Spatial Analysis of Base Flow and Stream Flow from the Abbay River Basin after Watershed Management Interventions

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***Abstract*—Recently, increasing concern in Africa has been registered on the potential impacts on base flow and stream flow due to the implementation of watershed management interventions. This research incorporates spatially monthly geographical hydrological data sets into a developed spreadsheet water balance model to estimate the changes in surface runoff, base flow and stream flow as a result of implementing watershed management interventions in the Abbay River Basin during the period (2010-2018). The model was implemented at sub-catchment level. Considering Year 2005 as a datum for watershed management intervention, results of the modeling and spatial analysis indicated that watershed management interventions relatively reduced surface runoff, increased deep infiltration to groundwater and accordingly increased base flow to the stream. Among the key results in the Abbay Basin that change from Year 2010 to Year 2018 was reduction of surface runoff from the Abbay Basin in the amount of 1,753 million m^3/yr. As a result, an increase in annual base flow in the amount of 23 million m^3/yr was estimated, leaving a reduction in annual mean flow of the Abbay River in the amount of 1,731 million m^3/yr of the Abbay River at El-Diem site. It is expected that the flow of the Abbay River will continue to decrease due to the continuous implementation of the watershed management interventions and agriculture expansion in the Abbay Basin.**

***Index Terms*—Abbay river basin, base flow, hydrological modeling, GIS & RS, soil moisture water holding capacity, surface runoff, stream flow, watershed management interventions.**

I. INTRODUCTION

Land degradation, deforestation and trees cutting for heating and cooking is very common practice in most of the rural areas of the African countries [1]. Increasing water yields and crop productivity are among the positive impacts of reducing soil erosion, deforestation and consequently sediment loads to streams [2]. Soil conservation and watershed management projects aim at decreasing surface runoff, reducing soil erosion, maintaining soil nutrition and improving crop yields [3]. Those actions were not taken care of for decades at sub-basin and sub-catchment levels in Ethiopia [4].

There has been little research on the potential impacts of extensive coverage of watershed management works, for example Soil moisture Water holding Capacity (SWC) interventions on water yield and stream flow. SWC is defined as the maximum ability of a soil to retain water as field capacity soil water content. That water remains in soil after water drained off the large pores. SWC is measured in mm of retained water in severy meter depth of the soil {mm/m} or percentage {%}. In the last 30 years; many watershed-related researches have been carried out by the Ethiopian and international experts and scientists [5], [6]. Reference [7] made provisional estimates on the impacts of constructing 5000 water harvesting ponds for small-scale irrigation schemes in Ethiopia on water yield and the Nile flow. Knowledge of the relationships between surface runoff, stream flow, erosion, sediment delivery and sediment load transport to rivers were still limited [8] and specifically to the Eastern Nile Basin [9], [10].

Soil erosion and land degradation have been identified as major constraints to agricultural development and poverty reduction [11]. Thus; there have been various watershed management interventions carrying-on since 2005 up to now in the Abbay River Basin. It started in small pilot scale, then the significant implementation on larger scale continued after 2009 [12].

Surface runoff is defined as the volume of water runs over the ground surface in a catchment area during a certain period of time. Base flow is defined as the volume of water infiltrates and penetrates within the soil's porous media in a catchment area then transports until it reaches the closest open stream, during a certain period of time. Stream flow is defined as the volume of water passing through a specific cross-section in an open stream during a certain period of time [8].

Whilst models to predict stream flows at the catchment or sub-catchment levels are relatively well developed, prediction at small-scale catchments is not. It is extremely demanding on temporal and spatially detailed hydrological data. In the absence of such detailed data, the use of spatial water balance models on medium-size catchments linked with geographical data on spatial precipitation, evapotranspiration, soils and land use have proved to be effective [13].

This research paper is sought to identify the problem of estimating the relative hydrological changes (not the absolute values) in medium-size sub-catchments, using spreadsheets spatial water balance models due to expanding watershed management interventions in the Abbay Basin between years (2010-2018). Therefore, the objectives of this research are to study, model, analyze and discuss the spatial and temporal relative changes in surface runoff, base flow and stream flow

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as a result of changes in soil conservation works and watershed management interventions.

II. Literature Review

Knowledge on the impacts of major watershed management programmes on base flow and stream flow has been extremely sparse [14], although in Ethiopia some work was carried out at the plot level [15]. A FAO workshop on "Land-water Linkages in Rural Watersheds" made no mention of the potential impact of watershed management (WSM) structures on water yield [16]. Reference [17] examined the impacts of extensive construction of soil and water conservation measures on reducing stream flows of the Yellow River on the Loess Plateau in China at different scales. At the macro-scale, 25% coverage of the catchment with watershed management interventions caused a reduction in flow of the Yellow River by 49% between (1959-1969) and (1990-1995). The variation in flow results inferred the importance of considering the hydrological processes on small catchment-level for more reasonable values estimate.

Work by [14] in the Merguellil Catchment, Tunisia, watershed management interventions coverage increased from 5% to 26% of the catchment in few years. That has resulted in a reduction in runoff coefficients from 4.1% to 2.5% (a 40% reduction) with no changes in precipitation or land cover over the studied catchment. Reference [18] also developed a grid-based water-balance hydrological model for the Nile Sub-basins as part of a research to determine the fluctuations of precipitation and stream discharges. That study made estimates of runoff coefficients for each sub-basin. References [19], [20] also used a similar approach to assess the annual Blue Nile flows in the context of climatic change. Reference [21] had also used a modified water balance approach to estimate runoff for the White and Blue Nile Basins using satellite derived rainfall and the other relevant hydrological parameters. In the Abbay-Blue Nile Basin; Reference [22] made use of a water balance model calibrated by stream flow data for a number of sub-catchments but not for the whole basin. At that time, the use of spatial water balance models was not technically matured enough.

