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HYDROLOGICAL SYSTEM ANALYSIS AND GROUNDWATER RECHARGE ESTIMATION USING SEMI-DISTRIBUTED MODELS AND RIVER DISCHARGE IN THE MEKI RIVER BASIN

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ABSTRACT: Groundwater recharge estimated from a soil water balance model and from river discharge records were compared in the Meki River basin located in a closed central Main Ethiopian rift. The first method is based on soil-water balance model (WATBAL) which uses long-term average monthly hydrometeorological data to quantify lumped soil water balance in three regions (rift, escarpment and highland). The second method involves estimation of recharge using discharge records with a computer code called BFI which uses a digital recursive filter to separate base flow from total daily discharge. The base flow was considered to be lumped catchment groundwater recharge with some adjustments for upstream channel losses (14.4 mm annually) estimated from field systematic river discharge measurements. The results from BFI and WATBAL show general agreement on annual basis. However, the base flow seems to indicate realistic temporal variations, especially in dry seasons. The annual weighed basin recharge excluding channel loss from BFI model and WATBAL is 80.1 mm and 79.2 mm respectively. The BFI model seems to provide realistic estimates of recharge for input into regional transient hydrological models and it also appears to be a viable method of defining the base flow from the river discharges against the classical manual base flow separation using regression curves. Both long-term and field discharge records clearly revealed that the total flow and recharge shows substantial temporal and spatial variations. The model results and discharge records demonstrate that the Meki River basin has relatively lower storage capacity and fast response to rainfall.

Key words/phrases: Ethiopian rift, recharge, hydrological behavior, river discharge, water balance

INTRODUCTION

The central Main Ethiopian Rift (MER), characterized by many lakes and perennial rivers, is one of the most important places for water resources development. A few decades ago much of the basin was covered with natural vegetation and the rivers and lakes were protected from large-scale human interferences (Halcorw, 1989). However, the fast growing population has induced land degradation and increased abstraction of water (Dagnachew Legesse *et al.*, 2003). This trend is still continuing. In the last few decades emphasis has been given to develop the water resources of the basin for various purposes, particularly the rift lakes were used for irrigation and soda ash abstraction. There are future diversion plans of the main rivers feeding the lakes for irrigation including Meki.

Utilization of water has proceeded without a basic understanding of the hydrogeological system of the basin. This has become a critical problem in water resources management (Wenner, 1973; Makin *et al.*, 1976; Dereje Hailu *et al.*, 1996, Tenalem Ayenew, 2002). Development plans were implemented with short-term interests, though it was understood that the recent increased abstraction of water from lakes and rivers caused some changes in the lacustrine environment. Any future, judicious utilization of water resources presupposes a good scientific data and assessment of the surface and subsurface components of the hydrological cycle. Previous studies focus mainly on the rift lakes. However, the hydrological behavior of the lakes is very much dependent on what happens in their catchments. Studying the temporal and spatial variation of the hydrological behavior and groundwater recharge processes is key element of lake watershed management schemes.

Accordingly the assessment of the hydrological behavior of feeder rivers and the temporal and spatial variation of river flows is vital as the rivers are interconnected with the complex delicate rift lacustrine environment. Aside from the continuous supply of input to the rift lakes, the rivers are partly the source of recharge to the aquifers. In the Ethiopian rift many villages and small towns rely on these aquifers for community water supply. Recharge from the rivers in low-lying areas occurs in the fractured volcanic rocks and loose alluvial riverbed and lacustrine deposits. Recharge estimation does not only enable us to have a grip on water quantity, but also helps in water quality management strategies. Furthermore, base flow of rivers constitute a critical design variable for reservoirs that must maintain sufficient through flow to satisfy various water uses (McMahon and Mein, 1986).

Scope of the study

Some studies were carried out on the geology (Di Paola, 1972; Giday Woldegebriel *et al*., 1990; Benvenuti *et al*., 1995) and hydrogeology (Tesfaye Cherenet, 1982; Tenalem Ayenew, 1998; Dagnachew Legesse, 2002) of the region. These studies provided an overview of the interconnection of the aquifer and the rivers and the relation of the rift lakes with the various water bodies. However, the spatial and temporal variation of groundwater recharge, which has important implications for conjunctive use of water, is poorly addressed. This is partly due to the fact that groundwater recharge estimation is not straight forward in the complex fractured rift environment and requires detailed hydrometeorolgical and hydrogeological data.

Groundwater recharge can be quantified by water balance studies or from river discharge records. In the former case recharge is quantified as a residual of other known water balance or hydrologic cycle components of the area under consideration. River discharge record has been used extensively by hydrologists to estimate groundwater recharge and for groundwater characterization in various parts of the world (Nathan and McMahon, 1990; Bevans, 1986; Hoos, 1990).

In this study both approaches are used to estimate basin groundwater recharge. The first is the soil water balance approach of Thronthwaite and Mather (1957), which simulates recharge from mean monthly hydrometeorological data for the three physiographic regions. The second method is based on a computer code called BFI, which employs digital recursive filter to separate base flow from total river discharge record on daily basis (Whal and Whal, 1988). Unlike the conventional manual base flow separation using a modified hydrograph recession curve displacement method (Arnold and Allen, 1999), BFI provides the ratio of base flow and surface runoff on daily basis. For the BFI model the daily discharge record of the Meki River (1985–2004) was used. The lumped basin-wide results of the BFI model was compared with the result of the WATBAL model after weighing the recharge of the three physiographic regions on monthly basis. Aside from quantifying the recharge attempt was made to asses the hydrological behavior from the hydrograph and field systematic river discharge measurements.

This study has two main objectives: (1) estimate the groundwater recharge using two independent methods taking all important influencing factors, and (2) assess the hydrogeological behavior of the basin from the stand point of the discharge characteristics in relation to the geology and geomorphology.

The contributions of this study are two-fold: (1) it should allow more accurate evaluation of the groundwater recharge rate, which is critical for sustainable conjunctive use of water; and (2) The result can be extrapolated to similar catchments in the region with little or no hydrological records.

