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Hydropower Reservoir and Sedimentation

A Study of Nam Ngum Reservoir

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Hydropower accounts for approximately one fifth of the world's electricity supply and is the best renewable energy source to meet the energy consumption of the world. With ever increasing energy demands hydropower-related construction is on the increase all over the world. Although the energy production from hydropower is efficient and cheap, the social and environmental cost can be high, with downstream ecosystem impacts caused by water quality, hydrological and sediment flux changes.

In the Mekong region, the most prominent impacts follow from sediment retention by hydropower reservoirs. Using mathematical models to simulate generation, transport and fate of sediments provides fundamental information for assessing environmental impacts caused by hydropower development. The Nam Ngum reservoir in Lao PDR was chosen as a case area for assessing quantitatively different processes and their impacts on sediment amounts. Sediment generation, sediment transport mechanism, downstream changes in total suspended solids concentration, sediment fluxes and seasonal flow and sediment concentration variation in the case area are described in this thesis.

The result shows that the amount of sediment produced in the catchment area and reservoir have an impact on sediment fluxes. The changes in downstream sediment fluxes can cause increased erosion and morphological changes and can profoundly affect ecosystem productivity and food security. The study results can be applied for hydropower reservoir construction, for sediment management and for mitigating downstream impacts.

Keywords	Sedimentation, Modeling, Sediment trapping, Impacts

List of Abbreviations

PDR	People's Democratic Republic
MW	Megawatt
GWh	Gigawatt hour
IWRM	Integrated Water Resources Management
GIS	Geographic Information System
EIA	Environmental Impact Assessment
TSS	Total Suspended Solids
MMF	Morgan, Morgan and Finney
DEM	Digital Elevation Model
Ts	Time Series Output Point
TE	Trapping Efficiency

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1 Introduction

Electricity is essential for day-to-day activities in most parts of the world. According to the International Energy Agency, electricity demand will grow at an annual rate of 2.5% by 2030 and the energy investment needs amount to $26 trillion in 2008–2030[1]. Thus, in the developing scenario of increasing energy consumption, hydropower is considered as one of the major renewable sources of energy. Hydropower has significant advantages over other sources of energy. It is widely available resource with very efficient energy conversion along with low operating cost. Apart from this, the benefits of hydropower include irrigation and flood control over the surrounding areas and low greenhouse gas emissions.

Hydropower development can have significant environmental and socio-economic impacts. In this thesis, the sediment and hydrological impact of hydropower development is described. The impacts of the hydropower development are not only localized to area around the reservoir but also to the downstream users, which may be trans-boundary. Some of the major impacts are visible in the sediment transport mechanism, in the flow and water quality in downstream, in resettlement requirements, in the potential restriction to navigation, in modification to local land use patterns, and in impact on terrestrial and aquatic habitats. Thus, a systematic approach to determine different environmental complications related to hydropower construction are required to overcome probable environmental impacts. This systematic approach is easier with the implication of a dedicated tool for simulating the changing environment.

1.1 Hydropower in Laos

Lao PDR has ample water resources with the Mekong River and its tributaries. Thus, the country has significant potential for hydropower development. Of estimated 23000 MW of exploitable hydropower potential in Lao PDR, about

15000 MW are internal to country and remaining represent the country's share in the Mekong mainstream with the Mekong region countries. At present, 1838 MW of the hydropower generation capacity have been installed with 1372 MW under construction, 3041 MW in advanced planning stage and more than 3300 MW with completed feasibility studies. Domestic electricity consumption of country in 2008 was 1578 GWh and is expected to grow around 10 percent per annum. [2]

This increasing energy consumption in the region is leading to increases in exploitation of hydropower resource, thus requiring in-depth study of the environmental impacts related to the hydropower development.

1.2 Aims of study

The main aim of the task was to study the dynamic model of sediment transport mechanism from the Nam Ngum river system and reservoir in Laos PDR. The project was aimed to determine sediment generation process, sediment transport mechanism, and sediment flux through the dam and to relate results to determine the possible morphological impacts of sediment trapping due to the hydropower dam.

To accomplish this, a computational model based on different characteristics of water and soil was used.

1.3 Model approaches

Currently, there are many different types of computational models available for simulating the sedimentation process. The model utilized in this thesis project not only simulates sediment generation and transport process but also provides support for agriculture planning and development, land management including hydrological responses, erosion control, and forestry. In addition, it also provides support for integrated water resource management (IWRM) for irrigation, hydropower, fisheries and ecological flows.

The IWRM model uses gridded approach with correspondence to GIS data for determining different watershed processes along with advanced modeling tools to simulate land use, erosion, overland flow, crops, reservoir sediment trapping and other water related simulation. The outputs of the model are based on calculations involving hydrological, geographical and meteorological data of modeled area. Further, outputs from the model depend upon the type of the problem but normally include flow-related calculation, ground water, soil moisture, irrigation water demands, reservoir sediment trapping, water quality parameters, erosion and flooding parameters. These outputs can be further adjusted to determine different environmental impacts on the modeled area.

2 Theoretical background

2.1 Introduction to erosion and sediments

When it comes to the soil and watershed area, erosion refers to the detachment of the soil particles mainly by the natural forces wind, water, ice or vegetation. When these detached particles mix with the different organic and inorganic materials during the process of erosion, sediments are formed. Basically sediments refer to complex mixture of organic and inorganic particles in the water.

In case of reservoir sediments, water is the major source of erosion. Water flow over lad causes increase in total suspended solids concentration in the river and hence adding the sediments to the reservoir.

2.2 Cohesive and Non-cohesive sediments

Cohesive sediments are a heterogeneous mixture composed of clay, silt and organic matter in solid, liquid or gaseous phases [3] with a particle diameter of less than 60 µm whereas non-cohesive sediments are primarily composed of fine and medium sands and have a particle diameter of more than 60 µm.

Cohesive sediments widely exist in rivers, lakes, reservoirs and stick together due to the action of electrostatic force or flocculation; they act at very small distances and are affected by the clay mineralogy, ion content and composition, pH and temperature. The major transportation method of cohesive sediments is in suspension state by convection, turbulent diffusion and gravity settling. Generally, flocculation increases the settling velocity of cohesive sediments, thus being responsible for deposition. [7]

2.3 Water Column Settling and Deposition to Bottom Sediments

According to Stokes' law, there are various factors affecting the settling of particles in water column. These factors include particle diameter, particle density, particle shape, particle concentration, flow velocity, turbulence, sediment bed roughness and flocculation. Of these factors, size, density and shape of the particle are responsible for the determination of settling velocity, whereas particle concentration and turbulence indirectly affect the settling velocity by formation of flocs.

For uniformly spherical particles of known diameter and density, settling speeds are in accordance with Stokes' law: [4]

$$Ws = \frac{d^2 g(\rho s - \rho w)}{18\eta}$$

Where, W_s=Settling Velocity (m S^{-1})

d=particle diameter (m)

g= acceleration due to gravity (m S^{-2})

ρ_s= particle density (kg m^{-3})

ρ_w= fluid density (kg m^{-3})

η= kinematic fluid velocity (kg m^{-1} s^{-1})

Lower settling velocities than those predicted by Stokes' law are observed for larger particles with a settling velocity that results in a larger Reynolds number. Also, suspended solids under natural systems are neither uniform nor spherical; therefore, drag characteristics and their settling behavior may deviate significantly. Further, chemical properties of the solids and water can also influence the deposition process through flocculation.

Thus, deposition of the sediments and their attachment on the bed is a probabilistic process that is affected by the turbulence at the sediment water interface and by the cohesiveness of solid material [4].

2.3.1 Critical Shear stress

Shield curve (Figure 1) is used to relate the particle size to the critical shear stress required for initiation of motion of the particles. It relates the critical shear stress parameter to grain Reynolds number. Generally, the area below the curve corresponds to no erosion or no particle motion.

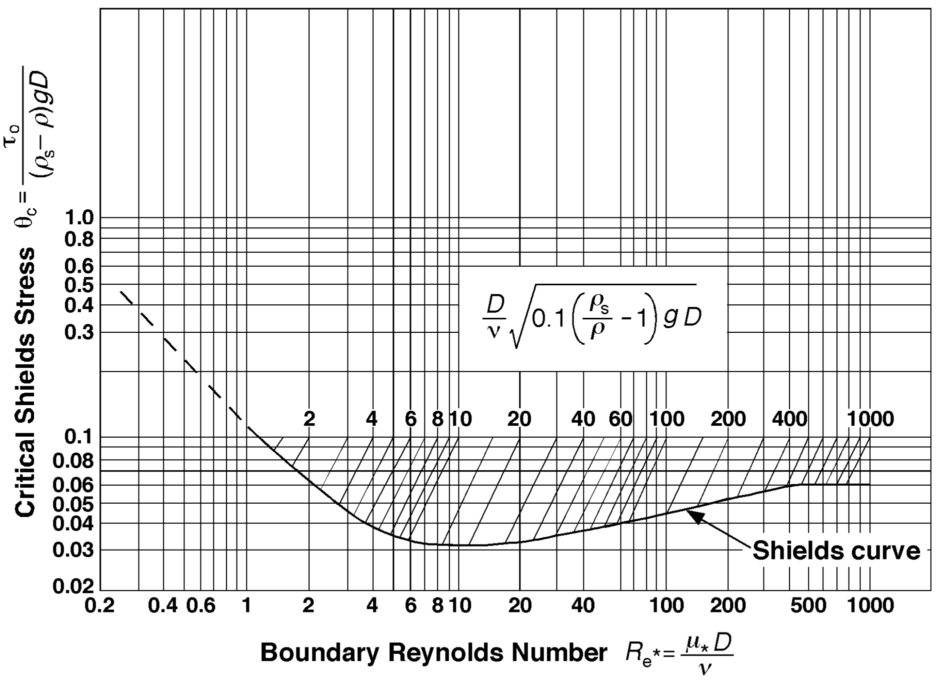

Figure1: Shield curve showing the relationship between critical sheer stress and boundary Reynolds number [7].

Critical shear stress defines the point at which the erosion of sediments is initiated [4]. Theoretically, the rate of erosion at the critical shear stress point is near zero, and as the shear stress increases beyond the critical value, the rate of erosion increases.

2.3.2 Grain size and sediment transport

A simple illustration of the relationship between grain size and flow velocity with sediment transport method is provided by the Hjulström diagram (Figure 2). It determines whether a river will erode, transport or deposit sediments. The diagram also shows the relationship between grain sizes and flow velocity (vertical axis) and transport mode.

When the flow cannot move, the sediment particle, i.e. the grain size, is large and flow velocity is low, the deposition of the particle occurs. Further, when the grain size is small, even smaller flow can erode the particles, and in between these grain sizes, flow can sustain bed load transport. Also, high velocity is required to erode finer particles, which is explained by the cohesive nature of the fine sediment. According to the diagram, flow velocity is able to sustain particle transport between clay and pebbles or even cobbles.