III. The Study Area and Its Hydrological Features

The Abbay-Blue Nile Basin (Fig. 1) covers an area of 311,548 km2. Its main stream channel length is of 922 km. It flows starting from Lake Tana about 1295 m downstream of the Lake, where the spectacular Tiss-isat Falls exists. Thereafter, the river enters the deep Abbay Gorge. The Abbay River extends from western Ethiopia crossing the borders to the low-lands of The Sudan at El-Diem, then becomes the Blue Nile till meeting the Main Nile at Khartoum. The Dinder and Rahad rivers rise to the west of Lake Tana then seasonally flow into westwards across the border with The Sudan joining the Blue Nile below Sennar. Along the way, the Abbay-Blue Nile is joined by a number of tributaries: Beshilo, Derame, Jema, Muger, Finchaa, Didessa and Dabus from the east and south, and the Suha, Chemoga, Keshem, Dera and Beles from the north. Fig. 1 shows the hydrological schematization of the Abbay Basin in Ethiopia.

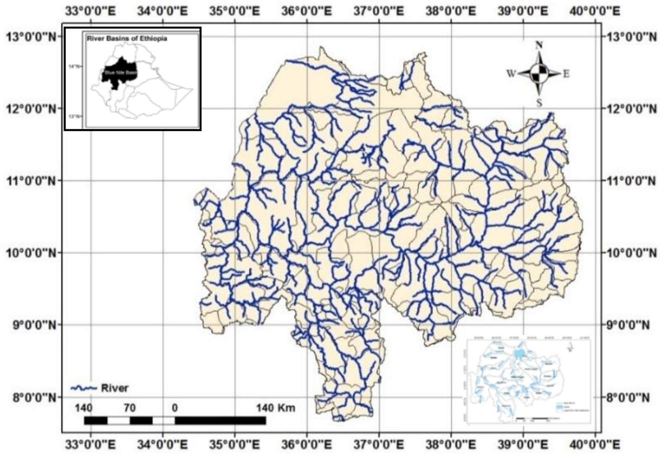

Fig. 1. Hydrological schematization of the Abbay Basin.

The total renewable water resources of Ethiopia were estimated at over 123 billion m^3. The Abbay Basin contributes about 50 billion m3 (40.6%). The irrigation potential of Ethiopia was assessed through master plan studies, and was estimated to be 3.5 million hectares (ha) [23]. Among the key challenges encountered those sub-basins, were sheet and gulley (ditches) soil erosion, reductions in agricultural production, breaches in soil nutrient cycles, loss of nitrogen and phosphorous, high sediment loads in the Abbay River and its tributaries, and the consequent siltation of dams' reservoirs along the course of Abbay-Blue River. This is evident in the Roseires, Senner and Maroes' reservoirs and in the Geizera-Managil and Rahad irrigation channels. Same sedimentation process could be expected to occur in the newly constructed Grand Ethiopian Renaissance Dam's reservoir. The intense precipitations, highly dissected nature of the Abbay Basin and its hilly topography led to shallow groundwater tables and no large groundwater aquifers exist [24].

A. *Physical Settings of the Study Area*

This research focuses on the Abbay Basin in Ethiopia (starting from Lake Tana till the borders with The Sudan at El-Diem site) with total basin area of about 187,464 km2 (equivalent to 18,746,457 ha) including catchments of all tributaries reaching and feeding the Abbay River [24]. The Dinder and Rahad rivers join the Blue Nile below the border with The Sudan (downstream El-Diem site). Their catchments are largely located within the low-lands with little high-lands agriculture and few seasonal flows; therefore, those two tributaries were excluded from this research paper. Ground surface mean elevations in the Abbay Basin range from 490 m above mean sea level (a.m.s.l), where Abbay River crosses The Sudan borders, to approximately 1788 m a.m.s.l at high-lands of Tana Lake. However, most of the Abbay Basin's lands are located between altitude 600 m and 2600 m a.m.s.l, with dominant altitudes ranging from 1300 m to 2200 m. As spatial distribution of temperature values is strongly related to altitude, the Abbay Basin is characterized by lowest minimum mean monthly temperature in Ethiopia that ranges from 3^oC to 21^oC.

B. Water Bodies in the Study Area

As Tana Lake has a surface area of 3,042 million m^2, it accounts for 50% of the total inland water of Ethiopia. The Lake stores 29.18 million m3 of water which seasonally fluctuates between altitude 1,785 and 1,787 m a.m.s.l. The outflow from The Lake is about 3.7 million m^3/yr. The Lake suffers from high annual evaporation rates (about 64% of its capacity). Prior to the construction of Chara-Chara Spillway at the Lake outlet in 1996, the average outflow of Lake Tana ranged from 10 m3/sec during (May and June) to more than 350 m3/sec during (September and October). After Chara-Chara Spillway, The Abbay River flow has been regulated and its discharge has been standardized at 110 m^3/sec [25]. Then, Beles Hydroelectric Power Plant, located near the outlet of Lake Tana, was completed in May 2010. It generates hydroelectric power while the flow runs freely without forming a reservoir. Additional water is discharged through its tunnel from the Lake into the Beles River, so that Abbay River releases flow with an average of 17 m^3/sec [25].

C. Precipitation and Potential Evapotranspiration

Precipitation distribution in the Ethiopian high-lands ranges from nearly 2000 mm/yr to less than 200 mm/yr at Khartoum. Annual mean precipitation across the Abbay Basin, as calculated using GIS from the digital precipitation map is about 1352 mm/yr, with monthly totals ranging from 10 mm in January to 304 mm in July. Annual precipitation ranges from 916 mm in the eastern part of the Abbay Basin to 1951 mm in its central western edge [26]. Annual mean potential evapotranspiration (ETo) across the Abbay Basin is about 1432 mm, ranging from 1809 mm on the far west to 1236 mm on the high ground around Mount Choke. Monthly totals range from nearly 140 mm in (March-April) to 104 mm in (July-August). Precipitation exceeds potential evapotranspiration from June to September [26]. Long-term mean monthly precipitation (P) and potential evapotranspiration (ET_o) across the Abbay Basin are in Fig. 2.

