**Prediction of Sediment Inflow to legedadi Reservoir Using SWAT Watershed and CCHE1D Sediment Transport Models**

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## Abstract

In this research, attempts are made to assess the amount of sediment inflow and the total quantity that is deposited to date in Legedadi Reservoir. This was executed as this reservoir is the main water supply source of Addis Ababa City that is losing its capacity due to sedimentation. This was obvious from the bathymetric surveys that were undertaken during the period 1979-1998, where sediments were found to be accumulating at a rate of 0.11 Mm3/year for the intervening period. The assessment was undertaken using SWAT watershed and CCHE1D sediment transport models together in tandem. As a conclusion, it was found that the computed values agreed well with the measured and bed profiles.

***Key Words*** CCHE1D, SWAT, Bathymetry, DEM, Sedimentation

## 1. INTRODUCTION

The Metropolitan Area of Addis Ababa is supplied with water from three main sources: Legedadi and Dire Reservoirs (constructed in 1967 and 1998, respectively) located at the east of the city; and Geffersa reservoir (constructed in 1943) and located west of the city. Silt deposits in Legedadi and Geffersa reservoirs reduced their live storage capacity, while the buildup of suspended solids in Legedadi Reservoir has affected the raw water quality thus increasing the treatment costs. Siltation of water reservoirs has a considerable impact on the reservoir functions. It reduced storage capacity and quantity of the harvested water that in return caused water shortage for the rapidly increasing Addis Ababa City residents (over 4 million). Moreover; the suspended solids in the eroded material increased the turbidity of the raw water (i.e., water becomes muddy and physically dirty), which increased the water treatment costs. According to AWSSA (please write what it stands for) reports, the cost of water treatment increased from 7.7 million in 1993 to 21.4 million in 2001 due to the increasing rate of reservoir sedimentation. On the average, the state incurs water treatment cost of 12.6 million birr (please write what it stands for) /year (AAWSSA, 2001).

## 2. THE STUDY AREA

In this section, the study area is introduced and described. The climate and hydrology are given. The soil and vegetation are described as well.

### 2. 1 Location

The study area is located about 25 km from Addis Ababa in the east direction. The reservoir catchment area exists in Oromia Regional State under the administration of North Western Shoa Zone in Aleltu Bereh district administration, Sendafa town. The catchment is bounded by latitude 9°01' N – 9°13' N and longitude 38°60' E - 39°07' E. In general, the catchment area has a total area of 234 km$^2$. Legedadi dam is administered by Addis Ababa Water and Sewerage Authority. Except the eastern part, which is mountainous, the rest of the reservoir area is accessible by four-wheel drive vehicles. The Addis Ababa-Dessie main asphalt road runs west-east across the central part of the reservoir catchment area. Dry weather road, which runs between Legedadi and Dire reservoirs, crosses the catchment area from South to North.

### 2. 2 Climate and Hydrology

The area is located in the upper northwestern part of the Awash basin. There are two seasonal patterns in the region of Addis Ababa. The weather is relatively cool in the wet season of July to September

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during the main rain falls, while the more or less rainless season of October to June has warmer temperatures with easterly winds. Rainfall usually occurs in the form of localized thunderstorms due to convective heating of the air masses during the day and rapid cooling at night.
Near the study area, there are two meteorological stations, which are located in Sendafa ($38^0$20'E, $4^0$05'N) and Addis Ababa ($39^0$04'E, $3^0$31'N).
Ten years of rainfall data were collected from the National Meteorological Agency for the stations from 1954 to 2006. The mean monthly temperature is between 16$^o$C and 26$^o$C throughout the year. The minimum monthly average temperature registered is 16.1$^o$C in July in Addis Ababa Station and the maximum monthly average temperature is 25.5$^o$C in February in Sendafa Station. The hottest season extends from December to late in March.

The Legedadi catchment area may be sub-divided into six sub-catchment areas , namely:
(1) The Lege Beri sub-catchment
(2) The Lege Sekoru and Lege Fule sub- catchment
(3) The Lege Bolo sub- catchment
(4) The Lege Sendafa sub-catchment
(5) South Eastern Tributary
(6) Others
Lege Sekoru and Lege Fule streams enter Legedadi Reservoir via a common course. Lege Bolo and Lege Sendafa also merge several hundred meters before entering Legedadi Reservoir. These catchments are not gauged. However, the volume of water in the Legagdi Reservoir could be used as indication of the amount of water draining from the subcatchments.