Site description

Figure 1 shows the Maki River basin. Meki River is one of the main perennial rivers which drains from the western highlands to the center of the central MER. The total basin area is 3051 km^2 with long-term annual discharges of 265×10^6 m^3. The central part of the MER is occupied by four major lakes; one of which is Lake Ziway. Lake Ziway is fed by Meki River from the west and Katar River from the East (Fig. 2). The hydrology of the lake depends strongly on the flow regimen of these major rivers which get sustained input from the highland rainfall and groundwater systems (Tenalem Ayenew, 1998). The rainfall is highly variable as the topography (Table 1).

Table 1. Long-term average monthly rainfall of selected stations in the Meki basin (mm).

No	Station	Altitude (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Bui	2027	26	46	79	82	73	111	213	199	112	35	8	6	992
2	Butajira	2088	38	67	136	127	115	125	173	172	116	45	11	14	1138
3	Koshe	1873	22	48	78	91	90	100	171	170	109	51	5	5	941
4	Meki	1663	13	35	56	65	64	77	170	149	87	34	8	4	762
5	Tora	2012	25	43	83	116	95	87	133	124	117	49	8	6	885

High altitude plateau to the west bound a large portion of the basin. The altitude in the Meki basin ranges from around 1,600 meters above sea level (m.a.s.l) in the rift floor to over 3,500 m.a.s.l in the large volcanic peaks of the western Guraghe mountains forming the major recharge area. The main tributaries of the Meki River originate from these mountain ranges and drains through the wide plains of the escarpment and the rift floor. These rivers often form water falls at the boundary of the highlands and the escarpment where sharp elevation difference exists (Fig. 2).

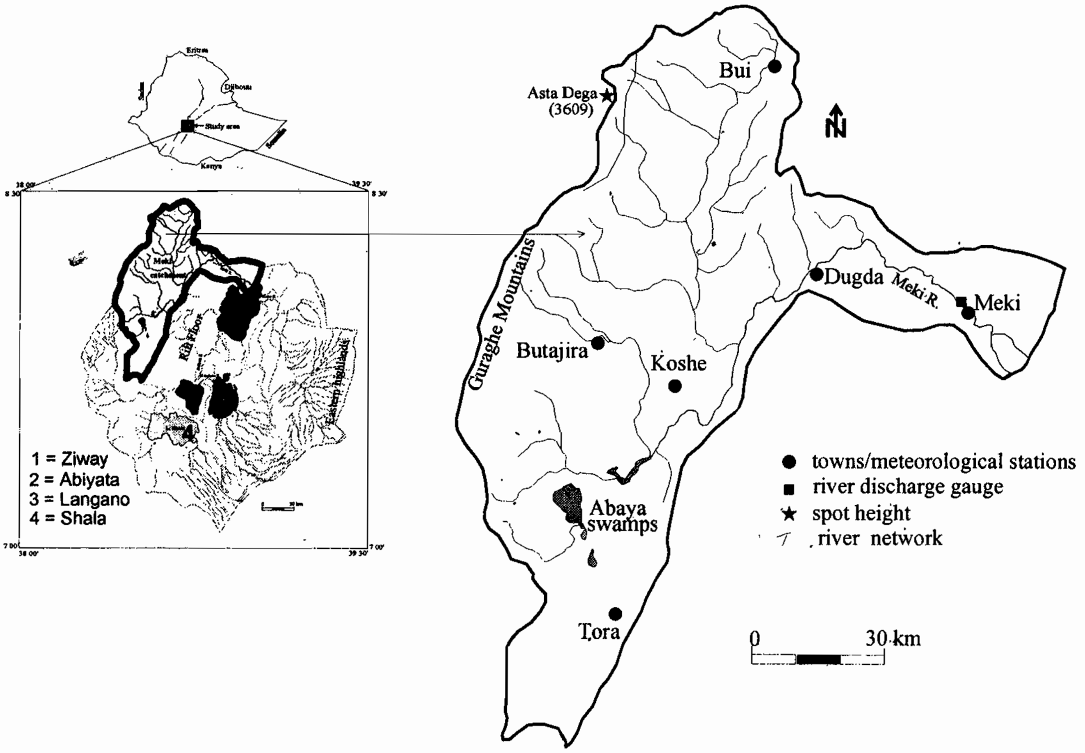

Fig. 1. Location map.

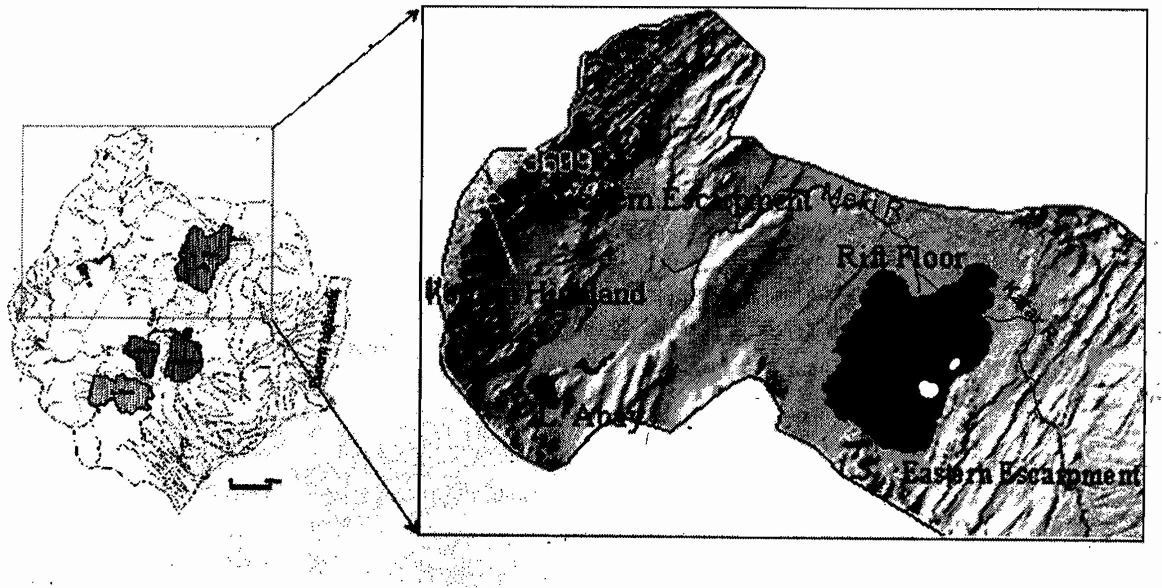

Fig. 2. Digital Elevation Model (DEM) of the Ziway basin including Meki.