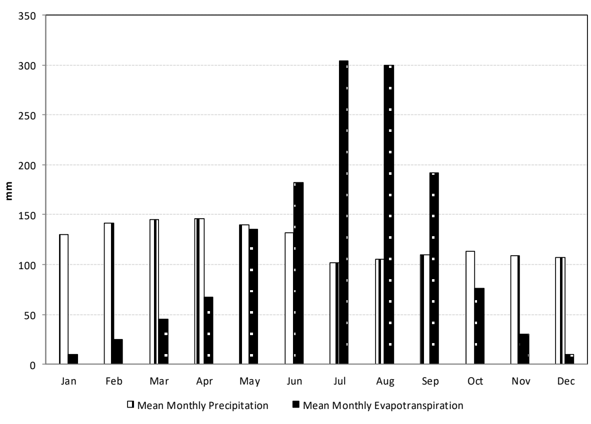

Fig. 2. Typical mean monthly precipitation (P) and evapotranspiration (ET_o) across the Abbay Basin - *source: Reference [26]*.

D. Soil Types and Land Cover

Soils in the high-lands overlying the Trapp Basalts are moderately deep (100 cm) clay loams except on steep slopes, where they are much shallower. On bottom-lands and flat areas heavy clay vertisols exist. In the low-lands overlying the basement complex rocks gravellier shallower soils exist on steeper slopes grading in to heavy black clays on the flat slopes near the borders with The Sudan. Area subjected to watershed management interventions was obtained from the updated Agricultural Census conducted originally by the Ethiopia Central Statistical Office (CSO). It was found that SWC ranges from 75 mm/m on steep slopes to 150 mm/m on the heavy clays [27]. The high-lands' land-cover is sedentary rain-fed agriculture (without human irrigation works induced) with communal grasslands and shrub-lands. In the low-lands there are extensive wood-lands with patches of shifting cultivation, although increasingly large areas are being cleared for large scale rain-fed agriculture. Land-cover spatial data in the Abbay Basin was obtained from FAO database (WBISPP-MARD Land Cover Maps) for Amhara, Beneshangul-Gumuz and Oromiya Regional States. Land-cover classification maps were standardized to the FAO Land Cover Classification System (LCCS), [16]. The principles of Curve Number (CN) method adopted in this research to determine the surface runoff depended on the United States Natural Resources Conservation Service (NRCS-CN) of the US Department of Agriculture [28].

E. Surface Runoff in the Abbay Basin

Although the Abbay Basin is the second largest drainage area in Ethiopia, it has the highest surface runoff, estimated at about 51 billion m^3/yr. The Abbay Basin accounts for about 50% of all water runoff in Ethiopia. Abbay River contributes to about 62% of the Nile flow into Lake Nasser/Nubia and about 72% of the total Ethiopian water contribution to the River Nile. Based on [25], comparing the mean monthly flows of Abbay River at Lake Tana and at The Sudan borders (El-Diem site) indicated that there is about 10 times increase in flow magnitude between sites of outlet of Lake Tana and The Sudan borders at El-Diem site resulting from the Abbay tributaries feeding along its course within Ethiopia.

The spatial analysis done by Reference [29] targeted the estimate of sub-catchments surface runoff within the Abbay Basin. Runoff from the individual sub-catchments was considered total runoff, which means no allowances were made for the small evaporation and other channel conveyance losses. The highest runoff areas were located to the southwest of Mount Choke, East Wellega and West Wellega High-lands. Didessa, Dabus, Middle Abbay and Beles catchments had the highest runoff rates. Beshilo, Durame and Dinder-Rahad had significantly lower rates.

F. Historical Stream Flow

Reference [30] informed that there were considerable seasonal variations in the Abbay-Blue Nile flow along its course during years (1912-1997). The monthly mean low flow of The Blue Nile was about 302 million m3/month in February and its monthly mean peak flow was about 15,151 million m3/month in August. In contrast to the White Nile, the flow is highly seasonal being concentrated between July and October, as in Fig. 3.

The annual mean measured flow of Abbay River at El-Diem site during the years (1912-1997) was about 48,658 million m^3/yr [30]. After 1997 and till 2013; the annual flow data-sets were acquired from the Nile Basin Initiative's data knowledge bank. El-Diem site's annual mean flow scored about 49,564 million m^3/yr during the period (1997-2013). The measured water levels and flow records after 2013 have not been accurate because El-Diem site was inundated by the expanded reservoir of the Roseires Dam after its heightening that was completed in 2013 [31].

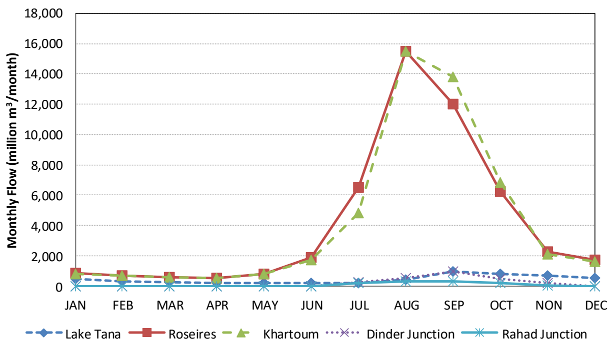

Fig. 3. Typical long-term monthly flow of Nile River at key sites during (1912-1997) - source: Reference *[30]*.