### 2. 3 Soil, Vegetation Cover and Land Use

There are four types of soils in the catchment area on which crops grows annually. Theses soils are Koticha (Black vertisol soil), Dalecha (Grey soil), Gembore (Light soil) and Key (Red soil), Bathymetric Survey (2002).

As for the land use and land cover, the following is a complete description:
**Lege Beri Sub watershed**: This watershed has a total area of 22km$^2$. According to woody biomass classification, 85% of the lege Beri sub watershed land is cultivated and the remaining 15% is a grass land.
**Lege Sekoru Sub watershed:** The combination of Sekoru and Fule rivers catchments is the second largest sub watershed in the Legedadi catchment area and has a total area of 50km$^2$. Cultivable land (Reunified cereal land cover system)–CRCL covers 70% of the area while 15% of the area is covered by grass land light moderate stock-GL. The remaining 15%, that has relatively the highest altitude, is covered with FBO and WO.
**Lege Bolo Sub watershed:** According to woody biomass classification 62% of the lege Bolo sub watershed area is grass land light and moderate stock-GL and the remaining 38% is cultivable land (Reunified cereal land cover system)–CRCL. This watershed has a total area of 26km$^2$.
**Lege Sendafa Sub watershed:** This is the largest sub watershed in the Legedadi catchment which accounts for about 62km$^2$ of the total catchment area (205km$^2$) and its land use classification is as shown on fig 4.4. Grass land light moderate stock-GL and cultivable land (Reunified cereal land cover system)–CRCL are the two dominant land covers in the sub watershed. Only 8% of its area is covered with FBO (please write what it stands for) and WO(please write what it stands for).
**Southeastern Tributary Sub watershed land use:** This watershed has a total area of 10 km$^2$. Cultivable land (Reunified cereal land cover system)–CRCL is the dominant land cover in the area. it covers about 93% of the total sub watershed area. The remaining 7% is a combination of grass land and light moderate stock-GL and U.

**Soil Type**
**Lege Beri Sub Watershed Soil**: This watershed has a total area of 22km$^2$ and Pellic Vertisol is the dominant soil.
**Lege Sekoru Sub watershed soil**: The dominant soil in this sub watershed according to woody biomass coding is also pellic vertisols and it covers 65% of the total sub watershed area. Calcic Xerosols, Orthic Solonchakes and Leptosols take the remaining 35% of the area.
**Lege Bolo Sub watershed soil**: The dominant soil on this sub watershed according to woody biomass coding is again pellic vertisols and it covers 93% of the total sub watershed area. The remaining 7% is covered by Orthic Solonchakes.

**Lege Sendafa Sub watershed soil**: The dominant soil in this sub watershed according to woody biomass coding is pellic vertisols and it covers 93% of the total sub watershed area.
S**outhern Tributary Subwatershed soil**: This watershed has a total area of 22km$^2$ and it has only one type of soil which is Pellic vertisols.

## 3. STATE OF ART

The state of the art currently in reservoir sedimentation is discussed in the following subsection. It is based on literature review of recent publications

### 3.1 Reservoir Sedimentation

It is well accepted that reservoir sedimentation possesses a serious threat to available storage. The annual loss of storage in reservoirs is roughly corresponding to about 50 Km$^3$ worldwide (Mahmood, 1987). Some reservoirs have a much higher storage loss, e.g., the Sanmenxia Reservoir in China looses about 1.7% (please mention to what the percentage is referred to) yearly.

The principle processes involved with sedimentation in a storage reservoir as treated in Sloff (1991 and 1997). The most important distribution principles of these sediments in the reservoir can be subdivided into the following groups: **Coarse sediment deltaic deposits; Fine sediments in homogeneous flow; Turbidity currents.**

### 3.2 Modeling

Three dimensional models are applied for studying local process that cannot be sufficiently described by 2D model approximation. The works by Sanjon and Nazu (2004), Fang and Roado( 2003), Cesare and Hermain( 2001), Lan and Faleoner (1997) are among the important works on 3D numerical modeling studies on sedimentation. Two dimensional models are the most predominantly used models in reservoir and river sedimentation studies to describe the quantity and spatial distribution of sedimentation. Examples on two–dimensional suspended sediment transport studies might be of Tesfaye (2007) and Michael, Y.G. (2004). One dimensional model is also widely used for modeling rivers that are nearly straight where longitudinal flows are predominant.