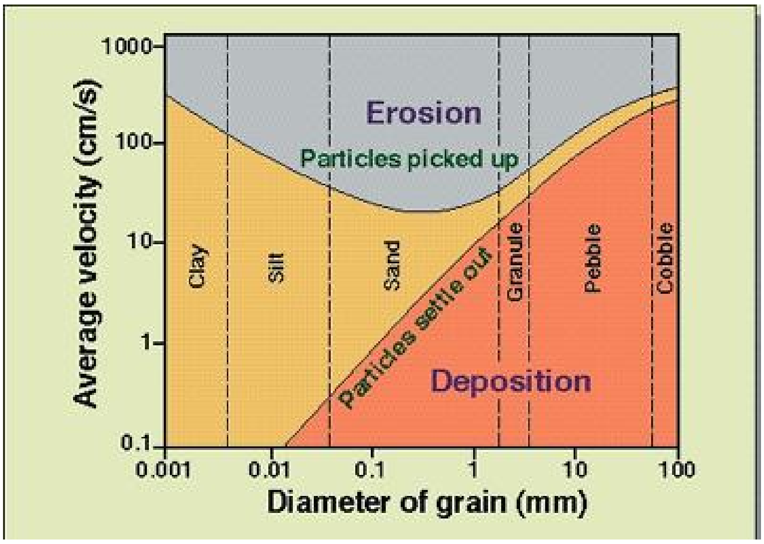

Figure 2: Hjulström diagram, showing the relationship between the velocity of a water flow and the transport grains [5].

2.4 Settling of sediments and re-suspension

Sediment erosion is a process by which hydraulic shear forces at sediment-water interface become sufficient to dislodge particles from the bed [4]. Settling is downward movement of sediments in water column. Thus settling is the process of deposition of sediments in riverbed.

Re-suspension is the process where sediments once settled in the bed are returned to the water column [4]. Some factors causing re-suspension are wind induced wave disturbance, flow or turbulence. Normally, cohesive fractions are more easily re-suspended than non-cohesive fractions. However, the rate of settling and the rate of re-suspension are not constant within the water body and exhibit large variation.

The sediment resuspended in shallow areas of water body is then often transported to deeper areas and deposited. This phenomenon is called sediment focusing [4]. Thus, on the basis of absence or occurrence of sediment erosion, a lake bottom can be divided into different categories. At erosion bottoms, there is no net accumulation of sediment. Areas at greater depths, where resuspension occurs periodically, are termed as transportation bottoms. The deepest areas, where settling material focuses, are called accumulation bottoms. A large proportion of wind energy can reach the bottom in the form of waves, currents and turbulent fluctuations, and this may cause sediment resuspension [6]. This phenomenon is normally visible in large lakes or reservoirs.

Settling of sediments and its resuspension affect the net sedimentation rate as well as the vertical distribution of the sediments in the water body. [7]

2.4.1 Net Sedimentation

Net sedimentation occurs when the bed shear velocity is smaller than the critical shear stress needed for resuspension. In case of cohesive sediments, flocculation strongly affects particle size and settling velocity. Sediment and turbulent flow characteristics affect flocculation. Sediment concentration can in turn impact flow characteristics [7].

Figure 3 shows how a particle (piece of rock, pebble, sediment grain) is resuspended from the bottom. During the process, velocity of the flow over the particle is lower than that of downstream, thus causing loss of pressure over the particle according to the Bernoulli principle. This difference in velocity and loss of pressure provides lift force that can entrain the particle in the moving fluid. Also, the vertical turbulence helps to lift the particle leading to re-suspension.

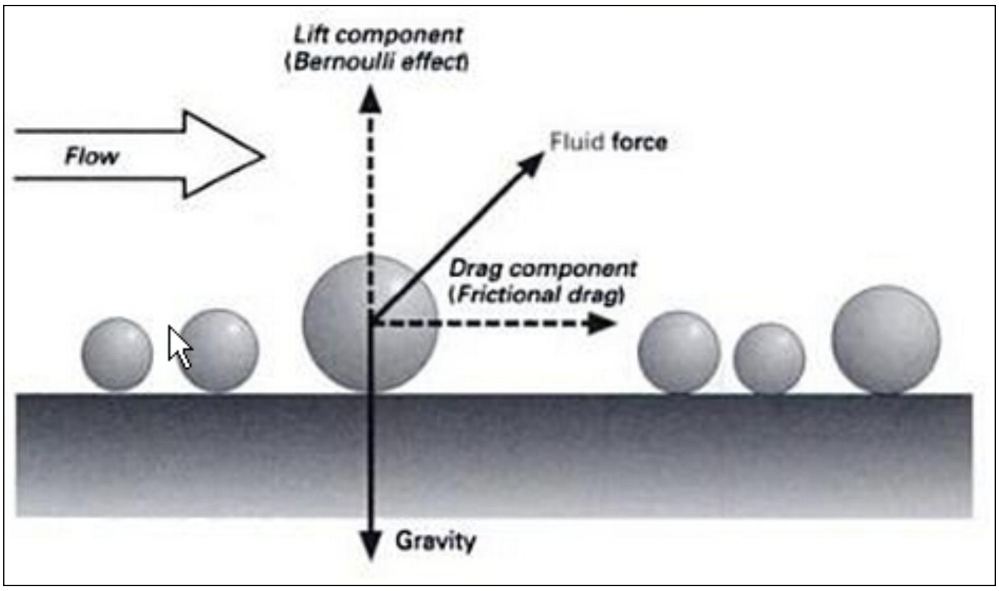

Figure 3: Forces acting on a grain in a flow [Collinson & Thompson, 1982 as quoted in [7].

2.4.2 Vertical Sediment Distribution in water body

Vertical sediment distribution has a peak near the bottom as the settling of sediment transfers the sediments from surface to bottom. In case of the Mekong River and its tributaries, the flow is usually fast and turbulent, thus mixing is efficient in comparison with the settling of particles and the vertical suspended sediment does not differ much on the surface and bottom. However, very near the bottom the difference between suspended and bedload is not clear, and concentrations can rise sharply. [7]

Thus, sediment distribution is uneven throughout the cross-section of the water body. Therefore, a different sampling measure is required to determine the actual TSS concentration in particular cross-section of the water body.

Figure 4 represents the sampling of sediment across the cross section of the river. In each cross-section three depths (surface, $0.2H_{max}$ and $0.8H_{max}$ where H_{max}=maximum depth) was determined and sediment concentration in each depth is measured to obtain the final sediment concentration at particular place.

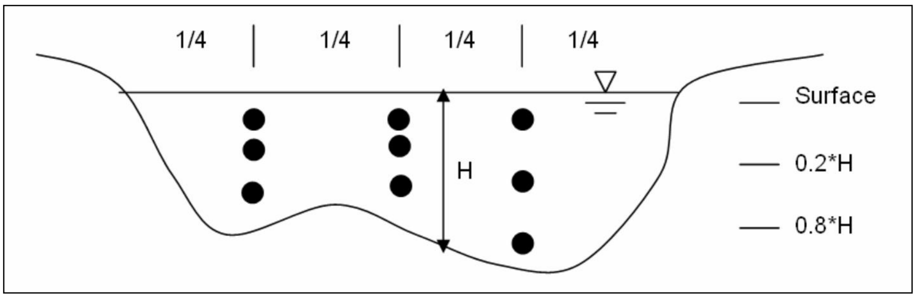

Figure 4: Sediment sampling in cross sections [7].

2.5 Turbidity

Turbidity attributes to the visual property of water, and an increase in turbidity normally accounts for an increase in the concentration of suspended solids in the water column. This increase in suspended solid is due to the increase in sediment concentration of the water body. Normally, fine inorganic particles are re-suspended easily and particles like clay and silt may remain in suspension state for a long period of time causing turbidity. An increase in the concentration of resuspended solids leads to a change in the amount of light available for the biological life in the water body and as the light is scattered or absorbed by the suspended solids, the depth of photosynthetic zone is reduced for phytoplankton, thus increasing the amount of cyanobacteria [6].

2.6 Sediment movement in water bodies

In the process of transportation of sediments in the water body, there are different types of sediment movement involved, which are divided as

1. Bed load

2. Suspended load
3. Wash load

Bed load is the portion of the total sediment load that moves on or near the streambed. It moves near the bed and is in frequent contact with the bed. The bed load layer is in the order of few particle diameters in thickness [4]. It is complimentary to suspended load and wash load. Suspended load is the portion of the total sediment load that is transported in suspension state in the water column without frequent contact with the bed. It includes suspended bed material load and wash load. Wash load is the portion of the total sediment load carried by the flow in such a way that it flows close to the top of the flow. It is mostly composed of particles of small grain size.

Wash load is limited by upstream sediment supply, whereas suspended bed material load depends on channel hydraulics. The division is pragmatic because in sufficiently slow flow conditions also wash load would behave like suspended bed material flow. The importance of the suspended bed material and wash load separation is that the sand/gravel fraction can be part of the suspended load and can be sampled in the TSS (total suspended solids) monitoring. In general, it can be assumed that the suspended load is all fine material. [7]

2.7 Physical processes affecting sediment concentrations

There exists a wide range of physical processes that have significant impacts on bed and suspended sediment concentrations [7]:

1. Flood flow
   Surface flow and river flow fills up the basin and brings in sediments both in suspension and as the bed load. It also flushes out sediments during receding flood and transports the sediments and is the major cause of bed resuspension through bed shear stress.

2. Wind flow

   Wind is a responsible factor for the induced flow in lake, river and flood-plain. It redistributes the material in the lake and flood plains through transportation and causes bed resuspension.
3. Wave action

   A wave generated near the bottom circular velocity causes bed resus-pension
4. Settling of sediments

   Settling and sedimentation redistribute material from the water column to the bottom.

2.8 Importance of sediments in natural ecosystem

Sediments in general have significant ecological function, such as habitats for benthic organisms, nutrient storage sites for different bio-geochemical cycle.
The organic components of the sediments include decayed living organisms, fecal particles, organic colloids, leaves along with bigger organic residues like logs of trees and dead living organisms. Thus, sediment is the major source of nutrients in the aquatic ecosystem, and in the agriculture land with the supply of nitrogen and phosphorous rich compounds.

Lack of sediments in the natural ecosystem can lead to damage in the aquatic ecosystem and to a reduction of natural organic content in agricultural areas.

3 Methodology

The methodology is presented with a description of the study area and theoretical background for sediment generation model. This is followed by a description of different datasets and the process involved in model development. After that, steps of model setup, model calibration and sensitivity analysis of the model are presented, and finally, data uncertainties are presented.

All the calculations were performed with Integrated Water Resource Management (IWRM) software developed by Environmental Impact Assessment Centre of Finland (EIA Ltd.) All the data used for the process of model development were provided by the EIA Ltd.

3.1 Study area

Nam Ngum reservoir is the biggest hydropower reservoir located 60 km North of Vientiane; the capital city of Laos, in Nam Ngum River. The Nam Ngum River, which is one of the major tributaries of the Mekong, joins the Mekong at about 60 km south east of the reservoir.