Accordingly, the annual mean flow at El-Diem site during the long time series of years (1912-2013) only -not up to now- was estimated at about 49,111 million m^3/yr. The long-term annual mean flow and its trend-line of the Abbay River at El-Diem site in million m^3/yr during (1965-2013) are in Fig. 4.

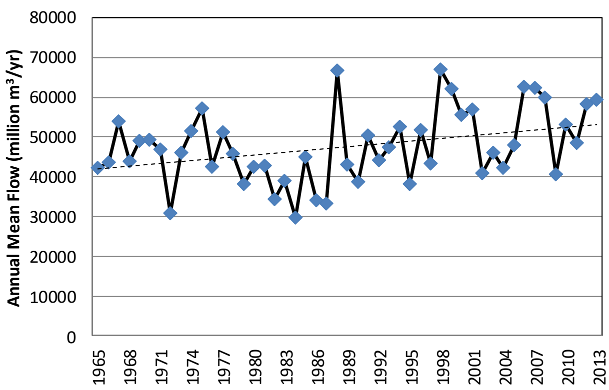

Fig. 4. Estimated annual mean long-term Abbay River flow and its trend-line of the Abbay River at El-Diem site during (1965-2013).

IV. Materials and Methods

A. *Modeling Methodology and Formulation*

Spreadsheet (Microsoft Excel) approach provides simple yet effective hydrological modeling [13]. This research developed and used a simple spreadsheet spatial water balance model to estimate precipitation distribution, soil evaporation (Es), crop/vegetation evapotranspiration (ETc), base flow (BF) and surface runoff (RO) in each sub-catchment (134 calculation units - so-called weredas in the Abbay Basin). The model used was linear, so that the calculation units were not hydraulically connected (no flow boundary). Monthly time-step of spatial measured precipitation and potential evapotranspiration data were used in this research. Those assumptions were considered fair as the target of this research paper is to estimate the relative changes in hydrological parameters not the specific values. Fig. 5 (a & b) illustrates the conceptual design framework and the hydrological processes simulated in the simple spatial spreadsheet (Microsoft Excel) modeling tool used in this research.

Estimating changes in surface runoff was done comparable to the United States Natural Resources Conservation Service (NRCS)'s runoff procedure [28]. The relevant hydrological parameters and coefficients used by the United States Department of Agriculture (USDA)'s Soil Conservation Service Curve Number (SCS-CN) method were adopted and used [28], [32]. The hydrological processes' equations described below were developed and impeded in the Microsoft Excel sheets.

The precipitation data used in this research was published by the International Institute for Applied Systems Analysis (IIASA) as indicated by [33]. The IIASA data was on a 0.5-degree grid. Monthly precipitation data for each cell were provided from weather stations averaged over the period from (1965 to 2013). This research used the mean monthly precipitation for each wereda in the Abbay Basin (134 weredas) based on the measured rainfall at the relevant weather stations within the Abbay Basin done by [26]. Using spatial extrapolation (nearest neighbour using Thiessen polygons), a value was computed for each calculation unit (wereda) based on values for the closest station [26]. The evapotranspiration data sets were estimated using the Penman-Monthieth method [34]. Finally, each wereda's monthly mean precipitation and potential evapotranspiration were estimated using the "Group" routine in ARCGIS. For verification purposes, digital monthly precipitation and potential evapotranspiration maps were obtained from the FAO's AQUSTAT. The potential evapotranspiration data were compared by IIASA for FAO. The resolution was the same (0.5-degree grid) of the mean monthly values during the same study period. The input data used in the calculations were part of the "CRU Global Data Set" developed by the Climate Research Unit of the University of East Anglia Climate Research Unit, UK and distributed by the International Panel on Climatic Change (IPCC).

Limited WSM program started in the Abbay Basin in 2005 on small scale, however has become effective with reasonable coverage few years after. The latest available data on watershed works and interventions that could be acquired for this research was up to year 2018. Remote sensing technology was used to determine the change in land-use/land-cover during the period (2010-2018) including the implemented watershed management interventions. Land cover in the Abbay Basin was obtained from FAO imageries database (WBISPP-MARD Land Cover Maps). Land cover classifications were standardized to the FAO Land Cover Classification System (LCCS) for both Year 2010 and Year 2018.

Soil classification and runoff retention (staying over lands for a certain period of time) coefficients for various watershed management interventions were estimated by the available date from the Ethiopian Soil Conservation Research Center (SCRC) including crops, soil bunds and grass strips. An average SWC of 102.5 mm/m was used in this research during the simulation of Year 2010 [26]. Whereas, with repeating cropping and harvesting processes; remaining crop roots and biomass residuals decayed forming additional organic matters to the soil, led to improved soil contents and structure [35]. Accordingly; SWC was assumed 104 mm/m for Year 2018. Although the difference in numbers (between 102.5 and 104 mm/m) appears insignificant, but SWC is a sensitive parameter in the derived equations used to estimate surface runoff and accordingly base flow in the Years 2010 and 2018.

Spatial hydrological data sets and variables were inserted monthly as input data in the simple spreadsheet Microsoft Excel spatial water balance model for the Year 2010 and Year 2018. The model parameters and coefficients were inserted as constant values. Calibration of the model used was done by comparing the summation of estimated surface runoff and base flow for specific weredas in the Abbay Basin with the measured stream flows at El-Dim and at Kessie sites on the Abbay River. The following are the key model parameters, coefficients and results during the hydrological simulation of the Year 2010.

1) Precipitation distribution (P)

The governing factor in the hydrologic mass balance equation is precipitation distribution (P). It included also actual crop evapotranspiration (ETc), soil evaporation (Es), deep drainage to groundwater (DD), soil water (SW) and surface runoff (RO). The estimated runoff is thus: RO = P – ETc – Es – DD - ΔSW. The Abbay Basin had an overall estimated annual mean precipitation (P) of 1,334 mm, for the Year 2010. This research assumed no change in precipitation volume for the Year 2018, as in Table I.