## 4. METHODOLOGY

The Methodology pursued in this research includes data collection, preprocessing data and model development. The Model developed for the catchment is calibrated and verified before any flow and sediment transport simulation is carried out

### 4. 1 Model Selection

The study demonstrates the estimation of sediment inflow for Legedadi Reservoir using SWAT watershed and CCHE1D that calculate the transport of non-uniform sediment in rivers and streams using the non-equilibrium transport model. Therefore, an effort is made to utilize the models with their requirements as possible.

*SWAT Watershed Model*

SWAT was selected for this modeling because model predictions are distributed spatially. A simpler alternative to a spatially distributed model is a lumped watershed model. Lumped models make a single prediction that only applies at the watershed outlet and therefore provide no additional spatial information regarding the upstream sources of the modeled quantities.

The other main reason for the selection of Arc view SWAT is sediment erosion from each hydrologic response unit (HRU) which is stimulated using the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt 1977). This equation replaces the traditional Universal Soil Loss Equation's (USLE) rainfall factor with a runoff factor in order to estimate event-based sediment yield estimates. MUSLE predicts sediment erosion when there is surface water runoff and it reduces the erosion estimates when there is snow cover.

*CCHE1D Sediment Transport Model*

CCHE1D model is applicable to the simulation of system responses to hydrological processes, agricultural management practices, and man- made modifications to the channels or upland areas. It can be used as a tool in the evaluation of the long term channel watershed system response to remedial measures for the control of erosion and sedimentation. The model is suitable for the determination of local erosion and deposition patterns, as well as, for the determination of sediment yield.

*Data and data analysis*

The necessary data for the Legedadi Reservoir catchment are prepared as follows:

As cited ealrlier, the Legedadi Reservoir is located in the Awash Basin. Hence, the DEM of the Awash Basin was processed and the Legedadi Catchment was extracted from this DEM as outlined here.. The DEM was taken from Landsat7 Consortium for Spatial Information (CGIAR CSI) website (http://srtm.csi.cgiar.org/), which provides the NASA Shuttle Radar Topographic Mission (SRTM) 3 arc second (≈90m) resolution and resampled to 57m resolution.

Zonal masks which are delineated from the 1:50,000 topographic map of the watershed catchment area using are implemented. Since the catchment area has five main subwatersheds, it is necessary to provide the five subwatersheds area, Figure 1, separately, as a masking map.

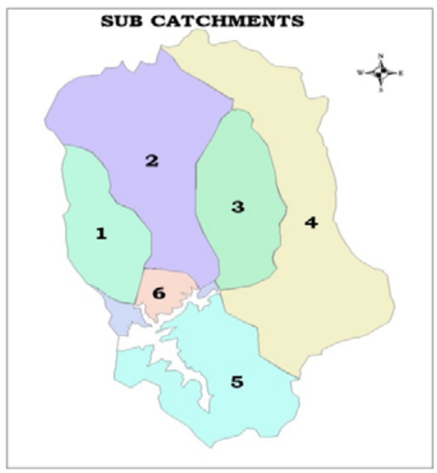


**Figure 1 Subwatershed masks of Legagdadi reservoir catchment**

Lege Beri, Lege Sekoru, Lege Bolo, Lege Sendafa and South Tributary have catchment areas of 22 $km^2$, 50 $km^2$, 26 $km^2$, 62 $km^2$ , and 10 $km^2$,respectively.

**Precipitation and Temperature Data**

National Metrological Agency (NMA) is the sole responsible organization for the supply of rainfall and temperature data on the country. Accordingly, a twenty-year daily rainfall data of five stations (Bole, Sendafa, Sululta, Sholla-Gebeya and Kotebe) is collected and made ready by converting it to a DBF. A twenty-year daily temperature data (Tmax and Tmin) of three stations (Bole, Sendafa and Sholla-Gebeya) is collected from NMA and made ready by converting it to a DBF file.

**Location Table**

The locations of the rainfall and temperature stations are given on table 1. These locations of the stations are found on the web page of NMA on geographic coordinate system. In order to make it similar to the DEM coordinate system, the data was converted to the Projected Coordinate System using Arc-GIS 9.2 projection technique and imported as a DBF file.

**Weather Generation**

For AVSWAT simulation using measured weather data, weather simulation information is needed to fill in missing data and to generate the average monthly rainfall, temperature, relative humidity, solar radiation and wind speed.