The Mekong is the largest river in Southeast Asia with the basin area of 816000 km^2 [15] and 4909 km in length. It originates from the Qinghai Province in Eastern Tibet, China. From there, the river flows through Myanmar, Laos, Thailand, Cambodia and Vietnam before discharging into South China Sea. With approximately 505 km^3 of water discharge each year, the Mekong is the world's 10th largest river. [10]

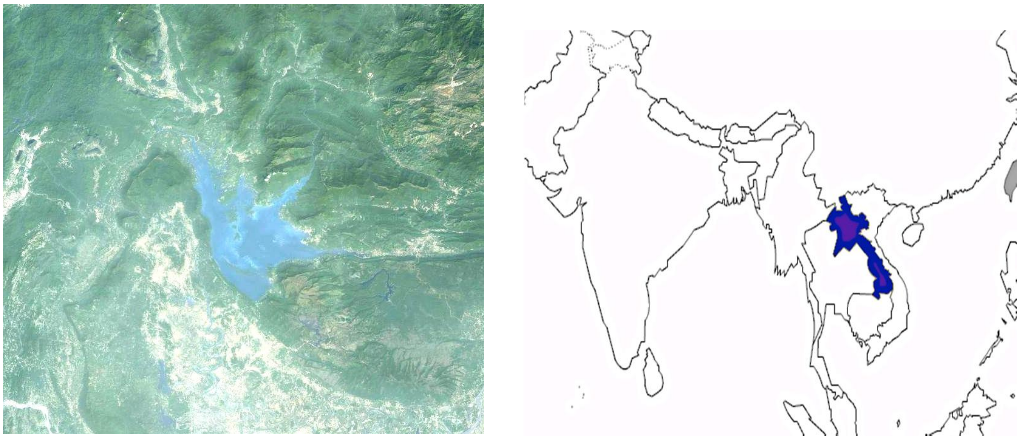

Figure5: Location of Nam Ngum reservoir in Lao [22].

The Nam Ngum (Figure 5) reservoir is the largest water reservoir in Laos created by construction of a 75m high concrete gravity dam across the Nam Ngum River. The construction started in the year of 1968 and ended in 1971. The primary objective of the reservoir was hydro-electricity production, flood control and irrigation, but is also expanded to fisheries and tourism. Five rivers, the

Nam Ngum, the Nam Sane, the Nam Ke, the Nam Pat and the Nam Xi, and many smaller streams rising in the surrounding hills contribute to the water balance of the reservoir. Some facts and figures about the Nam Ngum reservoir are summarized in Table1 below.

Table 1: Facts about Nam Ngum reservoir [9].

Province	Vientiane and Saysomboun Special Zone
Coordinates	18° 32’N, 102° 33’E
Primary Use	Hydropower
Owner	Electricite du Laos (EDL)
Electric Capacity (MW)	110
Dam Height (m)	75
Dam Length (m)	468
Annual Dam Discharge ($10^6 m^3$)	1000
Normal upper storage level (m) above sea level	212
Maximum surface area (km^2)	477
Gross Capacity ($10^6 m^3$)	7010
Live storage ($10^6 m^3$)	4910
Mean depth (m)	19
Shoreline length (km)	430
Catchment area (km^2)	8460
Catchment Rainfall (mm y^{-1})	2187

3.2 Watershed erosion modelling

The major sources of erosion on the watershed area are wind, ice, vegetation, precipitation and flow. However, for the modeling purpose, only precipitation and flow-initiated erosion is taken into account. Although, wind and ice might have impact on the erosion process, they have a relatively low contribution to the river sedimentation process.

When precipitation occurs over certain area, soil particles are either detached by impact of the raindrops or by the flow of water over the surface when the force (raindrop or flowing water) is more than the ability of the soil to resist the erosion. Further, when the weight of the particle exceeds the force responsible for its movement, deposition of the soil particles occurs. This condition is expressed as sediment load exceeding the sediment transport capacity. [7]

Most of the sediments generated in the catchment area are through erosion by natural forces. Morgan, Morgan and Finney Model is one of the erosion prediction model developed to determine amount of sediment generated in the catchment area due to erosive force of water.

3.2.1 Morgan, Morgan and Finney Model

The IWRM- model uses the empirical erosion formulation by Morgan, Morgan and Finney (MMF) developed in 1984. The MMF model is suitable for the Mekong conditions, as it was developed to predict sediment loss from the hills. It is not only simple to use but also covers the advances in understanding of erosion process and requires less data.

The model divides the erosion process into raindrop-and surface-runoff- based components (Figure 6). The model compares the predictions of total detachment by rain drop (*F*) and surface runoff (*H*) with the transport capacity of the runoff (*TC*). It uses lower value of the two for actual erosion rate. The formulation is conceptually simple and corresponds to an intuitive understanding of the erosion process.

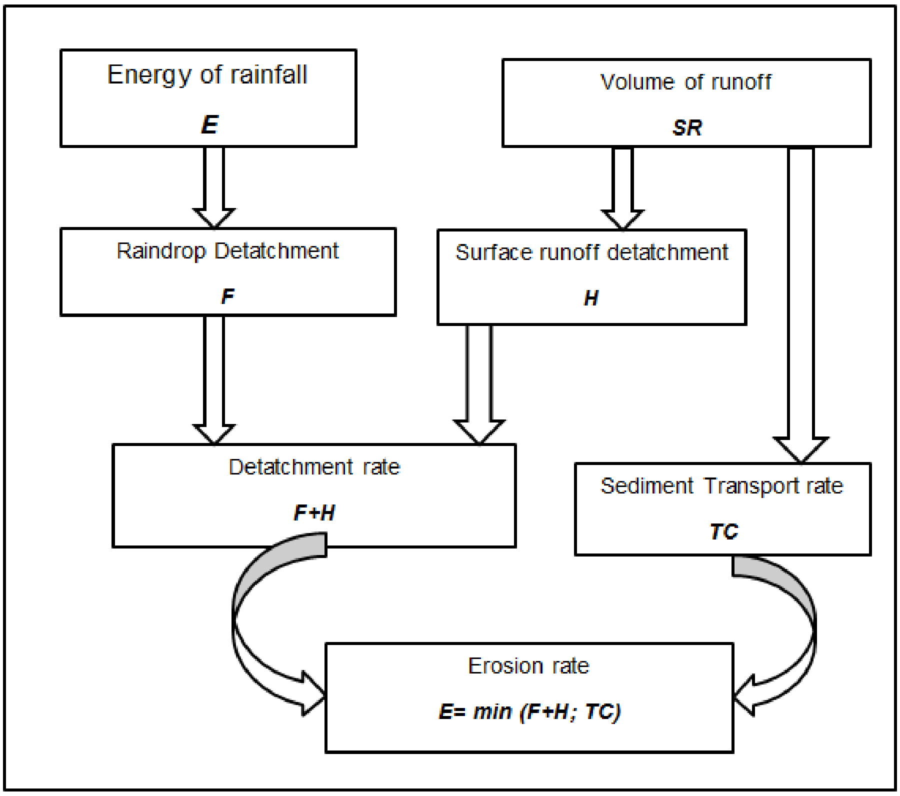

Figure 6: Morgan, Morgan and Finney watershed erosion model concept [Wageningen University, 2007 as quoted in 7].

A revised MMF model has been developed that takes into account canopy height, leaf drainage and more detailed soil particle detachment by flow. The MMF model implies water phase and soil phase for the calculation of erosion process. [7]

3.2.1.1 Water phase

The following equations apply to the water striking or flowing through the surface.

- Determination of kinetic energy of rainfall

$$E = R \times (11.9 + 8.7 \times log I)$$

Where,

E = kinetic energy of rainfall (J/m^2)

R = daily rainfall (mm)

I = intensity of erosive rain (mm/h)

- Determination of surface runoff and soil moisture storage capacity

The standard annual formulation for surface runoff is:

$$SR = R \times e^{\left(-\frac{R}{R_O}\right)}$$

Where,

SR = volume of surface runoff (mm)

R = annual rainfall (mm)

R_o = annual rain per rain day (mm) = R/R_n, where n is the number of rain days in the year

R_c = soil moisture storage capacity.

However, this formulation is not used in IWRM model calculations because the model calculates the surface runoff continuously.

- Soil moisture storage capacity calculation,

$$Rc = 1000 \times MS \times BD \times EHD \times \left(\frac{E_a}{E_p}\right)$$

Where,

Rc = soil moisture storage capacity

MS = the soil moisture content at field capacity (%,w/w),

BD = the bulk density of the soil (mg/m^3),

EHD = the rooting depth of the soil (m)

(*Ea/Ep*) = the ratio of actual to potential evapotranspiration.

3.2.1.2 *Soil phase*

The following equations are applicable for the determination of sediments produced.

- Determination of rate of soil detachment by raindrop

$$F = 10^{-3} \times K \times KE$$

Where,

F = rate of soil detachment by rain drop (kg/m^2)

K = soil detachability index (g/J)

KE = total energy of the effective rainfall (J/m^2).

- Determination of total energy of effective rainfall

$$KE = E \times e^{-0.05\,A}$$

Where,

KE = total energy of the effective rainfall (J/m^2)

E = kinetic energy of rainfall (J/m^2)

A = percentage of rainfall contributing to permanent interception and stem flow.

The IWRM-model modifies *A* on the basis of leaf area index which in turn depends on annual vegetation cycles for each land use class.

- Determination of Soil detachment by surface runoff

$$H = 10^{-3} \times (0.5\,COH)^{-1} \times SR^{1.5} \times \sin(S) \times (1 - GC)$$

Where,

H = rate of soil detachment by surface runoff (kg/m^2)

COH = cohesion of the soil surface (KPa)

SR = volume of surface runoff (mm)

S = slope (deg)

GC = fraction of ground (vegetation) cover (0-1).

- Determination of transport capacity of the runoff

$$TC = 10^{-3} \times C_f \times SR^2 \times Sin(S)$$

Where,

TC = the transport capacity of the runoff (Kg/m^2)

C_f = crop or plant cover which can be adjusted to take account of different tillage practices and levels of crop residue retention.

SR = volume of surface runoff (mm)

S = slope (deg)

The estimates of the soil particle detachment by raindrop impact, *F,* and by surface runoff, *H,* are added together to give a total detachment rate. This is then compared with the transport capacity of the surface runoff and the lesser of the two values is the annual erosion rate:

$$E = \min[(F + H), TC]$$

Where,

E = Erosion rate (Kg/m^2),

F = soil particle detachment by raindrop (Kg/m^2)

H = soil particle detachment by surface runoff (Kg/m^2)

TC = the transport capacity of the runoff (Kg/m^2).

As indicated above, the IWRM-model formulation differs in some points from the MMF-model. The differences are:

- IWRM-model includes formulation for snow-melt erosion
- Surface runoff is obtained from the IWRM-model hydrological component
- Vegetation state (leaf area index) modifies the total effective rainfall energy. [7]

3.2.2 Effects of different variables of the MMF model

MMF model depends on the following factors for the determination of sediment load produced.

- Topography

In the MMF model, an increase in the slope of the area accounts for the increase in surface runoff volume, thus increasing transport capacity of surface runoff. Transport capacity of runoff refers to the amount of sediment that the runoff can transport with its flow. On steep slope, runoff water is more erosive and can easily transport detached sediment; thus, on longer slopes increased accumulation of overland flow increases erosion [11].

- Rainfall Intensity

Rainfall intensity is described as the energy stored in the rain. When the intensity of rain increases, energy available for detachment of soil particles increases leading to increase in erosion rate. The different forms of precipitation (drizzle, snow, sleets and hail) have different impact on the sediment formation.