2) Evapotranspiration (ET)

The Abbay Basin had an overall estimated annual mean potential evapotranspiration of 1,429 mm (107% of P). The actual cropland evapotranspiration from the Abbay Basin was about 509 mm (39% of P). The actual non-cropland evapotranspiration was higher because the vegetation was transpiring for a longer period of time and was estimated at about 653 mm (54% of P) annually from the Abbay Basin, for the Year 2010.

3) Soil evaporation (Es)

Precipitation on or in the soil that is utilized by crop or non-crop vegetation evaporates up to the rate of potential evapotranspiration. Annual soil evaporation on cropland was estimated about 279 mm (21% of P) in the Abbay Basin. Annual soil evaporation on non-cropland was estimated about 61 mm (5% of P), for the Year 2010.

4) Change in soil water (ΔSW)

Soils on steeper slopes in the Ethiopian High-lands are generally shallow (less than 1.0 m depth) and of medium texture. The SWC in the Abbay Basin was originally assumed to be 103 mm/m in Year 2010. This was adjusted (from 102.5 to 103 mm/m) during the calibration of the calculated total runoff to river with the long-term measured annual mean flows. In the monthly calculations, precipitation that was not utilized by crops or non-crop vegetation or lost to soil evaporation went to SWC up to a maximum of 103 mm/m. This could be utilized in the following time-step (month) either by crop or non-crop vegetation or soil evaporation.

5) Deep percolation percentage to groundwater and to Abbay River (Base Flow – BF)

For determining the proportion of groundwater contribution to the deep groundwater aquifer and the portion goes to the river, that proportion during the dry season flow (November to April) to total groundwater flow was calculated. It was assumed that all-over-the-year groundwater would continue to contribute to river flow at the same rate of the dry season. The estimated proportion of the annual precipitation that contributes to groundwater was estimated about 17 mm (1.3% of P) from the entire Abbay Basin, for the Year 2010.

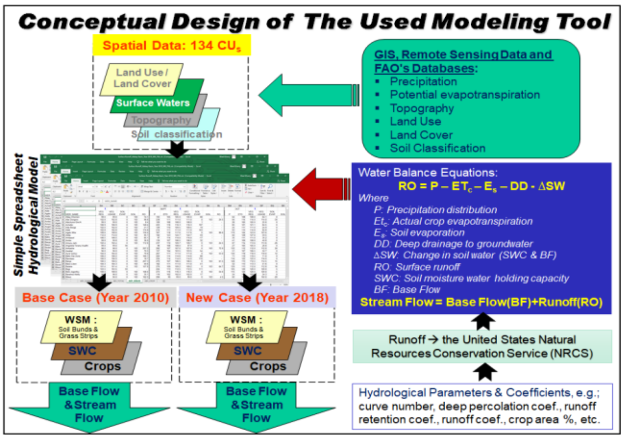

Fig. 5a. The conceptual design framework of the hydrological processes done within the simple spatial spreadsheet model used.

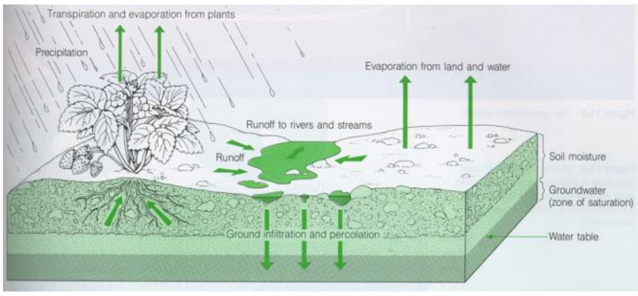

Fig. 5b. The physical hydrological processes considered in the simple spatial spreadsheet model used.

6) Runoff retention coefficient by soil conservation interventions

The Ethiopian Soil Conservation Research Center (SCRC) undertook a wide range of projects, observations and experiments in seven research areas of Ethiopia in the 1980's and '90's. That included the impact of a number of soil conservation interventions on surface runoff and soil erosion. The results were summarized by [15] and were used in this research. Two types of interventions were adopted in the WSM Programme in the Abbay Basin for Years 2010 and 2018; which are soil bunds and grass strips. There was ample evidence that in high rainfall areas, farmers used physical interventions (stone and soil bunds) and resulted in water-logging (water builds a depth stays over land for a certain period of time) behind the bunds thus depressing yields [2], [3]. Then, farmers used good agricultural practice by planting grass strips that are almost as efficient in retaining soil as soil bunds but slowly releasing surface runoff so as not to cause water-logging.

The SCRC found that level soil bunds retained between 25% and 94% of surface runoff, yet grass strips retained only

19% to 53% of surface runoff at the wereda level. For the Year 2010, an average of 60% surface runoff retention was adopted for level soil bunds and 30% for grass strips. While for the Year 2018, a proportional increase in the soil bunds and grass strips were considered that an average of 70% surface runoff retention was adopted for level soil bunds and 40% for grass strips.

The equivalent USDA's Soil Conservation Service Curve Number (SCS-CN) procedure to determine the surface runoff is using composite CN (grass, crops and bunds) ranges between (72-68) during the Years (2010-2018), under Antecedent moisture condition (AMCIII), provided that variable monthly measured precipitation, lower surface runoff with higher infiltration rates were expected (Hydrological Soil Group is "A"), hydrological soil conditions (poor to fair) and soil management was fairly practiced [26].

Reference [15] indicated that water-logging problems were significant where annual mean rainfall exceeded 1,300 mm. For those weredas with an annual mean rainfall of 1,300 mm or more it was assumed that farmers would adopt grass strips only. In the sensitivity analysis, the calculations incorporated a range of potential runoff retention rates for various soil bunds and grass strips percentages.