Geologically the lakes and the lower reaches of the rivers are situated in tectonically active volcanic terrain. The present day geological and geomorphological features are the result of Cenozoic volcano-tectonic and sedimentation processes. Faulting was accompanied by extensive basaltic and silicic volcanism restricted to separate centers aligned along the NE-SW trending rift axis. Several shield volcanoes were developed in the plateaux; the different volcanic episodes formed thick rock sequences (Giday Woldegebriel *et al.*, 1990). The major rock types in the rift are rhyolitic ignimbrites, basaltic lava flows, acidic rocks such as tuff, trachyte and pumice, associated with lacustrine, volcano-clastic, alluvial and colluvial deposits. Large-scale block faulting disrupted these rocks and formed extensional normal step-faults. As a result, the rift is distinctly separated from the highlands by a series of faults mainly trending parallel and sub-parallel to the axis of the rift (Fig. 3). Intense and active faulting and volcanic centers mark the floor of the rift. These faults have strong bearing on the movement and occurrence of groundwater.

The climate is humid to sub-humid in the highlands and semi-arid in the rift. Temperature and rainfall show strong altitudinal variations. Mean annual temperature is about 15°C in the highlands and around 20°C in the rift. The average annual rainfall ranges from around 650 mm in the rift floor to 1,150 mm in the eastern and western highlands. At the top of large volcanic summits the annual rainfall can be as high as 1,400 mm (NMSA, 2000).

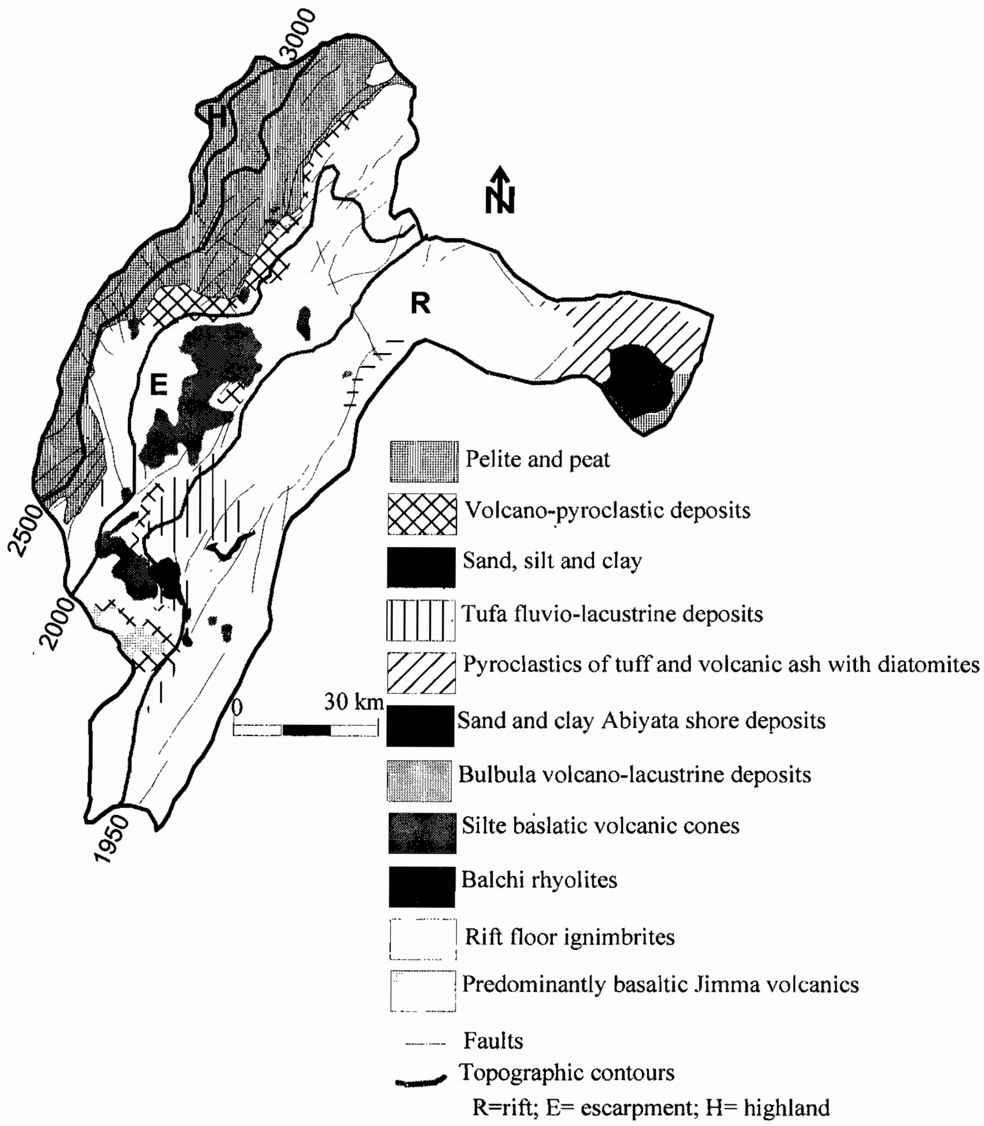

Fig. 3. Geological map.