**Legedadi Reservoir DEM**

The reach lengths, which can be used for the calculation of flow and sediment transport in channels, are directly extracted from the DEM by TOPAZ. For a better accurate result, CCHE1D model requires a 30 by 30 m resolution DEM. The topography map of the area, which is surveyed and plotted with 5m contour interval before the construction of the dam, is the only data from AAWSA for the 30 by 30 m DEM creation**, Figure 2**.

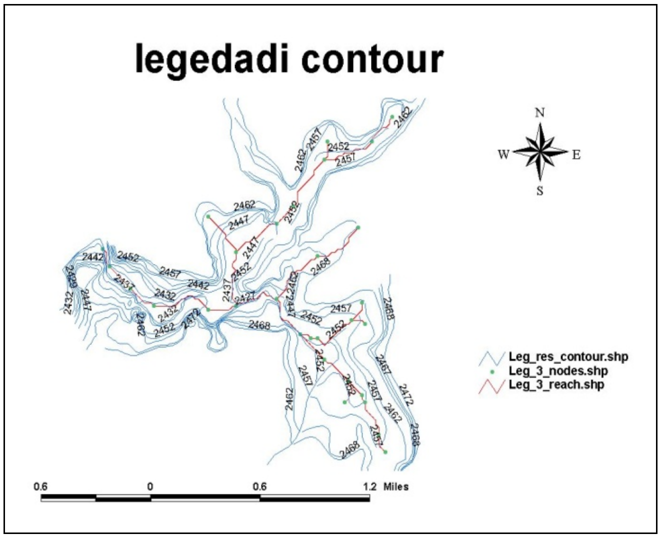


**Figure 2 Legagdadi reservoir digitized contour**

This topography map is scanned and geo-referenced to the correct coordinate system using known control points on the area. The digitizing of the contours is done using ArcGIS 9.2 to generate the 30 x 30 meter resolution DEM. Once the DEM is imported to the CCHE1D model. pre-processing the DEM is done. Pre-processing is required as a channel network cannot be extracted from a DEM if it contains depressions without an outlet for the surface flow. Flat areas are also eliminated by imposing a relief that is based on the terrain configuration of the surrounding areas.

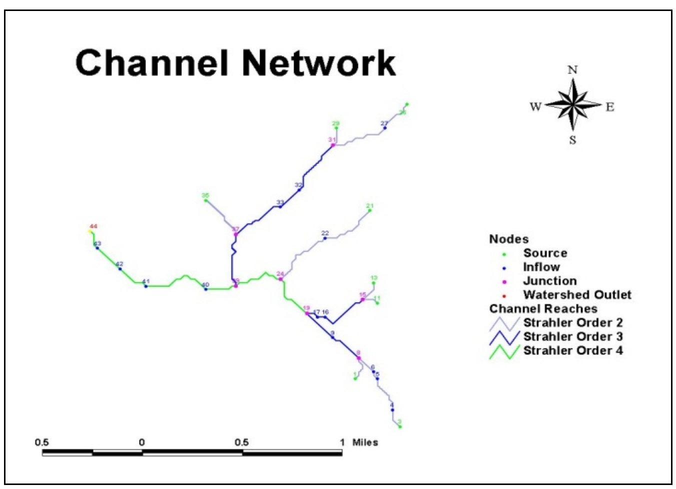


**Figure 3  Extracted channel network of Legedadi reservoir**

In the extracted channel network, nodes are assigned to different types, according to their function. Source, inflow and junction nodes. Also, watershed outlet is defined. The cross section geometry is interpolated from the topographic map of the area which is done with 5m contour interval and to define the dimension of the main canal.

This includes the physical properties and grain size distribution of the main channel. Both channel bed and bank sediment data are described by the grain size composition and a number of other parameters. The sediment size composition is given as percent fractions for a number of sediment classes. The sieve analysis result which is found from AAWSA Legedadi Dam and Water treatment department clearly describes the grain size distribution and used as a sediment data input. In order to have a channel network that is suitable for the numerical computations, automatic generation of the computational network was done and new nodes were added.

### 4. 2 Model set-up, calibration and runs

*SWAT Model Calibration*

Recorded data for the runoff and sediment inflow for the Legedadi Reservoir is not available and hydrological calculations based on the hydrology similarity method were performed. Since the previously discussed hydrological stations are situated in a nearby catchment basin with similarly physic geographical, soil and geological conditions, as well as other hydrological parameters, then the un-gauged unknown discharges can be estimated on the basis of known discharges in the nearby basin according to their catchment areas, mean annual rainfall and elevations.