Normally, largest proportion of precipitation occurs in the form of rain [11] Thus, raindrop size in particular has a significant impact on erosion which is calculated based on the rainfall intensity formulation.

- Vegetation Cover

Vegetation cover is significant in determining the sediment load of the area. Lack of vegetation in the area increases the amount of sediment produced as all the rainfall intensity and surface runoff is involved in detaching the soil particles from the area. Also, vegetation state (area with higher leaf area index) tends to decrease the sediment load produced as it diverges the total rainfall intensity creating less energy available for the rainfall in order to detach the soil particles [7].

- Soil Characteristics

Surface runoff is generated only when surface depression storage is filled and the infiltration capacity of soil allows overland flow of water. Thus, for the generation of sediments through surface runoffs, the soil must reach the limit of its moisture storage capacity [11].

Physical properties of soil that affect the infiltration capacity are soil detachability and soil transportability. In general, soil detachability increases as the size of soil particles increases and soil transportability increases with decrease in particle size. Also, the soil structure, texture, organic matter, water content, clay mineralogy, density, as well as chemical and biological characteristics of soil have a significant effect on erosion [11].

3.3 Model Setup

The sediment model used in thesis project was developed using the geographical, hydrological and meteorological data of the Nam Ngum Catchment area. For model construction, all the geographical data was converted into 1000m resolutions with the UTM 48N coordinate system.

3.3.1 Description of the Catchment Area

For the purpose of determining sediment load on the reservoir, first the Nam Ngum river catchment area was determined. As all sediments and water flowing through the reservoir is originated in the catchment area, it is important to create a model to cover the whole catchment area of the Nam Ngum River. Different datasets were then incorporated into model to simulate the behavior of catchment area. These include precipitation, rainfall, soil type, land use, infiltration and many other datasets and model parameters of the catchment area in order to determine runoff and flow in different parts of the modeled area, which is further utilized to estimate the sediment load on the reservoir.

Presence of high hills of up to 2274 m at the highest point and low land of above 150 m at the lowest point with areas dominant by Acrisols and lithosols are the basic characteristics of the Nam Ngum catchment area. The total catchment area used for modeling is 16900 km^2 shrubs or grassland, and forest cover majority of the catchment areas with relatively, small and sparsely populated urban areas. The average annual temperature ranges from 20 to 34 °C and the rainy season is from May to October [Kuraji et al., 2001 as quoted in 8]. Most of the hills have a slope of between 15-30%, thus making the area vulnerable for the sediment loss through erosion.

3.3.2 Geographical data

The model grid for the Nam Ngum watershed area was constructed using the digital elevation model, the Nam Ngum catchment boundary, land use and soil data of the catchment area. These geographical data are described in more detail in the following subsections.

3.3.2.1 Digital Elevation Model

An elevation model of the Nam Ngum catchment area was created with the box size of 1000m x 1000 m, which is a resolution of 1 km. The average value of elevation within the model grid box was used to determine elevation of particular grid box. After the grid was prepared, the Nam Ngum catchment area was extracted using catchment boundary data.

The Nam Ngum catchment area with its elevation profile is presented in Figure 7. Here, areas marked with red colors are hilly areas with an elevation of more than 800m and the blue areas correspond to low land area with an elevation above 150m.

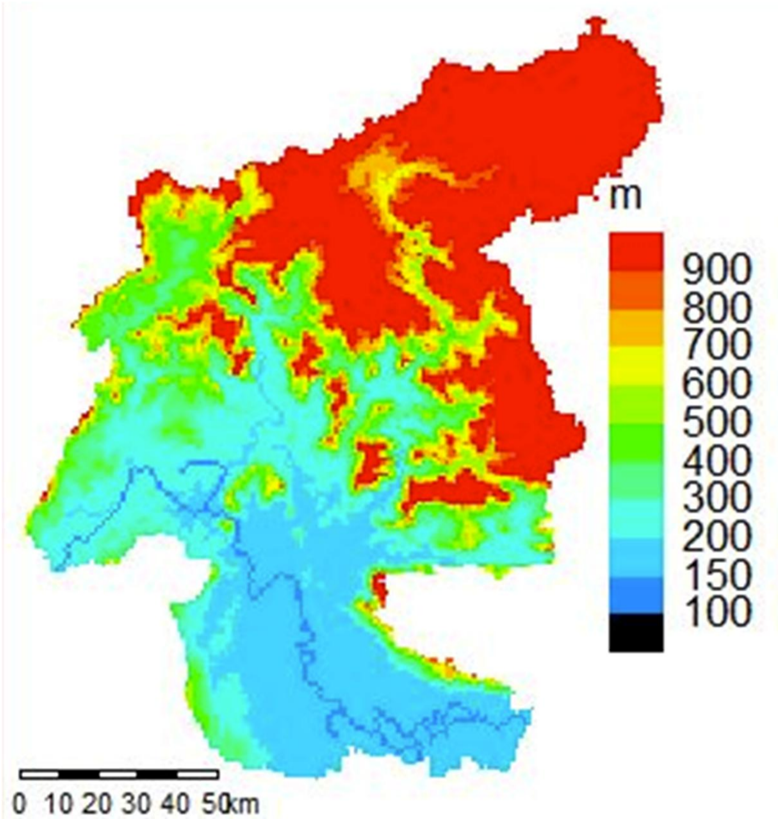

Figure 7: Nam Ngum DEM cut with catchment boundary.

Using DEM, the river network of the catchment area was calculated. To calculate the river data in the model, DEM was first lowered by 10 m in the grid box to determine the flow network and the right connection of the tributaries in the river. Then river discharge point was selected as lowest point in the grid. This was followed by computing the flow network of the river starting from the lowest point on DEM. Finally, river data was created using a specific discharge rate of 10l/s/km^2.

3.3.2.2 Soil Classification

Soil types were reclassified by assigning a particular number for a particular soil type to make computation easy. Soil is reclassified so as to ensure soil type in a grid box represents the true characteristics of the soil. For soil data, the most common class within the model grid box was used for the particular value of the grid box.

From the soil types present in the Mekong River Basin, a new classification of soil typse was obtained by analyzing different hydrological behavior of each soil type and associating soils with common characteristics. The description of re-classified soil is presented in Table 2.

Table 2: Soil reclassification of Mekong Basin

	Soil Type - (FAO Number)	New Soil Class	
1	Acrisols (1,2,3)	Acrisols	Soils with subsurface accumulation of low activity clays and low base saturation.
2	Histosol (14)	Histosols	Organic material.
3	Planosols + Luvisols (18,12)	Argic	Argic/ochric horizons
4	Ferrasols (7)	Ferrasols	Deep, strongly weathered soils with a chemically poor, but physically stable subsoil.
5	Gleysols + Fluvisols (8,10)	Alluvial	Permanent or temporary wetness.
6	Lithosols (9)	Lithosols	Very limited soil development. Over hard rock or in unconsolidated material.
7	Nitosols + Vertisols (13,17)	Cracking/Swelling	Hard when dry, very friable to firm when moist and sticky and plastic when wet.

Properties such as sand, silt and clay percentages were obtained from soil profiles; for cases where two soil classes were merged into a new one based on their similarities, their properties were averaged. After the textural classes percentages were identified, parameters for the IWRM model such as *thr* (soil residual water content), *thf* (field capacity) and *ths* (maximum water content/saturation) were estimated by using the soil water characteristics. [8]

For the Nam Ngum catchment area, different soil types and their distribution in model grid is presented in Table 3 below.

Table 3: Nam Ngum soil type and corresponding distribution on model grid.

Soil Value	Soil Type	Number of Grid Box
1	Water	512
2	Acrisols	13873
3	Histosols	73
4	Agric	43
5	Ferrasols	69
6	Alluvial	27
7	Lithosols	2300
8	Cracking	0
9	Calcisol	0
10	Residential Area	1
11	Rock	0

Here, the area covered by residential area, rock, calcisol and cracking are practically missing even if they are present in the original GIS data. This is because of averaging of original data into coarser 1 km resolution. For each soil type different parameter values were used for different parameters like infiltration, erosion.

3.3.2.3 Land Use Classification

Like soil types, land use types were also reclassified by assigning a particular number for particular land use type for making the computation easy. Also, the land use type most common in the grid box was chosen to represent the particular grid box. Different land use classes and the corresponding explanation are described in Table 4 below.

Table 4: Land use classes in Nam Ngum Catchment area

Land use Value	Land Use Type	Number of Grid Box
1	Water	511
2	Deciduous Forest	6018
3	Evergreen Forest	191
4	Shrub and Grassland	8713
5	Irrigated agriculture	1273
6	Agriculture	106
7	Flood Plan	32
8	Urban	54

For each land use type different values were used for different parameters like precipitation, evaporation, snow model, vegetation and surface model. The land use type in Nam Ngum catchment area is presented in Figure 8.

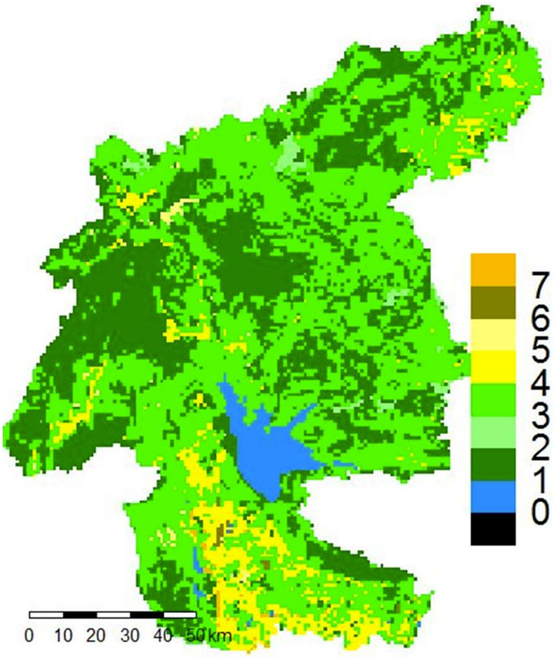

Figure 8: Land use types in Nam Ngum Catchment area. Dark blue area shows the location of Nam Ngum reservoir in model grid.

3.3.3 Meteorological data

Meteorological data were obtained from different weather stations located in the catchment area of the Nam Ngum River. Most of the weather station record precipitation and temperature data, which is utilized to determine flow and evaporation. Locations of different weather stations are shown in Figure 9 as blue squares and different small river systems of the Nam Ngum catchment area are represented as blue lines.

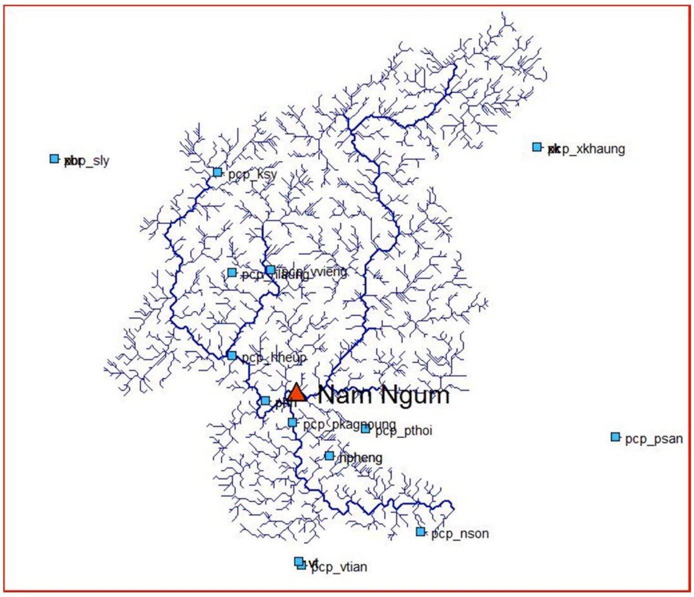

Figure 9: Location of different weather station in Nam Ngum catchment area.