METHODOLOGY

Field hydrogeological investigation was carried out to develop the preliminary conceptual hydrogeological behavior of the basin. These include conventional hydrogeological mapping, water point identification, piezometric survey and river discharge measurements. Geological and hydrometeorological data, aquifer hydraulic parameters, well lithologic logs, etc. were collected from relevant sources (UN, 1973; Tesfaye Chernet, 1982; EGS, 1993; Berehanu Gizaw, 1996). The data provided important initial grip on the hydrogeological setting of the entire basin, ultimately leading to proper identification of sites for field river discharge measurements to study aquifer-river relationships and channel losses. Attempt was also made before to estimate the groundwater recharge from base flow from the daily river stage records using manual conventional base-flow separation technique using two years (1988–1989) daily discharge data (Tenalem Ayenew, 1998). However, that time the upstream channel losses were not considered leading to underestimation of the actual distributed basin groundwater recharge. Studies show that channel losses limit the applicability of base flows in estimating lumped catchment recharge (Ponce *et al.*, 1999). Therefore, more reliable base flow estimation is required using long period discharge records. At least, the conventional base-flow separation result has to be compared or checked by computer-based base flow separation techniques. The classical methods are unlikely to provide accurate real-time estimates of base flow except during periods of no direct runoff. Therefore, alternative methods are sought in this study.

Monthly hydrometeorological data (rainfall, temperature, wind speed, *etc.*) were collected from 22 stations in the region (1960–1994). The point data was weighed using Thiessen polygon method to get distributed aerial rainfall of the catchments under GIS environment using the software called Integrated Land and Water Information System (ILWIS) developed at the International Institute for Geo-Information Science and Earth Observation. Daily river discharge data (1985–2004) was collected from the Ministry of Water Resources. This data was used for flow characterization and groundwater recharge estimation. The river discharge recording station is located at Meki town not far from the confluence with Lake Ziway. For some years, data are missing. The river is considered to be non-regulated *i.e.*, there is no upstream diversion of water.

In addition the United Nations Food and Agricultural Organization (FAO) has developed a comprehensive agricultural and environmental information data base for the member states of the Intergovernmental Authority on Drought and Development (IGADD), including Ethiopia, Sudan, Uganda, Kenya, Somalia, Djibouti and Eritrea (FAO, 1995). Additional data on soil, land use and potential evapotranspiration was obtained from this data base.

Aside from the recorded discharge data at Meki town, exhaustive field river discharge measurement was conducted using current meter (SIAP model 601407) for almost all perennial tributary streams, at least at one time and at one place along their course. All measurements were made at the beginning of the dry season in September and October. Therefore, discharge values of these rivers represent essentially the initial recession flows. The main purpose of the field discharge measurement is to estimate channel losses and assess the flow regimen as influenced by geology and geomorphology.

After collecting the relevant data and conceptualizing the hydrogeological conditions two independent computer codes (BFI and WATBAL) were used to estimate the groundwater recharge and characterize the hydrological behavior.

BFI code

In a catchment where diversion of river water, inter-basin water transfer and channel losses are negligible, the aerial catchment groundwater recharge can be estimated from river discharge records. This demands separating the surface runoff and base flow component from river hydrographs. A variety of techniques have been suggested for base flow separation and useful reviews are presented by many authors (Nathan and McMahon, 1990). One popular method is the recession-curve-displacement method, which is commonly referred to as the Rorabaugh method (Rorabaugh, 1964). This is usually made by manual graphic methods based on semi-empirical approaches. However, manual base-flow separation methods are labor intensive and are generally not objective; different analysts given the same data would probably arrive at somewhat different values for base flow. Recently, numerous other computer-based analytical methods have been developed to separate base flow from total stream flow based on digital filtering techniques as in the case of BFI (Whal and Whal, 1988). Although most such procedures are based on physical reasoning, elements of all base flow separation techniques are subjective. Such techniques were originally used in signal analysis and processing (Lyne and Hollick, 1979). Arnold *et al.* (1995) compared the digital filter results with results from manual separation techniques (Rutledge and Daniel, 1994) for several watersheds in the United States (White and Slotto, 1990) and found reasonable agreement. The BFI code was developed by the British Institute of Hydrology (IH a&b, 1980). The program implements a deterministic procedure with a recession slope test with filtering approach. The program estimates the annual base-flow volume of unregulated rivers and streams and computes an annual base-flow index (BFI): the ratio of base flow to total flow volume for a given year, for multiple years of data at one or more gauging sites. The method uses the filtering technique as described by Bevans (1986) and Rutledge and Daniel (1994).

WATBAL model

WATBAL is a simple soil-water balance model developed at the International Institute for Geo-Information Science and Earth Observation (Donker, 1997) and uses the soil-water balance approach of Thornthwaite and Mather (1957). Dunne and Leopold (1978) provided extended description of the model. Here a brief description of the considerations behind the water balance model is given.

The model calculates the water balance for a single soil profile by using a simple book-keeping procedure based on average monthly precipitation, potential evapotranspiration and available water capacity of the soil, which is equal to the rooting depth and the water holding capacity of the soil. The soil-water balance approach uses the following relation to calculate actual evapotranspiration and distributed recharge (R) from precipitation (P):

$$P = Eta + R + Sr \pm \Delta S \quad \ldots\ldots (1)$$

where, Sr and ΔS represent surface runoff and the change in soil moisture, respectively.

The depletion of moisture from the soil is calculated using the following equation:

$$S_m = W.e^{-(\frac{L_{am}}{w})} \quad \ldots\ldots (2)$$

where, S_m : soil moisture (mm)

L_{am} : accumulated potential water loss (mm)

W : available water capacity of the root zone (mm)

The basic assumption is that when monthly precipitation is greater than or equal to the corresponding monthly potential evapotranspiration, actual evapotranspiration equals potential evapotranspiration if the moisture storage in the soil zone is at maximum capacity. When the precipitation is less than the potential evapotranspiration, actual evapotranspiration equals precipitation plus the depletion from soil moisture storage. Any water surplus in the soil zone reaching the groundwater table can be considered as recharge.