The basin represented by the Sibilu hydrological station can be considered as having similar physio-geographical conditions to the Legedadi subwatershed catchments. Thus, the average inflow to the Legedadi Reservoir, using the formula given below and the discharges predicted from the Sibilu River, has been assessed.

To calculate the mean monthly discharges for the five subcatchment areas the following formula was used:

$$Q_i = Q_s * K_1 * K_2 * K_3$$

*Where:*

$Q_i$ – mean monthly discharge at $i^{th}$ ungauged catchment

$Q_s$ – mean monthly discharge at the hydrological station used for evaluation of stream-flows in the $i^{th}$ catchment

$K_1 = A_i/A_s$ = catchment area comparison coefficient

$A_i$ – Area of $i^{th}$ un-gauged catchment;

$A_s$ – catchment area of the hydrological station

$K_2 = P_i/P_s$ – mean annual average rainfall comparison coefficient

*where:*

$P_i$ – mean annual rainfall over the $i^{th}$ un-gauged catchment

$P_s$ – mean annual rainfall over the basin of the hydrological station

$K_3 = H_s/H_i$ – groundwater decrement comparison coefficient

*where:*

$H_s$ –average elevation of hydrological station catchment

$H_i$ – average elevation of the $i^{th}$ un-gauged catchment

In humid regions, where watersheds are generally homogeneous throughout the basin, the spatial distribution of monthly seasonal rainfall doesn't significantly vary from one part of the basin to the other. In this situation, estimated flows ($Q_i$) can be mainly based on the watershed areas and average elevation of the catchments. The measured inflow data of Siblu River is a stream flow but SWAT gives only the surface runoff. As for the calibration, the stream flow is separated to surface runoff and base flow using the base flow separation program. The result shows that 33.0%, 36.2%, 39.4%, 35.6% and 40% of the flow is contributed by the base flow for Beri, Sekoru, Bolo, Sendafa and Southern tributaries, respectively and the rest by the surface runoff. The base flow recession constant (alpha factor), which is the rate at which groundwater is returned to the stream, for the five sub watersheds is given below.

As discussed earlier, the sub watershed catchments, which contribute their flows to the Legedadi Reservoir, are not gauged and hydrological calculations, based on the hydrology similarity method, were performed from the mean monthly discharge of Sibilu River that has similar physio-geographical conditions, and was adopted for the calibration. The result of the calibration result is summarized in the charts shown below.

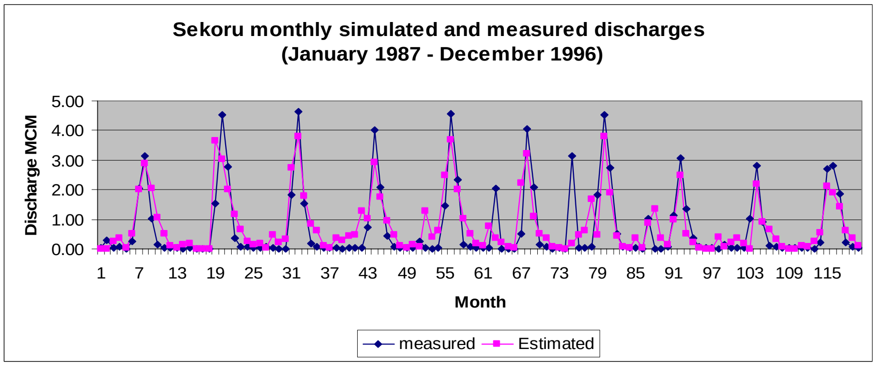


**Figure 4 Calibrated discharges of Sekoru subwatershed**

*SWAT Model Validation*

The SWAT model is validated in order to evaluate the performance of the model, in the period from January/1981 to December/1984. This was achieved without any adjustment to the parameters that were adjusted during the calibration. This resulted in 12.12 % error in the monthly average discharge.

The comparison of the measured and simulated average monthly flow discharges, for the Sekoru sub watershed, is given on Figure 5. The agreement between the measurement and simulation is generally good. The overall trend of the flood routing, for this and the other sub watersheds, as well as the peak discharges and the time to peak are generally well predicted. Some deviations exist which might be attributed to the error in the estimation of the tributary inflow together with other factors.