3.3.3.1 Precipitation

Precipitation data were obtained from 16 different weather stations located in the catchment area for the period of 1995 to 2008. A typical precipitation time series data is presented in Figure 10.

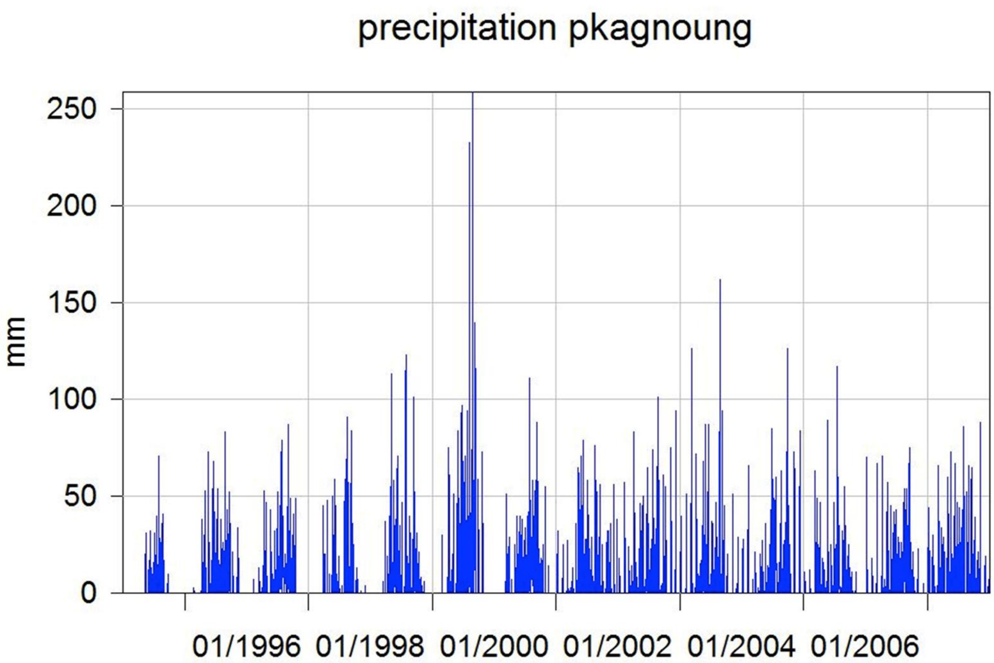

Figure 10: Precipitation data recorded in Pkagnoung weather station from 1995 to 2008.

Precipitation data shows the difference in precipitation over time of year. Blue color in the graph (Figure 10) corresponds to the rainy season and the periodic gap corresponds to the dry season. Maximum precipitation from graph is then related to the increase in reservoir volume and discharge, which is presented further in subsections below. For analysis purposes, data are manipulated as function of different parameters. An example of average precipitation derived from the above precipitation data is presented in Figure11.

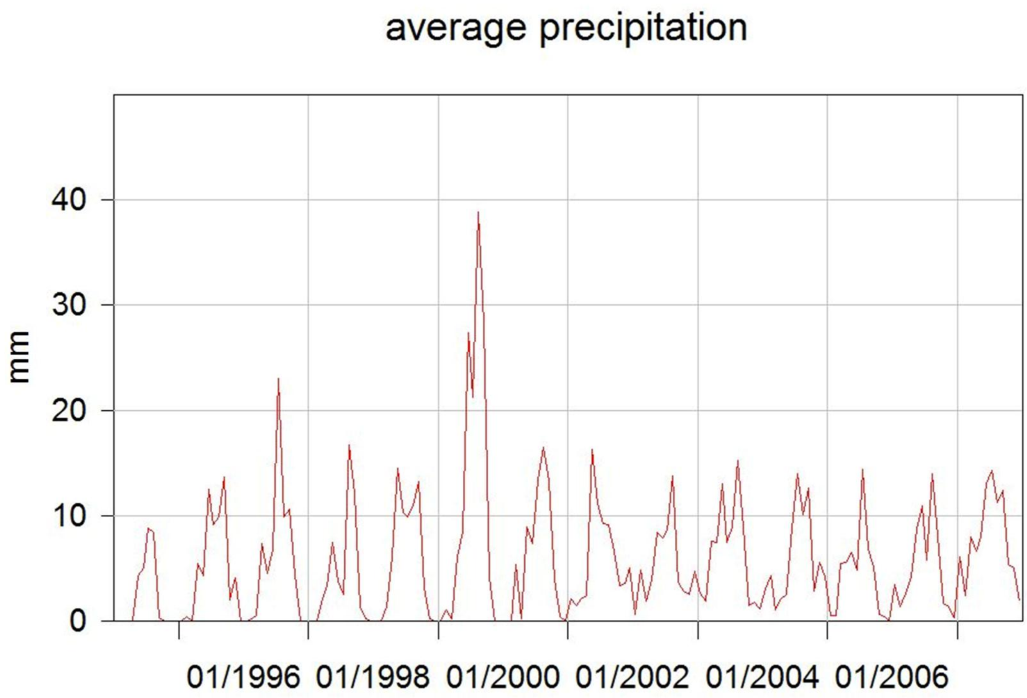

Figure 11: Average monthly precipitation recorded in Pkagnoung weather from 1995 to 2008.

For distribution of precipitation data over the entire model grid, weather data interpolation was carried out with Interpolation type 2 (data from closest station, additive height correction). For precipitation and temperature, elevation correction factors were used. The correction factor, corrected the model data using the difference of elevation between the model grid box elevation and precipitation observation elevation. Different interpolation types and corresponding height corrections are presented in Appendix 1.

3.3.3.2 Temperature

Temperature is one of the important factors affecting different parameters such as the amount of rainfall available for surface runoff and the volume of reservoir. Daily minimum and maximum temperature was used in the model to calculate the amount of evaporation and hence to determine the water level in the reservoir and the reservoir storage capacity.

Daily maximum and minimum temperature at the Nam Ngum reservoir are presented in Figure12.

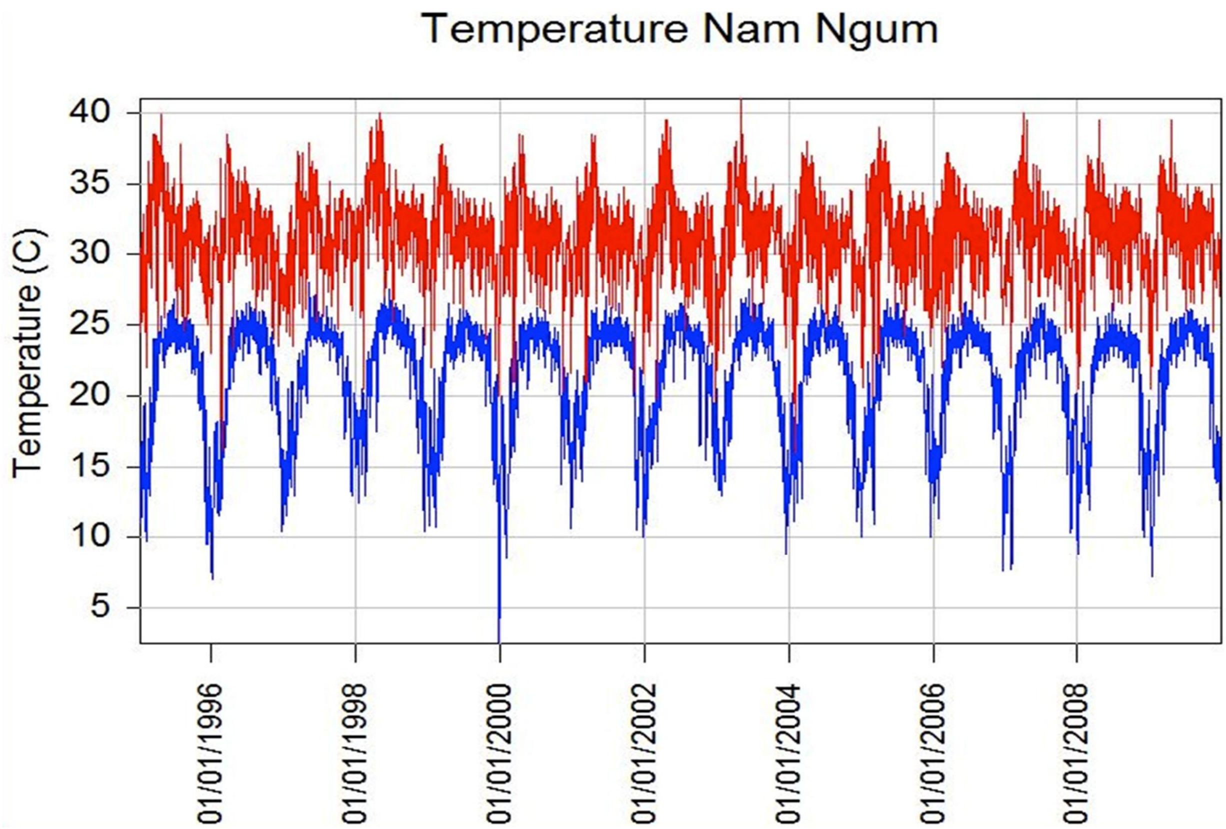

Figure 12: Daily maximum (red) and minimum (blue) temperature at Nam Ngum from 1995-2008.

3.3.4 Hydrological data

The discharge from the reservoir is controlled for hydroelectricity generation. In the model, the reservoir discharge can be either given from observations or based on for instance volume-discharge curves for each month.