Calculation of actual recharge using this method requires determination of precipitation, potential evapotranspiration and available water in the root zone, which accounts for the rooting depth of vegetation. The soil and land use parameters were estimated using the available data (Tenalem Ayenew, 1998). The potential evapotranspiration required by WATBAL was derived from the FAO database (FAO, 1995).

A base flow from this method gives lumped catchment recharge. Due to the large differences in rainfall, geological and geomorphological conditions in the three physiographic regions, the amount of recharge is expected to vary over a wide range. In the WATBAL model three independent model runs have been made for the rift, escarpment and highlands. The final result for each model simulations are weighed based on the aerial proportions of the three physiographic regions.

RESULTS OF MODEL SIMULATION AND DISCUSSION

Figure 4 shows the hydrograph of the Meki River indicating the measured total flow and the BFI estimated base flow. Table 2 summarizes the monthly relevant data and recharge estimated by the two methods.

The lumped total recharge or base flow from the BFI and WATBAL model is 80.1 and 79.2 mm. On annual basis the WATBAL compares favorably with BFI excluding the channel losses. As addressed below if the channel loss (14.4 mm annually) is incorporated with the BFI result, the difference in the annual estimated recharge will be 15.3 mm. This indicates fair good agreement. However, the results from monthly values show wide variations. This is partly attributed to the limitations of the WATBAL model in incorporating short period hydrological variability.

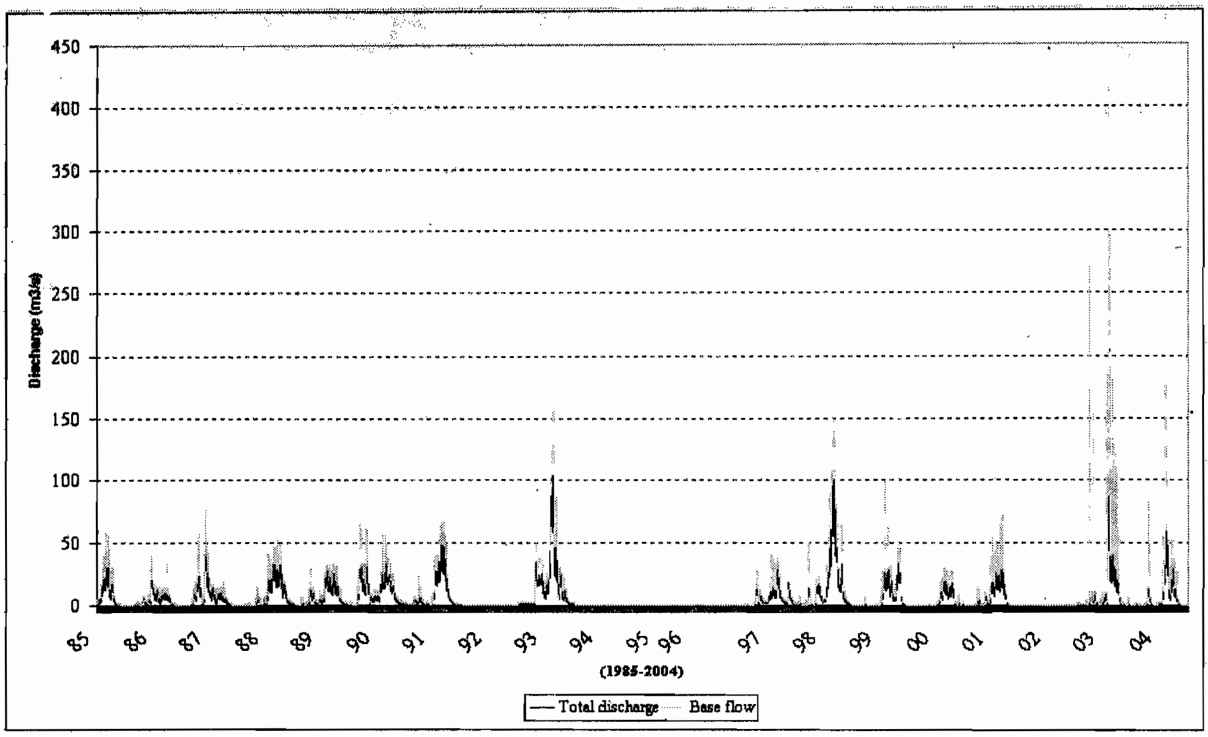

Fig. 4. Total Meki discharge and BFI simulated base flow at Meki town station.

Table 2. Summarized monthly recharge (mm) of the Meki basin obtained from the two methods.

Result of BFI model

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	In percent
Catchment rainfall (mm)	24	56	87	88	94	88	138	146	110	34	13	9.1	887.1	
Meki discharge (mm)	1	1.2	5.1	3.5	4.4	5.7	26.7	36.1	28	8	2.2	0.5	122.5	100
Base flow	0.6	0.9	2.9	2.2	3	3.3	16.6	23.8	19.2	5.4	1.8	0.4	80.1	65.4
Surface runoff	0.4	0.3	2.1	1.3	1.5	2.4	10.1	12.3	8.8	2.6	0.4	0.1	42.4	34.6

Result of WATBAL model

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Remark
Basin weighed rainfall (mm)	24	56	87	88	94	88	138	146	110	34	13	9.1	887.1	Model input
Basin potential evapotranspiration (mm)	116	116	131	114	120	93	73	80	89	110	116	114	1272	Model input
Direct recharge (mm)	1	2.5	5.4	4.5	3.6	4.8	17.1	17.8	11	7.7	2.9	0.9	79.2	Compare with base flow

Previous estimates of recharge for the escarpment and highlands was found to be 23 and 103 mm respectively. Considering the aerial proportion of the rift (27%), escarpment (28%) and highlands (45%) within the Meki basin, the distributed basin recharge was found to be 53.9 mm. The direct recharge in the rift valley obtained from the old estimate was almost zero or negligible, as the area is rainfall deficit. In fact this is not the case as demonstrated from systematic river discharge measurements, and groundwater model simulations (Tenalem Ayenew, 2001, Alemu Deribessa, 2006) and field observation of the hydrogeological conditions. The model result is simplification of the reality. As stated below some direct and indirect recharge occasionally takes place in the rift during high rainfall events through permeable alluvial deposits and fractured zones. The infiltration through fractured rocks has been demonstrated using a Stochastic Discrete Fracture (SDF) model in the eastern half of the Ziway-Shala basin (Tenalem Ayenew, 1998).