7) Runoff (RO)

Precipitation that was not utilized in crop or non-crop transpiration, lost to soil evaporation and which exceeded the SWC went as surface runoff (RO). Gross RO was estimated in this research so it did not consider allowances for evaporation losses or other conveyance losses. Based on the analysis done in this research, which was also in good match with the analysis done by [18]; annual RO from cropland amounted about 218 mm (17% of P) in some catchments in the Abbay Basin. While annual runoff from non-crop vegetation amounted about 237mm (18% of P), for the Year 2010.

8) Runoff coefficient

Maximum, minimum and average runoff coefficients in the Abbay Basin was estimated by [36] as 17%, 15% and 16.6%; respectively. The product of annual mean precipitation rate and area of each wereda was summed to obtain an estimate of the total annual volume of precipitation over the study area. Summed runoff of each wereda was divided by the total volume of precipitation to obtain Abbay Basin's estimate of the overall runoff coefficient. The estimated overall RO coefficients in this research were about 17.43% for croplands and about 17.71% for grass strips for the Year 2010, with weighted average of 17.60%. However; the estimated RO coefficients were about 17.30% for croplands and about 17.28% for grass strips in the Year 2018, with weighted average of 17.29% within the Abbay Basin.

9) Area of cropland

The rainfed cropland areas within the Abbay Basin were considered in this research (estimates of Year 2010 and Year 2018). The area of cropland was estimated as the product of current number of farm families and average cropped area in the same wereda, based on the available official Ethiopian Agricultural Censuses. It was also verified by calculating areas of the detected cropland with soil loss (erosion) rates above 12.5 tons per ha/yr from the digital soil erosion map of Abbay Basin. This soil erosion rate is considered high compared with its values in forests and other similar high-lands with steep slopes [26].

B. Watershed Management Interventions Extent for Year 2010 and Year 2018

Ethiopia targets to implement a long-term national land development program including watershed management and soil conservation projects in a number of river basins. This program aims at stopping deforestation, soil erosion, nutrients depletion and improving crop productivities. The Abbay Basin comes at the top of the national development priority agenda of Ethiopia. Within the Abbay Basin, a set of water management projects as well as rainfed-agriculture expansion projects have been under implementation since the (datum) year 2005 [10]. Up to 2030, Ethiopia's national plan targets to cover up to 40% of the Abbay Basin area. In year 2010, that implementation covered 28% of the Abbay Basin area [24]. References [37], [38]; informed that up to year 2018, land development projects in the Abbay Basin covered only about 30% of its area (equivalent to about 5,623,937 ha). In the agricultural expansion areas, surface irrigation is practiced using the nearby small tributaries of the Abbay River [39]. The watershed management interventions (soil bunds, small shrubs and grass strips) have increased from 18% in Year 2010 to 20% in Year 2018 in the agricultural expansion areas (equivalent to 3,374,362 ha and 3,749,291 ha; respectively) [40]. Table I highlights the estimated hydrological, SWC and land cover changes considered and used in the water balance model developed and adopted in this research for Year 2018 vs. Year 2010 in the Abbay Basin.

TABLE I: THE HYDROLOGICAL VARIABLES AND PARAMETERS USED IN THE SIMULATIONS OF YEAR 2018 VS. YEAR 2010 IN THE ABBAY BASIN

Hydrologic, SWC or Land Cover Change (for the modeling purpose)	Year 2010	Year 2018
Total Abbay Basin area 134 calculation units (weredas)	18,746,457 ha	
Total precipitation (P) distributed monthly over 134 weredas	255,965 million m^3/yr	
Grassland area	72% 13,489,362 ha	70% 13,121,003 ha
Cropland area	28% 5,257,094 ha	30% 5,625,453 ha
Croplands rainfed area with soil bunds and grass strips	18% 3,374,362.17 ha	20% 3,749,291.30 ha
Soil Water Holding Capacity (SWC), mm/m	102.5 - 103	104
Runoff retention behind soil bunds	60%	70%
Runoff retention behind grass strips	30%	40%
Soil evaporation (E_s) of total (P) – cropland	42%	42%
Soil evaporation (E_s) of total (P) - grassland	27%	27%
Evapotranspiration (ET_c) of total (P) – cropland	39%	39%
Evapotranspiration (ET_c) of total (P) – grassland	54%	54%

Base flow to groundwater (BF) of total (P) – cropland	1.30%	1.30%
Base flow to groundwater (BF) of total (P) – grassland	1.25%	1.25%
Percentage of base flow to River flow	100%	100%
Overall runoff coefficient - cropland	17.4%	17.3%
Overall runoff coefficient - grassland	17.7%	17.2%

V. Results and Discussion

A. Verification of the Modeling Tool

The summation of all individual runoff and base flow values from the 134 weredas represents the estimated stream flow at El-Diem site. Therefore, and for calibration purpose, the spatial spreadsheet model showed that the hydrological simulation of the Year 2010 estimated the total annual mean flow of the Abbay River at El-Diem site is about 48,372 million m^3/yr, which was within 1.5% error tolerance less than the long-term measured annual mean flow (49,111 million m^3/yr). The annual measured flow at El-Diem site in 2010 by [41] was 52,958 million m^3/yr, thus measured and estimated values were within 8.6% error tolerance. In addition, a validation check was conducted in this research through comparing the total annual mean flow of the Abbay River at Kessie site. The measured flow at Kessie site is equivalent to the summation of individual runoff and base flow from 66 weredas in 8 sub-catchments: Mirab Gojam, Semen Gonder, Debub Wello, Semen Shewa, Awi, Semen Wello, Misrak Gojam and Debub Wello. That value was compared with the simulated value during Year 2010 simulation. It was found that simulated base flow was 1,315 million m^3/yr and surface runoff was 18,688 million m^3/yr. Thus, the estimated annual mean flow at Kessie site was 20,004 million m^3/yr while the measured long-term annual mean flow at Kessie site was 20,480 million m^3/yr [42]. This was a good match within 2.3% error tolerance. It was decided that the model performance is good enough to predict the relative changes in base flow and runoff within the Abbay Basin between Years 2010 and 2018.