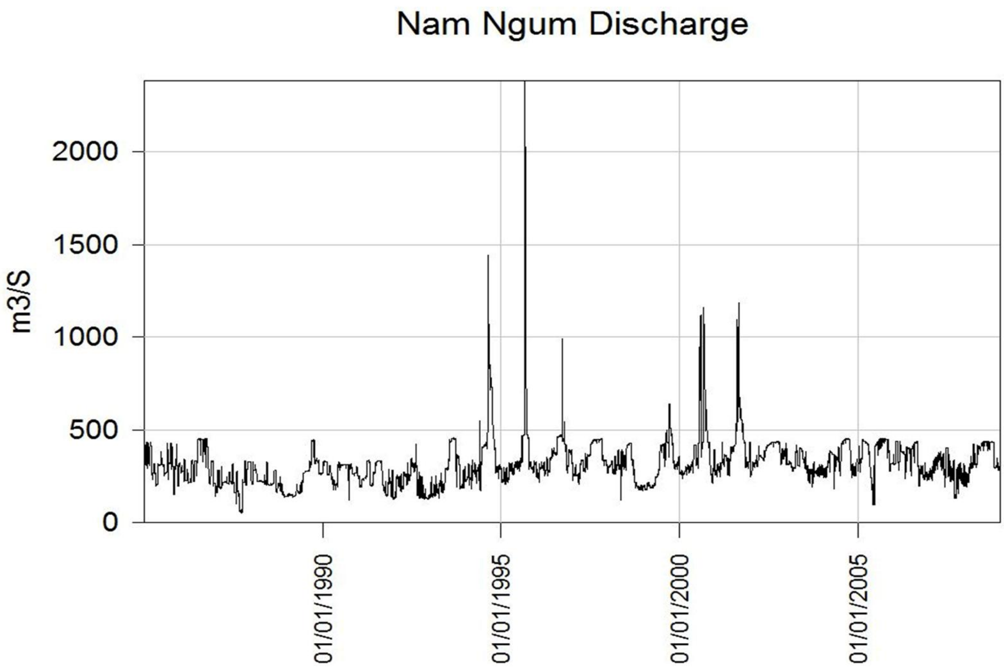

Figure 13: Daily measured discharge at Nam Ngum (1985-2008).

Reservoir discharge (Figure 13) shows some high discharge of up to 2384 m^3/s, which may be due to high precipitation in the catchment area. The average flow was calculated as 350 m^3/s during the year of 1995-2008. Using these data, statistics were calculated in IWRM model to determine the sediment load beyond dam and sediment trapped on the reservoir.

As the reservoir outflow is controlled, the seasonal flow of the river is maintained to certain level, which is presented in Figure14. The Flow downstream of the reservoir during the dry season is roughly constant, but the wet season flow is normally higher than that of the dry season.

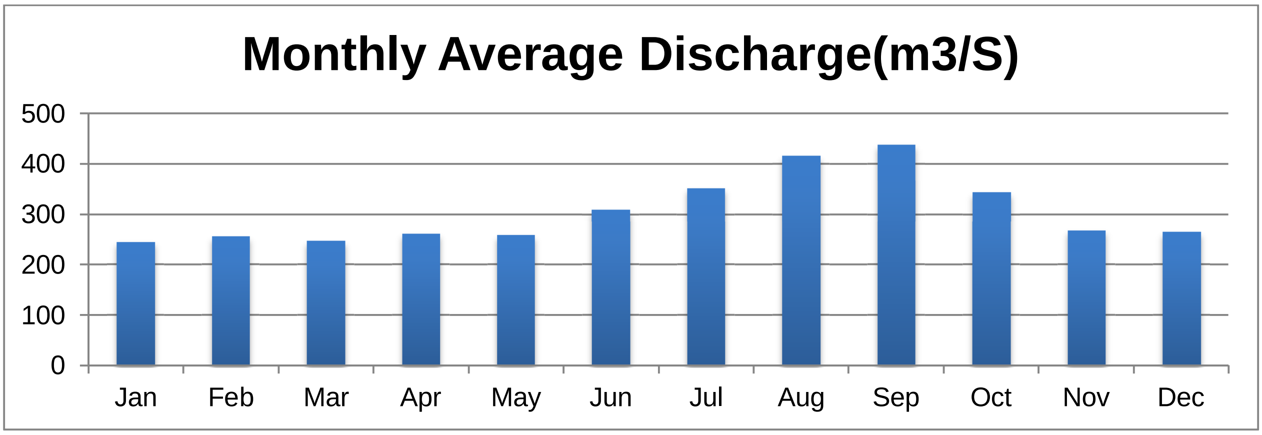

Figure 14: Average monthly discharges at Nam Ngum Reservoir for the year 1990.

3.3.5 Observation points

To obtain result from the model, different time series output points (Ts point) were defined in the model area as represented in Figure15. The output points were selected according to the requirement. In each Ts point, different output variables like flow, TSS, sand, silt and clay concentration, temperatures were recorded. For the reservoir area Ts point, reservoir discharge, reservoir storage and water level were predefined as they are controlled by dam operation. However, reservoir storage and water level could be determined using inflow data as well.

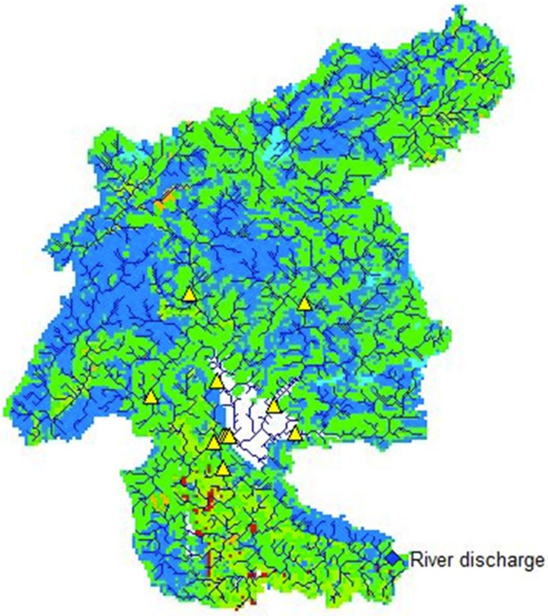

Figure 15: Locations of Ts points on the model area (denoted by triangles) and river discharge point of the Nam Ngum river system.

Finally, the IWRM model was setup-using data presented in the previous chapters. All the model parameter values required were obtained from the previous models developed by EIA Ltd. Initial model parameterization with soil and land use characteristics were obtained from previous model used in the area.

3.3.6 Simulation period

The simulation period of the model was determined to be 1 July 1995 to 31 December 2008. The simulation period was chosen on the basis of available observation data from different weather stations and TSS monitoring stations. All the calculations performed in model are based upon the observation data of the simulation period.

3.4 Sediment model calibration

The sediment model was calibrated using the observed values of the sediment load obtained from the sediment monitoring station. Calibration of the model was particularly important to adjust the computed values with the observed values. During the process, simulated values are adjusted with observed values of particular location by changing different parameter values.

Calibration was performed in two steps. First, model was calibrated on the basis of observed and simulated flow (Figure 16). For this purpose, flow was calculated and parameters affecting flow were evaluated so that simulated flow was fit to observed values.

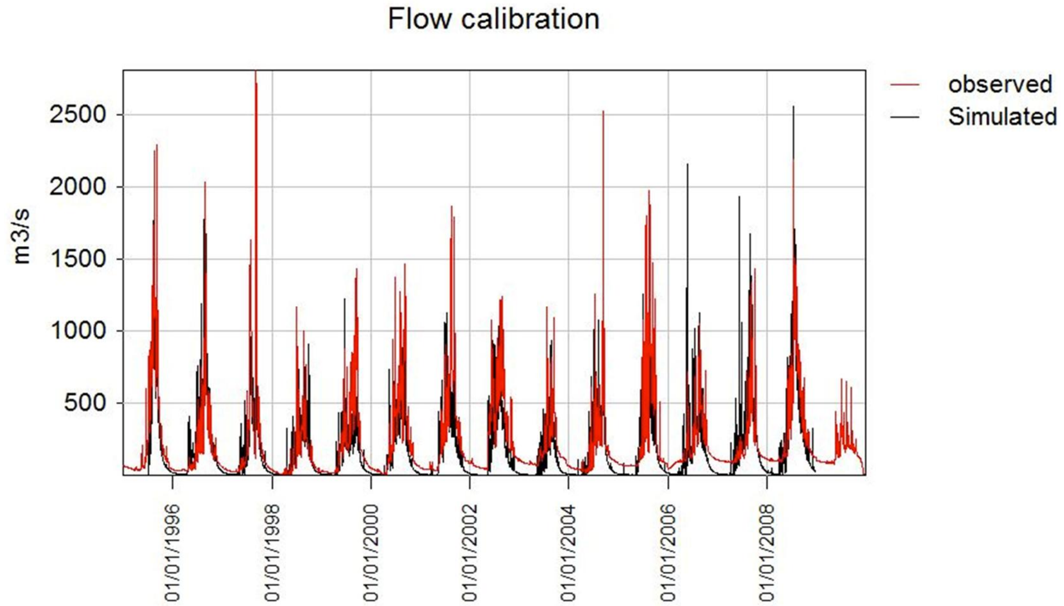

Figure 16: Observed and simulated flow at Nik Hinheup Station.

In Figure 16 above, daily-simulated flow was fitted with daily-observed flow measured at Nik Hinheup station. Monthly values of simulated flow and their corresponding fit with observed flow is represented in Figure 17.

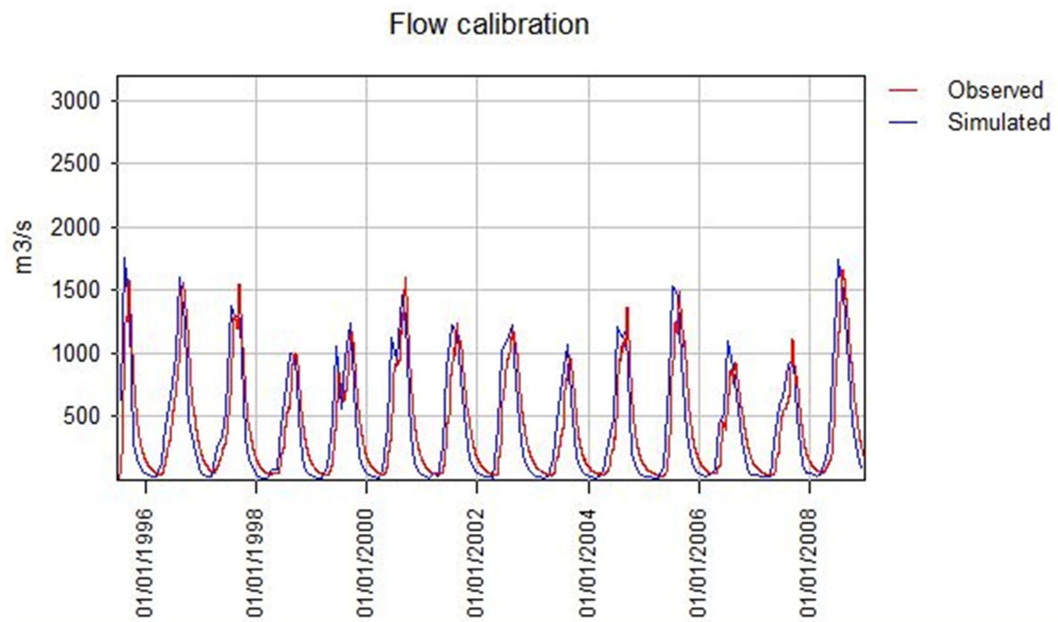

Figure17: Observed and simulated monthly flow at outflow point of Nam Ngum reservoir.

Further, in the second step, TSS load was calibrated using historical observations (Figure18).