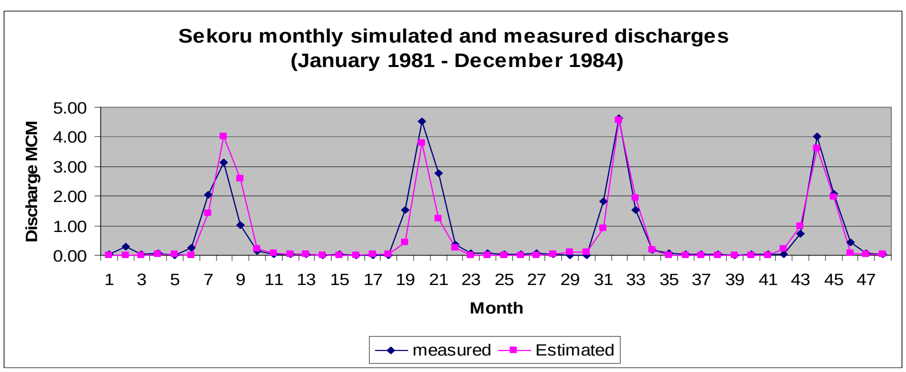


**Figure 5 Validation result of measured and simulated discharges for Sekoru subwatershed**

*CCHE1D Calibration*

CCHE1D model was calibrated employing the bathymetry data of 1979, Figure 6. Noticeable is the agreement between the simulated and measured Thalweg elevations. For the bed roughness, a reasonable value was selected and for the porosity a default value was taken.

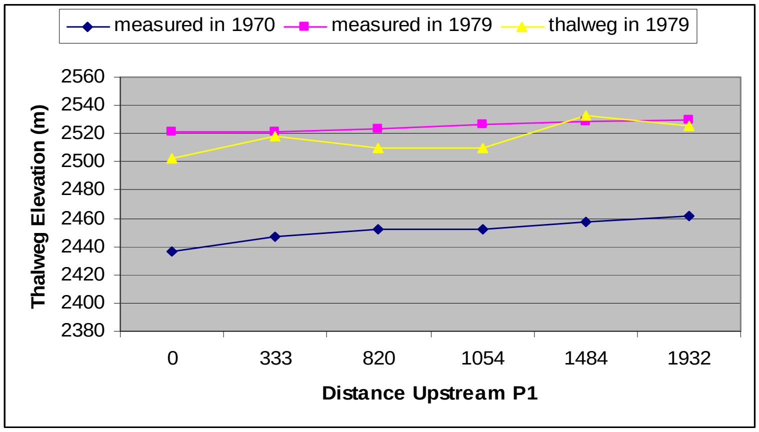


**Figure 6 Calibration of the thalweg of Legagdadi reservoir**

## 5. RESULTS

*SWAT Model Sediment Result*

After calibration of the SWAT model, a simulation was executed and the hydrographs are well captured for all subcatchments. The result for the Sekoru subcatchment is shown on Figure . In some cases, the peaks are underestimated and in only few cases the peaks are overestimated. There are also cases where the peak is nearly captured. In the absence of measured data, the agreement was found to be good and plausible.

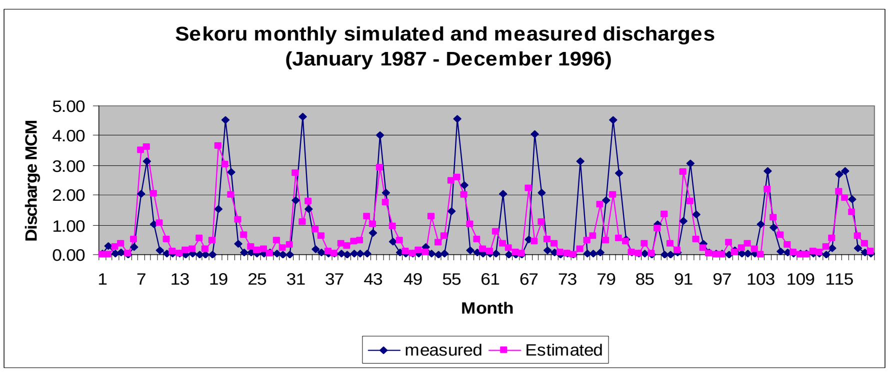


**Figure 7 Simulation and measured discharges of Sekoru subwatershed**

*Sensitivity Analysis*

The sensitivity analysis for the Legedadi Reservoir sub watersheds was done for ten years (January/1987 to December/1996).

