil infiltration testing along with environmental investigation, it was observed that preferential flows seem to be more the rule than the exception in the study catchment. As a result, the 10 % direct recharge rate estimated through the SWB modelling should be considered as the minimum possible groundwater recharge rate for the catchment. Moreover, recharge from leakage of perennial streams, reservoirs, water mains and sewers are not incorporated to the present model.

**Fig. 8** SWB mean annual groundwater recharges rate distribution map for the Akaki catchment



**Table 6** Average rainfall chemistry (mg/l) for samples in the Akaki catchment (sampling year: 2003–2005)

Station name	Location		Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	NO <sub>3</sub> <sup>-</sup>	Na/Cl	Sampling season
	X	Y									
AAO1	472136	996721	0.55	1	5.25	0.4	1.55	20.7	11	0.35	Winter
AAO2	472136	996721	0.23	0.17	1.41	0.13	0.49	2.6	1.3	0.55	Summer
BO1	475977	993369	0.5	0.65	2.75	0.25	1.25	4.5	7.25	0.4	Winter
BO2	475977	9933369	–	–	–	–	2.02	6.64	1.9	–	Summer
AAG1	474208	998523	0.27	0.33	0.2	1.07	0.37	2.27	0.87	0.72	Winter
AAG2	474208	998523	0.17	0.1	1.53	0.1	0.38	2.44	3.06	0.53	Summer
Gefersa	459777	1003400	0.2	0.35	0.35	0.2	0.6	1.75	1.55	0.33	Winter
<sup>b</sup> Sendafa	503448	1012814	2.2	4	8	0.9	6.5	10.8	5.3	0.34	Winter

<sup>a</sup> AAG is Addis Ababa Geophysical Observatory

<sup>b</sup> Data not used for recharge estimation due to anomalously high chloride level

Results of a 3-year (2003–2005) rainfall average chemical analysis sampled at five measuring stations are presented in Table 6. The results show apparent variation of major ions with rainfall amount, time and space in the studied catchment. The variation of these major ions could also be interpreted in terms of the circulation of land-derived dusts with the prevailing wind direction within the catchment. Values for chloride concentration varied from 2.2 mg/l in March to 0.15 mg/l in August with a mean

value of 0.95 mg/l which is less than a mean value reported by Edmunds et al. (1992) for the area of Abu Delaig in the Sudan, Edmunds and Gaye (1994) in the Sahel zone in Senegal and Rhodhe et al. (1981) for East Africa. However, it is a reasonable value for continental Addis Ababa region relatively far from the coast and with low atmospheric dust.

The results of groundwater chloride concentration along with groundwater recharge estimated through the saturated zone CMB method are presented in Table 7. The mean

**Table 7** Results of groundwater recharge estimated through saturated zone chloride mass balance

Sample I.D.	Location		Groundwater Cl (mg/l)	Areal rainfall (mm)	Runoff (mm)	Effective rainfall (mm)	Average rainfall Cl (mg/l)	Cl <sub>p</sub> /Cl <sub>gw</sub>	Total recharge (mm)
	X	Y							
GW-4	462788	992425	1.3	1,207	268	939	0.95	0.73	686
GW-5	503833	1012823	17.6	1,111	268	843	0.95	0.05	45
GW-6	501208	1013728	1.8	1,111	268	843	0.95	0.52	444
GW-7	503448	1012814	3.2	1,111	268	843	0.95	0.29	250
GW-10	481266	981756	8	992	268	724	0.95	0.11	86
GW-11	479544	981260	10.8	992	268	724	0.95	0.08	63
GW-13	493917	1005045	1.2	1,111	268	843	0.95	0.79	667
GW-14	493167	1004737	3.5	1,111	268	843	0.95	0.27	228
GW-15	491200	1004464	2.9	1,111	268	843	0.95	0.33	276
GW-18	473369	1005062	1.3	1,253	268	985	0.95	0.73	719
GW-19	456121	1002559	12.7	1,253	268	985	0.95	0.075	73
GW-20	458156	998337	1.5	1,207	268	939	0.95	0.63	594
GW-21	464365	988869	6.7	1,207	268	939	0.95	0.14	133
GW-26	479954	977334	6	992	268	724	0.95	0.16	114
GW-27	479700	976927	6.4	992	268	724	0.95	0.15	107
GW-28	478347	976750	8.2	992	268	724	0.95	0.11	84
GW-42	479031	977601	10	992	268	724	0.95	0.09	68
Average values			6.06	1,102	268	835	0.95	0.3	273

annual groundwater recharge of 17 sites estimated using the CMB method is 273 mm or 25 % of the mean annual areal precipitation for the catchment. The chloride mass balance equations relate recharge inversely to chloride concentrations in the saturated zone; thus, the chloride mass balance estimates of recharge should be considered as average point recharge values over longer period of time. It appears that the results have overestimated the groundwater recharge compared to the SWB result and previous estimates through other methods (AAWSA, BCEOM, SEURECA and Tropics 2000; TAHAL Consulting Engineers Ltd 1992) and what is expected for a sub-humid tropical catchment with a considerable runoff and evapotranspiration components. This overestimation has emanated from the low concentration of chloride in some springs and dug wells as a result of possible fracture-dominated recharge mechanisms. Thus, the results have clearly explained and supported onsite permeability test results and earlier isotopic evidence of the existence of bimodal (diffuse and preferential flow) recharge mechanisms. The dominant mechanism varies depending on the thickness of the unsaturated soil horizon and the degree of fracturing in the outcropping bedrock. Additionally, the result further shows a strong spatial variability of groundwater recharge in the studied catchment. The absence of lysimeter data and unreliability of available borehole water-level fluctuation data mean that calibration of the SWB and CMB recharge estimates is difficult.

## Conclusion

The hydraulic conductivity tests undertaken using Guelph Permeameter indicated strong vertical and horizontal heterogeneity of the soils within the studied catchment. This heterogeneity exacerbated by the presence of hydraulic discontinuities or the presence of rodent and root holes which not only supports the vertical heterogeneity within the soils but also enhances the permeability and preferential infiltration pathways. The wide and deep cracks developed over the black cotton soils as a result of the long dry period contribute to preferential flow recharge at the beginning of the rainy season. Areas that were assumed to have poor infiltration capacity and hence no recharge areas, particularly those covered by black cotton soils are found to be permeable enough to contribute to groundwater recharge in the catchment.

Natural groundwater recharge estimated through a semi-distributed SWB model is 105 mm or 10 % of the mean annual areal precipitation over the catchment. Considering 1,299.7 km<sup>2</sup> recharge contributing area of the catchment into consideration, the annual direct natural recharge volume is  $137 \times 10^6$  m<sup>3</sup>/a. This recharge value is much less than the recharge estimated through the CMB method which is 273 mm/a (about 25 % of the weighted mean annual areal precipitation of the catchment). The large discrepancy in recharge estimates between the two methods is partly attributed to additional preferential flow path



recharge captured by the CMB method which was identified by onsite observation and permeability tests explaining the fact that the catchment gets recharged both from direct and preferential flow recharge mechanisms. Therefore, the direct recharge estimated through the SMB method should be considered as the minimum possible recharge for the area, and the maximum possible recharge for the catchment is the mean of the SWB and CMB results which is about 18 % of the mean annual recharge or 198 mm/a ( $257 \times 10^6 \text{ m}^3/\text{a}$ ). Although calibration was not possible, the catchment SMB recharge is found highly sensitive to changes in precipitation input. The two methods favourably captured the variability of recharge commensurate with variations in depth of precipitation, topography, land use–land cover, soil and other catchment characteristics.

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