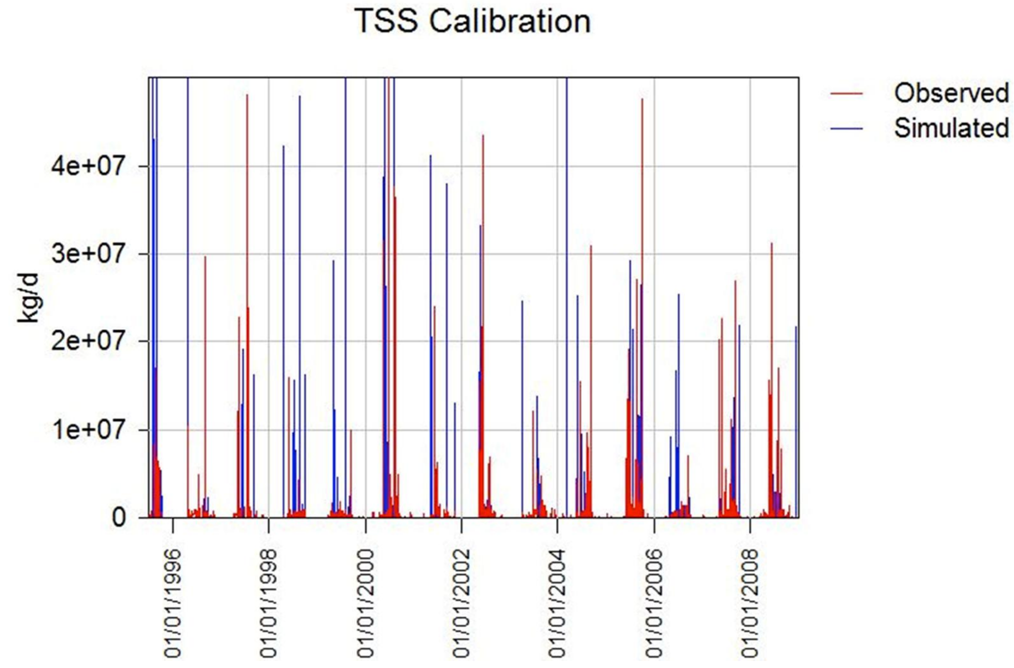

Figure 18: Observed and simulated TSS load at Pak Kanhoung.

Parameters affecting TSS load were evaluated to determine the proper fit of simulated TSS load with observed values. After ensuring proper fit of observed values with simulated values, further calculations were performed.

3.5 Sensitivity analysis of sediment model

Sensitivity analysis was performed to determine output change in relation to model parameters and input changes. For clear understanding of the output change, sensitivity analysis was performed only using the soil type and land use parameters.

3.5.1 Important model parameters

Different variables and corresponding parameters involved in the formation of surface runoff are presented in Figure19. The Evaporation Correction Factor, Petcorr, modifies the available surface runoff along with infiltration of water in different soil layer. Surface runoff and infiltration values are then determined and further used in model calculation. The Precipitation Correction Factor, Rainmult, determines the amount of precipitation available for the location by correcting the precipitation amount.

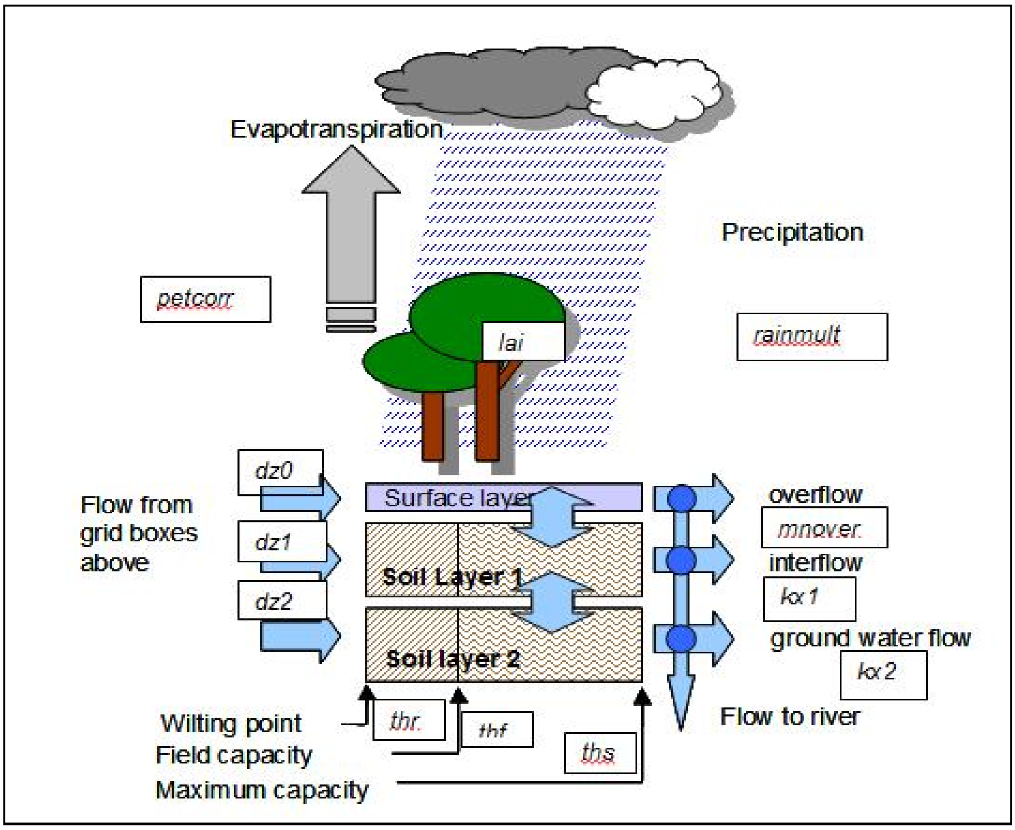

Figure 19: Important model process and corresponding parameters of IWRM model.

Apart from this, Critical Shear Stress (Tau0), Soil Splash Detachment (Ksd), Soil Erodability (Ker) and Portion of land cover that is bare (Pbare) have an effect on the sediment generation process. Thus, these parameters were determined to be more significant than other parameters of the model, and sensitivity analysis of the model was performed using these parameters.

3.5.2 Basis of Sensitivity analysis

The simulation period for the sensitivity analysis was chosen to start on 1 April in 2004 and to end on 31 December in 2005, and both the land use and soil type class were changed to value 2 which are *deciduous forest* and *acrisols,* respectively. The important model parameters were divided into primary and secondary calibration parameters and the effects of these parameters on the flow were determined. The cumulative flow for the simulation period was determined to be 265080 m^3, with a dry season flow (base flow) of 415 m^3/S, and a peak flow of 2285 m^3/s. Also, the cumulative TSS load for the simulation period was determined to be 2.68 x 10^9 kg, with a dry season load (base load) of 4.19 x 10^6 kg/d, and a peak load of 1.21 x 10^8 kg/d. With these initial values, different important input parameters were changed, and a new value for flow was determined to determine the effect on the flow. With these initial values, different important input parameters were changed and a new value for flow and TSS load was determined to determine the effect on the flow and the TSS load.

3.5.3 Result of Sensitivity analysis

Out of many parameters, Rainmult, had maximum effect on cumulative flow, base flow and peak flow. A thirty percentage increase in Rainmult value increases the cumulative flow, base flow and peak flow by up to 13 percentage and TSS load by up to 6 %. Whereas, 50 % increase in Petcorr value decreases cumulative flow and base flow by 6% and small decrease in TSS load. Maximum Leaf Area Index (Laimax*)* when increased by 37 % decreased the cumulative flow and base flow by almost 50 % whereas increases the cumulative and base TSS load by 20 %. Further, Ksd had no effect on the flow but 100% increase in *Ksd* changed the cumulative and base TSS load by almost 35%.The results of sensitivity result are presented in Table5 below.

Table 5: Sensitivity analysis of the different model input parameters

Parameters	Base Value	New Value	Change	Cumul Flow	Base Flow	Peak flow	Cumul TSS	Base TSS	Peak TSS
			%	%	%	%	%	%	%
Rainmult	1	1,3	30	13,20	13,00	13,48	6,00	6,04	4,43
Petcorr	0,8	1,2	50	-5,69	-5,87	-2,79	-0,72	-0,72	-0,48
Laimax	5,1	7	37	-48,47	-48,75	-30,72	20,20	20,21	36,43
Ksd	0,27	0,54	100	0,00	0,00	0,00	34,69	34,69	10,98
Tau0	0,3	2	567	0,00	0,00	0,00	0,03	0,00	0,00
Ker	0,02	0,1	400	0,00	0,00	0,00	0,00	0,00	0,00
Pcanopy	0,8	1	25	0,00	0,00	0,00	0,39	0,39	0,33
Cerosion	0,5	1	100	0,00	0,00	0,00	0,03	0,03	0,01
Rrough	25	50	100	0,00	0,00	0,00	0,03	0,03	0,01

Beside these parameters, all other parameters had relatively low contribution to flow and only contribute to change in flow when the parameter values were significantly higher than initial value. The detail result of sensitivity analysis performed is presented in Appendix 2.

3.6 Data Assumption and Uncertainties

In order to acquire the result and utilize the data, several assumptions were made:

- No wind-generated erosion was taken into account.
- The soil data may not truly represent the particular soil type of the area.
- Considering most common class in soil type and land use data might contain some error.

Using the higher resolution for the geographical data can produce more accurate results, but this causes an increase in the calculation time.

4 Practical Implementation of Sediment Trapping Model

4.1 Hydropower development impacts in Mekong region

Currently, 2.2% of the world's primary energy production is generated by hydropower installations. As a consequence of dams and reservoir storage, the water renewal time of world's river has increased dramatically from 20 to 100days [Golubev, 1993 as quoted in 12]. The self-purification capacity of the river has thus decreased, and major impacts in river hydrology and ecology are noticed [12]. Around 70 % of the world's rivers are intercepted by large reservoirs, and it is estimated that 1% of the existing storage volume is lost every year due to sediments. Further, the theoretical sediment trapping efficiency of reservoirs are high with half of the reservoirs with trapping efficiency of 80% or higher. [Vörösmarty et al. 2003 as quoted in 12]. In the Mekong region, the rapid increase in economic activity has led to an increase in hydropower production and water-related developments and Mekong tributaries in central and southern Laos are the most important contributors to Mekong flow in the lower basin [12]. Thus, the lower Mekong basin is directly affected by upstream hydropower development in the Mekong mainstream and tributaries and these effects could be viewed easily with the model developed for sedimentation.

4.2 Suspended Sediments Fractions

For determining the different suspended sediment fraction in the outflow; clay, silt and TSS concentration were simulated in observation points. As sand particles are relatively heavy, thus settling down in the reservoir, they do not contribute to the suspended solids concentration in the outflow. Therefore, the TSS concentration in outflow was calculated as a sum of clay and silt fraction of the suspended solids in the inflow. The outflow concentration of different sediment fraction is presented in Figure 20.