B. The Estimated Target Hydrological Components

The following Tables II and III present the major estimated results from the hydrological simulations carried out using the simple spreadsheet spatial water balance model developed and used in this research for the Year 2010 and the Year 2018.

C. Stream Flow, Surface Runoff and Base Flow Analysis

The hydrological simulation of the Year 2018 showed total stream flow of the Abbay River at El-Diem site as 47,520 million m^3/yr. That value was less than its value in the Year 2010 by about 852 million m^3/yr (within 3.2% less of the long-term measured flow at El-Diem site). In Year 2010, about 17.8% of cropland was served with watershed management interventions (about 937,482 ha) while in Year 2018, about 40.2% of cropland was served with watershed management interventions (about 2,260,468 ha). Therefore, runoff from cropland was about 26.9% and about 29.0% of total runoff, for Year 2010 and Year 2018; respectively.

TABLE II: Comparison of Estimated Hydrological Values in the Abbay Basin as a Result of the Watershed Management Interventions, Year 2010 Vs. Year 2018 – at El-Diem Site

Hydrological Values	Unit	Year 2010	Year 2018	Δ%
Runoff cropland (rainfed)	Mill. m^3/yr	12,155	12,856	+5.77
Runoff grassland (rainfed)	Mill. m^3/yr	32,973	31,419	-4.71
Total direct overland runoff	Mill. m^3/yr	45,128	44,276	-1.89
Base flow goes to groundwater	Mill. m^3/yr	3,244	3,244	+0.03
% of base flow to groundwater vs. direct overland runoff	%	7.19	7.33	+1.95
Estimated Total flow at Abbay River	Mill. m^3/yr	48,372	47,520	-1.76

TABLE III: Comparison of Estimated Overall Relative Results as a Result of the Watershed Management Interventions, Year 2010 vs. Year 2018 in the Abbay Basin

OVERALL RESULTS	Unit	Year 2010*	Year 2018*
Area cropland with watershed management interventions	ha	937,482	2,260,468
Runoff retained	Mill. m^3/yr	869	2,645
Runoff thru soil bunds and grass strips	Mill. m^3/yr	986	2,487
Increased base flow to the Abbay River	Mill. m^3/yr	11	34
Percentage increased base flow to the Abbay River	%	0.3	1.0
Reduction of total surface runoff	Mill. m^3/yr	858	2,611
Percentage reduction of total surface runoff	%	1.8	5.3
Net Reduction in the Abbay River Flow	Mill. m^3/yr	847	2,578
% Net Red. in the Abbay River Flow	%	1.7	5.2

* *Datum is WSM starting Year 2005*

Considering Year 2005 as a datum year, the total reduction in stream flow (i.e. due to reduction in surface runoff) caused by the watershed management interventions up to Year 2010 was estimated at 858 million m^3/yr (about 1.8% of the long-term annual mean flow at El-Diem site). This was offset by an increase in base flow to the river of 11 million m^3/yr (about 0.3% of base flow to the river) or (about 0.02% of total estimated annual mean flow at El-Diem site). The net reduction in annual mean flow was estimated at 847 million m^3/yr (about 1.7% of the long-term annual mean flow at El-Diem site).

Total reduction in stream flow caused by the continued implementation of watershed management works and interventions as well as implementing the agriculture expansion plans up to Year 2018 was estimated at 2,611 million m^3/yr (about 5.3% of the long-term annual mean flow at El-Diem site). This was offset by an increase in base flow to the river of 34 million m^3/yr (about 1.0% of base flow to the river) or (about 0.07% total estimated annual mean flow at El-Diem site). Thus, the net reduction in annual mean stream flow was estimated at 2,578 million m^3/yr (about 5.2% of the long-term annual mean flow at El-Diem site).

The relative reductions in annual mean stream flow resulting from the implementation of the WSM program should be seen from the prospective that it causes significant variation in stream flow similar to the potential variations in stream flow due to change in precipitation pattern. It is evident that the stream flow increases in the Abbay River as the trend-line shows in Fig. 4, of the long-term annual mean flows of the Abbay River at El-Diem site during (1965-2013). Reference [26] informed that the minimum flow of 21 million m^3/yr was scored in year 1913 (a reduction of about 43% of the long-term annual mean flow), while the highest flow of 71 million m^3/yr was scored in year 1929 (an increase of about 45% of the long-term annual mean flow). Therefore; the estimated reductions in annual mean flow of the Abbay River at El-Diem site due to the WSM program were thus considerably less than the long-term recorded natural variation in flows. Although that reductions in Abbay River flow is small, the continuous implementation of the national planned WSM program in the Abbay Basin with the same pace or with a higher pace warns more significant reductions in the Abbay River flows in the future.

D. *Change in Surface Runoff Due to Change in Watershed Management Intervention*

It was found that from Year 2010 to Year 2018, changing the runoff retention from 60% and 30% to 70% and 40%; respectively behind soil bunds and grass strips, reduced the net stream flow from about 1.7% to 5.2%. On the other hand, changes in surface runoff through soil bunds and grass strips was estimated to be increased from about 986 million m^3/yr in Year 2010 to the amount of 2,487 million m^3/yr in Year 2018. Summary results for that hydrological analysis is in Table IV.