Table 3 indicates the average annual flow rate, base flow and surface runoff of Meki River estimated by BFI from the daily record. From long-term average monthly data both methods show that at any given month the base flow is greater than the surface runoff component (Table 2). The large differences exist during rainy months from July to September. The BFI result from the daily discharge show that not all years show similar base flow - surface runoff ratio. The base flow ranges from 50.7 to 68.3% of the total river discharge. It is evident from the result that the Meki River flow regime is groundwater dominated. The dry season small rains do not contribute much to the surface runoff component at least for gauging stations located within the rift floor.

Synthesis of the hydrological behaviour

Field river discharge measurements made by the author between 1994 and 1998 revealed that the tributary rivers draining in the Guraghe mountains have different discharge characteristics than the rift rivers. In the Butajira and Silte areas base flow increases downstream to the foothills of the Guraghe mountains. When these rivers reach the rift discharge decreases due to channel losses; this has been observed from field base flow measurements of the Meki River (Tenalem Ayenew, 1998; Alemu Deribessa, 2006). Between measuring point 16 and 17 (Fig. 5) the Meki River losses water to the groundwater system at a rate of 18.4 l/s/km. Assuming the same rate of river channel loss, and the total length of the river course between measuring point 16 and the confluence with Ziway to be 76 km, the total channel loss will be around 44×10^6 m^3 annually. If this value is distributed over the total catchment area of 3051 km^2, the distributed catchment recharge from the Meki River to the groundwater system is 14.47 mm annually. This loss has to be added to the total annual recharge obtained from BFI code to account upstream indirect recharge from the river.

The channel loss in the rift floor is evident in some other measured rivers during the same discharge measurement campaign. For instance, the Horakelo River, connecting Lakes Langano and Abiyata, shows a decrease in discharge downstream from 5.2 m^3/s to 4.5 m^3/s in a stretch of about 6 km. The loss of river water in the rift groundwater system was independently demonstrated using groundwater flow modelling (Tenalem Ayenew, 2001).

An attempt was made to correlate river discharge and catchment area based on the field base flow measurements as shown in Figure 5 and Table 4. In smaller catchments of the highlands relatively moderate positive correlation ($r = 0.54$) exists between catchment area and river discharge because of the similarity in geology, topography, vegetation cover, amount and distribution of rainfall. This does not hold true in the rift valley due to changes in geology. The linear correlation coefficient between the annual recharge for each upstream catchment of the 17 measuring sites and the respective catchment area is extremely low ($r = 0.11$). This clearly indicates that the one time measurement of river discharge may not indicate the total recharge. This demands certainly systematic long-term measurements at different points to show the spatial variability. It also indicates that the river discharge is strongly influenced by the permeability of the riverbed deposits and the type and density of the complex fault systems within the rift floor.

Table 3. **BFI estimated average annual base flow and surface runoff percentages.**

Year	Total flow (10^6 m^3)	Average annual flow rate (m^3/s)	Base flow (%)	Surface runoff (%)
1985	172	5.5	53.0	47.0
1986	181	4.1	55.6	44.4
1987	216	6.9	51.7	48.3
1988	230	7.3	64.5	35.5
1989	220	7.0	67.5	32.5
1990	331	10.5	61.5	38.5
1991	271	8.6	66.6	33.4
1992	No data	No data	No data	No data
1993	456	13.0	56.4	43.6
1994	Incomplete data	Incomplete data	Incomplete data	Incomplete data
1995	261	8.3	53.7	46.3
1996	535	17.0	64.2	35.8
1997	185	5.9	67.3	32.7
1998	499	15.8	68.3	31.7
1999	281	8.9	76.4	23.6
2000	299	9.5	65.4	34.6
2001	437	13.9	62.4	37.6
2002	No data	No data	No data	No data
2003	365	11.6	51.4	48.6
2004	294	9.3	50.7	49.3