The results of the sensitivity analysis, with its parameter ranking, show that the curve number (CN2), the soil available water capacity (SOL_AWC), and the soil evaporation compensation factor (ESCO) are the three most sensitive parameters controlling the surface runoff in the sub watersheds. The threshold water depth in the shallow aquifer for flow (GWQMN), the saturated hydraulic conductivity (sol_k), the deep aquifer percolation fraction (rchrg_dp), and the groundwater revap coefficient (GW_REVAP) have also the highest influence in controlling the flow. The relative sensitivity of all parameters is given in the annex.

As discussed, the Legedadi watershed is divided into five main sub-catchment areas and the SWAT model is carried out separately for the five sub watersheds from 1970 to 2000. Each of the sub catchment contributes its share of sediment each year. Accordingly, the average annual sediment yield of the five sub watersheds for the intervening period is summarized on Table 1

**Table 1 Sediment contribution of the five subwatersheds**

| No | Sub Basin Name | Sub-Basin Area (km$^2$) | Average Annual Sediment Outflow (m$^3$/year) |
|---|---|---|---|
| 1 | Lege Beri | 22 | 26,000 |
| 2 | Lege Sekoru + Lege Fule | 50 | 52,000 |
| 3 | Lege Bolo | 26 | 28,000 |
| 4 | Lege Sendafa | 62 | 68,000 |
| 5 | South Tributary | 10 | 9,000 |
| | Total | 170 | 183,000 |

*CCHE1D Model Result*

CCHE1D was used to predict bed changes in the Legedadi Reservoir for a thirty years simulation period (1970 and 1979).

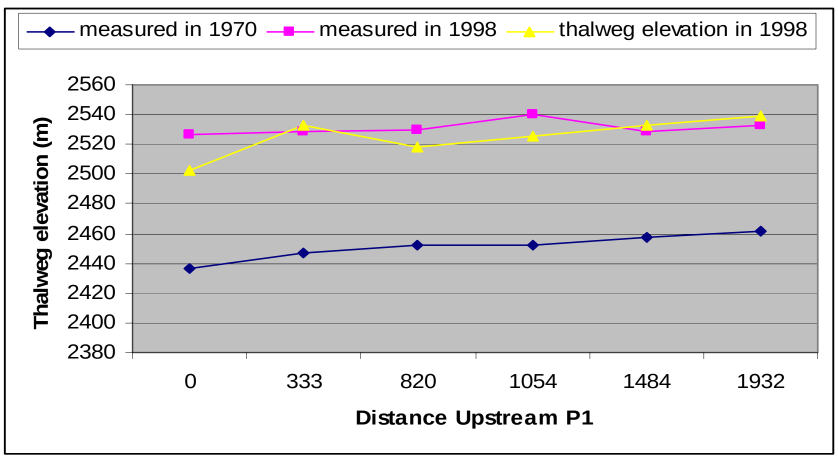


**Figure 8 Measured and simulated thalweg elevations (1970 and 1979)**

The CCHE1D sediment transport model performed well in simulating the thalweg elevations for the periods outside the domain of the calibration period, based on the adjusted parameters, during the calibration time. Therefore, these adjusted parameters can explain the characteristic of the Legedadi Reservoir. Therefore, based on these parameters, further simulations could be carried out for any extra period of time and longitudinal channels on the reservoir. The validation results agreed well within an error of 8.33 % (referred to what?).

## 6. CONCLUSION

SWAT and CCHE1D models performed well in predicting the Legedadi Reservoir sedimentation. Apart from the intensive effort in preparing the data for the models, the models were very friendly to work with and hence they should be incorporated in the prediction of sedimentation for other cases,. In other words, the models proved to be worthwhile in capturing the one dimensional processes of flow and sediment transport in Legedadi Reservoir.

The data utilized are all from secondary sources. These data are checked for consistency. The models have run successfully using these data. The calibration and validation for both stages of modeling were good and plausible.

## 7. RECOMMENDATION

It is recommended to collect regularly primary data. The data collection includes bathymetry, flow into the reservoir and the sediment transport rate. Moreover, data on sediment gradation should also be collected. The model developed could be used in the prediction mode in order to take appropriate measures in advance.

Further research is recommended using a CCHE2D in order to consider the later variation in sediment deposition.

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