TABLE IV: SUMMARY OF WSM IMPACTS ON RELATIVE BASE FLOW AND STREAM FLOW VALUES IN THE ABBAY BASIN

Case	Gross Impact on Runoff		A portion goes to Base Flow		Net Impact on Flows*	
	Mill. m^3/yr	% total flow*	Mill. m^3/yr	% base flow*	Mill. m^3/yr	%
Year 2010	-858	-1.8%	+11	+0.3 %	-847	- 1.7
Year 2018	-2,611	-5.2%	+ 34	+ 1.0%	- 2,578	- 5.2%

* *In comparison to the long-term annual mean flow of Abbay River at El-Diem site.*

E. *Sensitivity Analysis*

This research examined the sensitivity of change of surface runoff retention when percentage of coverage and intensity of soil bunds and grass strips interventions differ in the Abbay Basin considering the Year 2018. The purpose of this analysis is to determine the limit of applying watershed management interventions that should not be exceeded in the Abbay Basin, so as to gain better crop productivity and prevent water logging problem. The simulations incorporated various intensities of soil bunds and grass strips and estimated the equivalent potential surface runoff retention, Table V.

Surface runoff retention and coverage of watershed management interventions are directly proportional. The sensitivity of surface runoff retention indicatively showed further increase when the coverage and intensity of soil bunds and grass strips interventions exceeded the limit of (60% & 30%); respectively. So, it is not recommended to increase watershed management interventions passing that limit in order to avoid water-logging occurrence and accordingly the possible reduction in crop productivity afterwards.

TABLE V: SENSITIVITY ANALYSIS CONSIDERING THE YEAR 2018 SIMULATION

Changing percentage of runoff retention (% soil bunds & % grass strips)	Net reduction in annual Abbay River flow at El-Diem site	
	Mill. m^3/yr	%
30% & 15%	1,066	2.2%
40% & 20%	1,421	2.9%
50% & 25%	1,776	3.6%
60% & 30%	2,132	4.3%
70% & 40%	2,645	5.4%

F. *Spatial Demonstration of Results*

For the Year 2010, Fig. 6 shows the spatial patterns of the annual mean runoff (mm/yr) on weredas level in the Abbay Basin. For special comparative illustration; the equivalent spatial patterns of the annual mean runoff in the Year 2018 are in Fig. 7. The spatial runoff distribution differed slightly between the Year 2010 and Year 2018 (within the same color pallets/rages). The overall amounts decreased from 45,128 to 44,276 million m^3/yr. It is anticipated that more variations in surface runoff should appear with the continuation of the WSM implementation. It is obvious form Fig. 6 and 7 that the highest runoff amounts occurred in the central parts and southern parts of the Abbay Basin.

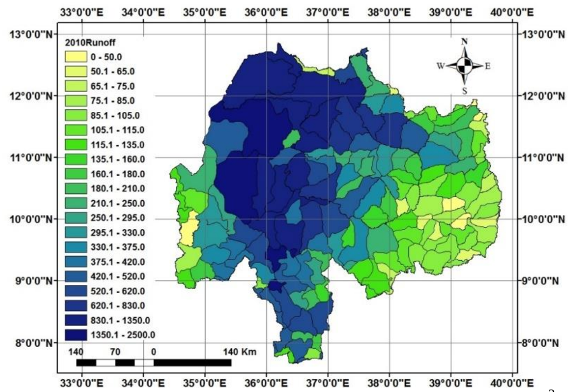

Fig. 6. Simulated annual spatial runoff in the Abbay Basin (mill. m^3/yr) – year 2010.

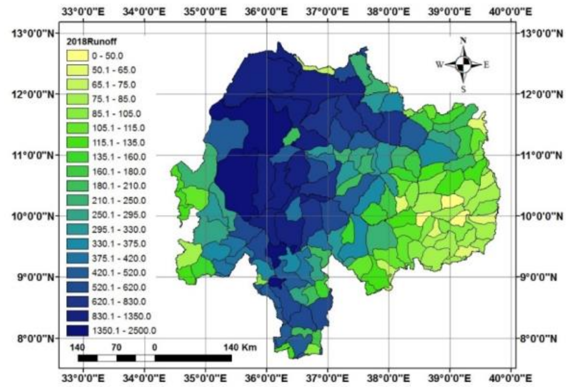

Fig. 7. Simulated annual spatial runoff in the Abbay Basin (mill. m^3/yr) – Year 2018.

VI. Conclusion and Recommendations

That detailed spatial analysis using the geographic data and the spreadsheets water balance model led to realistic estimates of relative surface runoff, base flow and stream flow components in the Abbay River Basin. Results of the modeling tool indicated that watershed management interventions reduced surface runoff and increased base flow in croplands significantly. Focusing on the period (2010-2018); it was found that expansion in cropland (by 2%), soil bunds and grass strips in the Abbay Basin reduced surface runoff by about 3.4%, thus accordingly increased soil moisture and infiltration into the groundwater. Although more base flow resulted from the expansion in the watershed management interventions (about 0.7%), less flow of the Abbay River was estimated (about 3.5%) due to the additional crop water requirements in the Abbay Basin. Watershed management interventions reduced surface runoff from croplands during Year 2010 till Year 2018 by about 1.8% and 5.3%; respectively. It also increased base flow by about 0.3% and 1.0%; respectively and accordingly decreased flow of the Abbay River by about 1.7% and 5.2%; respectively.

Although the reductions in Abbay River flow is relatively small, the continuous implementation of the national planned WSM program in the Abbay Basin with the same pace or with a higher pace warns more significant reductions in the Abbay River flows in the future. In general, current and future agricultural expansion plans in the Abbay River Basin could lead to significant reduction in the Abbay River flows to the downstream of the Nile River.

Mathematical modeling of small catchments on small time-step (10-days or daily) using GIS tools including the hydrological processes as well as its interconnected processes is needed for reliable estimate of spatial and temporal changes in surface runoff, base flow and stream flow from the Abbay Basin. Also; integrated strategic and community-level planning supported by a strengthened agricultural services and research is needed for sustainable development of the Abbay Basin.

Conflict of Interest

The author declares no conflict of interest.

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