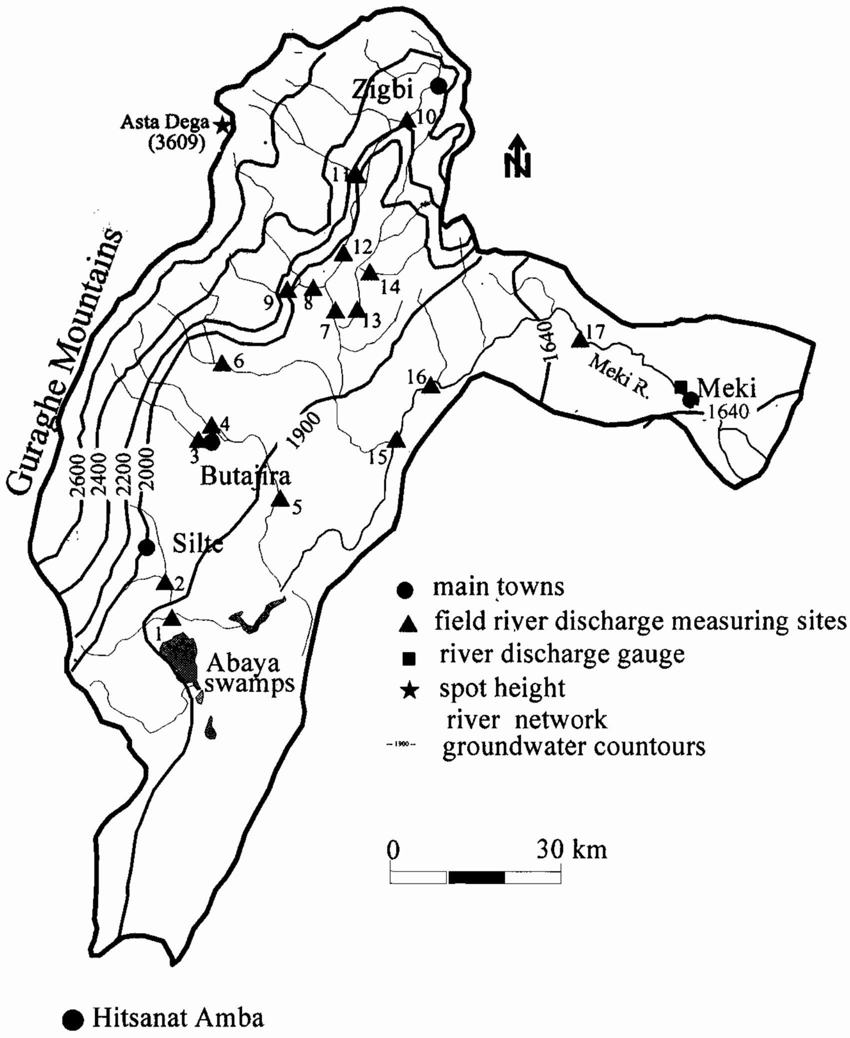

Fig. 5. Groundwater contours and field discharge measuring sites.

Table 4. Field discharge measurements results and catchment areas in selected tributaries.

No.	Discharge (m^3/sec)	Catchment area (km^2)
1	0.163	157.6
2	0.063	50.6
3	0.003	27.4
4	0.002	22.5
5	0.473	1082.9
6	0.002	60.8
7	0.289	202.6
8	0.022	55.4
9	0.025	54.3
10	0.082	77.9
11	0.149	110.2
12	0.26	233.8
13	0.289	260.5
14	0.091	108.9
15	0.436	815.9
16	0.624	882.3
17	0.261	1345.5

The master recession curves, flow duration analysis and the base flow separation reveal that the eastern half of the basin is different from the western half in terms of total runoff, recession characteristics and aquifer storage (Tenalem Ayenew, 1998; Dagnachew Legesse *et al.*, 2003). There are differences in the specific discharge of the eastern and western river catchments. These differences are mainly related to differences in geology, geomorphology and rainfall. The eastern highlands have higher rainfall than the western highlands (about 8% more annually). The eastern half of the basin appears to have higher storage capacity, a lower recession constant, more consistent flow and lower surface runoff components, as observed from the Katar River discharge analysis, compared to the Meki River data (Tenalem Ayenew, 1998).

Despite their common highland origin Katar and Meki Rivers have different flow regimes. The Meki catchment has a very rapid response to rainfall, the flow is less consistent and most of its tributaries are ephemeral. From the recession analysis the average recession constant was found to be 0.0714. Katar has a recession constant of 0.0527. Most of the tributary streams of Meki originating from the Guraghe mountains have little discharge or cease to flow after the rainy season. These streams do not maintain their discharge for longer periods. The steeply sloping recession curve of Meki indicates highly variable flows with a large quick flow component and high recession rates during low flows. The drainage pattern and the scattered rainfall events in the Meki catchment create a series of runoff events from tributaries arriving after each other at the gauging station in the rift floor.

The presence of more permeable rocks, high rainfall conditions and gentler slope in the eastern highlands result in a large discharge and more sustained base flows in the Katar River. In the western highlands the small catchments sustain base flow for short periods. The high recessions in these areas are mainly related to the acidic volcanics, characterized by low permeability, and the steep slopes of the Guraghe mountains. The higher recession constant and low dry season base flow of Meki River, compared to rivers of the eastern highlands, is related to the low storage coefficient of the volcanics of the western highlands where many tributary rivers originate.

Attempt was made to correlate discharge of Meki and catchment rainfall record. The result shows that there is no strong linear correlation between discharge and rainfall. The monthly discharge of Meki is poorly correlated with monthly catchment rainfall, with correlation coefficient of 0.31. The poor correlation is mainly due to the effects of evaporation in the dry season, low moisture conditions in the soil and absorption of rainfall in the interfluves. Another major factor is the time lag between rainfall events in the highlands and the discharge, which is recorded in the rift including channel losses in rift sediments and large faults. Higher correlation coefficients can be obtained when highland stations with complete wet season rainfall records are correlated with discharge for the corresponding months. For example, regression analysis between the wet season rainfall record of Butajira station for 15 years (June to September) and the Meki River discharge over the same period gives a correlation coefficient of 0.79. This means that the summer highland rainfall has an important control over the discharge.

Limitations and comparsions of the two models

Although the recharge seems to be reasonably estimated, both methods have inherent errors and uncertainties. Many authors have addressed the uncertainties of the different recharge estimation methods. Holtschlag (1997) showed the largest discrepancies between different recharge estimation methods. However, general trends were evident and results compared favorably when examining the comprehensive water balance of large areas. Generally many simple soil water balance models involve uncertainties. Rushton and Ward (1979) concluded that uncertainties of 15% should be expected with the soil water balance approach in estimating recharge. Winter (1981) also discussed various errors inherent in measurement and computation of the various components of the water balance, indicating that long-term averages had less error than short-term values. He suggests errors in annual estimates of precipitation, stream flow, and evaporation ranged from 2–15% whereas monthly rates could range from 2–30%.

As a matter of fact strict comparison of the results of the two methods is not straight forward, since there are quite a number of influencing factors varying with time and space. These include the difference in the time of recording, the lumped nature of the results from BFI, against the semi-distributed approach of WATBAL simulations, and channel losses, which are not accounted by the WATBAL model.

In fact comparisons are important as it indicates which method seems to be more realistic in showing the relative importance of the recharge process in the different physiographic regions and the temporal variations. Certainly the BFI model shows better result in demonstrating the temporal variations. While the BFI model is good in indicating the relative importance of recharge in the three physiographic regions.

The general trends of monthly variations of base flow and surface runoff is similar in both methods. At basin wide scale confidence can be put on WATBAL result due to previous validation efforts using integrated approach (Halcrow, 1989; Tenalem Ayenew, 1998). In the transitional escarpment and rift floor WATBAL is expected to underestimate the recharge due to the high degree of fracturing and low rainfall, because, the model does not account such geologic features. At the same time the filtering technique or manual base flow separation may overestimate recharge in the highlands when comparing recharge to other estimates of runoff and base flow. WATBAL tends to overestimate recharge in high runoff regions with deep soils (Walton, 1970).

The advantage of the BFI filter techniques is that it requires only daily stream flow and is easy to apply. On the other hand, water balance models require input data for weather, soils, land use, geology, and topography. The advantage of models is their ability to simulate climate scenarios. Climate scenarios include changes in precipitation, temperature, radiation, humidity, etc. The disadvantage of using base flows as recharge (in BFI model) is eminent when there is upstream substantial channel loss, inter basin groundwater transfer, direct diversions. In this case diversion is negligible and the channel loss is reasonably estimated from field rivers discharge measurements, although the temporal variation of the channel loss may not be well represented.

In case of the WATBAL model, it is important to simulate the major components of the hydrologic budget to determine the impacts of proposed land management, vegetative changes, groundwater withdrawals, and reservoir management on water supply and water quality. To simulate such management scenarios realistically, a model should be able to simulate the individual components of the hydrologic budget. Unfortunately, most field studies at the watershed scale only attempt to measure limited water balance component (*i.e.*, total stream flow, evapotranspiration, *etc.*). For large watersheds under short time periods (months to years), the filtering technique appears to provide additional verification of model parameters and thus aids in model calibration and validation. The inherent problems of such large scale modeling efforts will always be a balancing act between the spatial and temporal variability of the data and the sophistication of the model itself. This research indicates a methodology, which should assist in validating regional scale hydrological analysis efforts.

Unlike the BFI the advantage of WATBAL is that spatial changes in the evapotranspiration component, as influenced by soil and vegetation variations, can be incorporated in this model. The method also has a simple scheme to distribute surplus water over successive months, which can be used for calibration by comparison with the monthly base flows. The model assumes water surplus in the soil zone to be direct recharge. However, there are obvious limitations of the soil-water balance approach in this case.

One of the main drawbacks of the soil-water balance model is the inability to simulate daily hydrometeorlogical data. Large errors can be introduced when the temporal variation of recharge is ignored, *i.e.* by using monthly or annual averages. For example, a soil moisture balance based on monthly data usually indicates no recharge in arid and semi-arid areas, whereas daily or event time steps will show that some recharge can occur (Simmers, 1990). A particular rainfall amount may not cause recharge if it falls as a low intensity event in a period of high evapotranspiration but may produce recharge if it occurs as a high intensity event during the cold time of the year. Average recharge estimates over longer periods should be obtained by summing values over shorter periods; working with longer time intervals may misestimate the recharge. The accuracy of recharge estimation from soil-water balance method depends on proper quantification of the catchment water balance components. The water balance methods of recharge estimation are inherently difficult because of errors involved in determining the required inputs such as precipitation, direct runoff, actual evapotranspiration and changes in soil moisture storage. The major disadvantage is that recharge is the residual of the soil moisture budget and is sensitive to changes of the input variables of aerial precipitation and potential evapotranspiration, which are difficult to measure. However, the advantage of water balance methods is that they use readily available data.

CONCLUSIONS AND RECOMMENDATIONS

The annual lumped basin recharge from BFI and WATBAL models is 80.1 mm and 62.7 mm, respectively. The indirect recharge or channel loss obtained from the Meki River discharge measurement is 14.4 mm. This shows that the result from the two methods agree well.

Considering long-term average data, at any given month base flow of the Meki River is greater than the surface runoff component.

The BFI simulated the temporal variations of base flow well as compared to the classical manual graphic separation, especially during wet seasons. That means the base flows that have traditionally been computed by manual separation of the base flow from the daily discharges can be reproduced using a computerized BFI code easily. Using the BFI value of long-term averages it is possible to estimate the base flow directly from total discharges. These results can be extrapolated for ungauged catchments of similar nature to estimate the runoff coefficient and groundwater recharge. However, such an approach for the rift and escarpment areas has to be considered in extreme caution.

There is a strong positive correlation of river discharge and catchment area in the highlands. This relation diminishes when the catchment area increases due to the presence of climatic gradient and abrupt changes in the geological and geomorphic setting in the rift floor.

The field river discharge attests that the eastern rivers have different flow characteristics and river-aquifer relationships than those of the western escarpment and highland. In the western highlands base flow increases downstream to the foothills of the Guraghe Mountains. Rivers lose water in rift floor sediments and faults unlike the elevated areas where rivers gain water from aquifers.

Strictly speaking neither the soil-water balance model nor the base flow measurements adequately describe the spatial variations of the different recharge processes. The former represents only direct recharge; the latter aggregates recharge in the three physiographic regions and it gives no information on the spatial variation of direct and indirect recharge in the different catchments. However, by using the weighted results of the soil-water balance method for the rift, escarpment and the highlands, a fair agreement can be obtained for the two methods on annual basis.

The rift valley groundwater system is very much dependent on the recharge process in the highland and escarpments and the channel losses from rivers. Therefore, future damming of rivers upstream should seriously consider the effect on the critical rift aquifer system and interconnected rift lakes.

More vigorous long-period systematic river discharge measurements along the course of the rivers may lead to better estimation of the temporal and spatial variations of recharge in a more detailed manner. This has important implications not only for the recharge estimation, but also in lake water balance and level change studies.

Future detailed groundwater recharge estimation in the catchment demands installation of additional automatic river gauges at different points.

Tracer techniques and isotopic study will help in understanding the recharge in the fractured rift floor and the altitude-recharge relationships in the highlands, respectively.

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