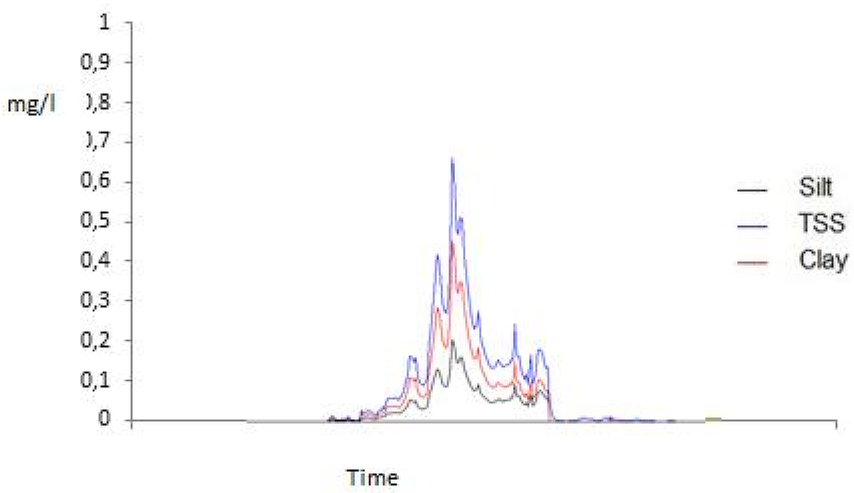

Figure 20: Clay, Silt and TSS concentration of different sediment fraction in the outflow of Nam Ngum reservoir.

4.3 Dam Trapping Modeling

Sediment trapping by the dam is calculated using reservoir net sediment settling rate for three different sediment fractions (clay, silt and sand) and determining reservoir sediment mass balance. As different sediment fractions have different sedimentation patterns, different sediment settling rate and re-suspension rate is required to acquire a net sediment trapping value.

Further, for more detailed and comprehensive sediment modeling, the IWRM toolbox includes the following features:

- Flow generated shear stress
- Waves and wave generated shear stress
- Boundary layer shear stress formulation
- 3D sediment transport (suspended load)
- Simple bedload formulation
- Cohesive sediment model using simple density dependent parameterization
- Land use and vegetation dependent transport and erosion
- Calculation of bed adjustment (bed elevation changes with sedimentation/ erosion)
- Classification of bank erosion risk based on horizontal and vertical near-shore velocities. [7]

4.4 Sediment Load Estimation

From the result obtained from the model, sediment load flowing to reservoir was estimated by determining TSS concentration and reservoir discharge value at a particular time. Sediment load was then calculated using the formula

$$S = TSS \times Q$$

Where,

S=Sediment Load (mg/S)

TSS=Suspended solid concentration (mg/l)

Q= Reservoir inflow (m^3/S)

Applying correct unit conversion, sediment load inflow was then estimated for the simulation period. Sediment load instead of sediment concentration is used throughout the process because it provides better insight of the overall process. The results of sediment load estimation are discussed in chapter 5 below.

4.5 Theoretical Trapping Efficiency

Trapping efficiency of dam refers to the amount of sediment retained by the dam from total sediment inflow. It is influenced by different factors like sediment velocity, reservoir discharge and flow rate. Higher trapping efficiency accounts for higher amount of sediment trapped in the reservoir; thus, less sediment flow downstream and vice versa.

The theoretical sediment trapping efficiency of a dam can be determined using the Brune's empirical method. For this, residence time of water in reservoir is calculated using the formula

$$T = \frac{V}{Q}$$

Where,

T= approximate residence time of the reservoir (year)

V= Operational Volume of reservoir (km^3)

Q=Discharge at reservoir (km^3/year)

And the corresponding trapping efficiency is determined using the equation

$$T = 1 - (\frac{0.05 * \alpha}{\sqrt{T}})$$

Under Mekong condition, α=1 representing median in Brune's curve (Figure 21) [10]

Residence time is particularly important in calculating sediment load as higher the residence time is, the higher the settling of sediments is in the reservoir. This method of calculation of trapping efficiency is simple because it does not require detailed data of reservoir or sediments and also provides estimates for long term mean trapping efficiency [12]. The Nam Ngum reservoir resembles a normal pond with no sediment release mechanism to flush the trapped sediment during flood time. Thus, it is suitable to calculate trapping efficiency with the help of Brune's mean curve [10].

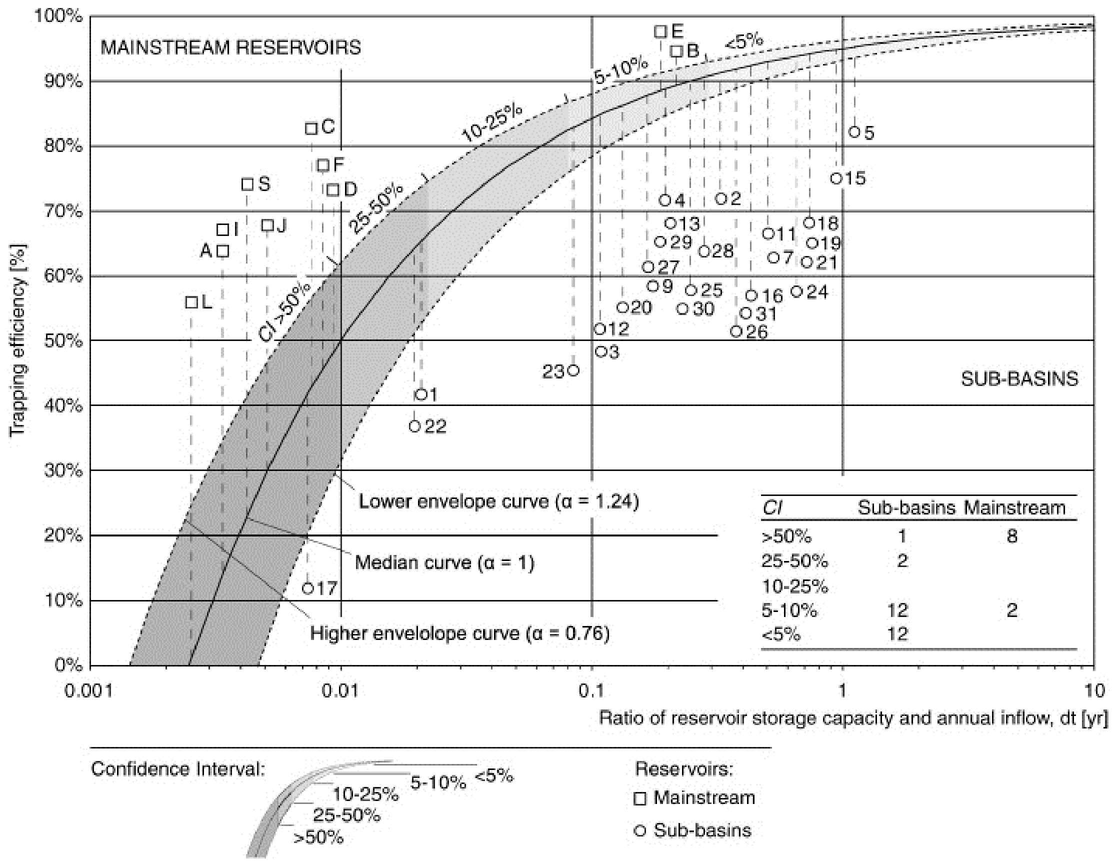

Figure 21: Median and envelope curves for Brune's method presented with *TE* estimations for the sub-basin and mainstream reservoirs of Mekong [10].

The envelope around Brune's mean curve addresses the issue of sediment particle size through an upper bound corresponding to highly flocculated and coarse sediments and a lower bound for colloidal, dispersed, fine-grained particles [Vörösmarty et al.2003 as quoted in 10].

From the results derived from the model, reservoir discharge and reservoir storage capacity were obtained and Brune's' method was used to obtain the trapping efficiency of the Nam Ngum dam. The result of calculated trapping efficiency is presented in result section.

4.6 Modelled sediment trapping

Sediment trapped in the reservoir can be calculated as difference of cumulative TSS load in inflow and outflow of the reservoir. Alternatively, sediment trapped can be determined as trapping efficiency percentage of the inflow TSS load:

$$Sl = TSS_{in} - TSS_{out}$$

Where,

Sl= Sediment Trapped (Kg)

TSS_{in}= Cumulative TSS load in inflow (Kg)

TSS_{out}= Cumulative TSS load in outflow (Kg)

So,

$$TE = \frac{TSS_{in} - TSS_{out}}{TSS_{in}}$$

Where,

TE= Trapping efficiency

The use of two different methods; Brune's and sediment trapping, is relevant as it is more reasonable to conclude the results using two different ways. The two different ways of obtaining the results provides comparison of different process. However, sediment trapping method is less reliable in determining the theoretical trapping efficiency.

5 Results and Discussion

5.1 Reservoir water balance

The daily water inflow, average yearly inflow and daily water outflow from the Nam Ngum reservoir for the period of 1996-2000 is presented in Figure22.

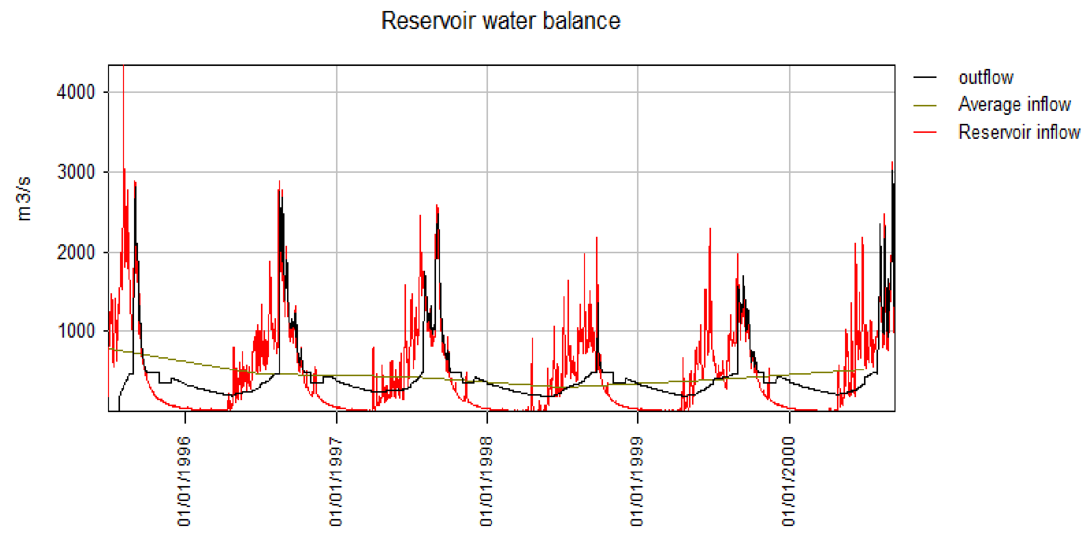

Figure 22: Reservoir water from 1996-2000.

High flow periods in Figure 22 are wet season flows and periods between are dry season flows. Naturally, the wet season inflow is comparatively higher to that of the dry season. In the reservoir, balance in water flow is obtained by higher outflow during the wet season and almost constant outflow during the dry season where the outflow from the reservoir is slightly lower than the average inflow. As the outflow from the reservoir is guided by the reservoir operational procedure, the outflow during the dry season is normally higher than without reservoir. This is also due to fact that the reservoir needs to store enough water in order to produce power throughout the year.

5.2 Sediment Transport to reservoir

To calculate the amount of sediment transported to reservoir, sediment load was analyzed in three different points at the inflow of reservoir (Figure 15). The total sediment inflow was then calculated by adding the results from three points. The daily TSS inflow and the yearly average TSS inflow to the reservoir from year 1996 to 2008 is presented in Figure 23. Here, the sediment inflow is particularly low during the dry season as the amount of precipitation available for sediment transport is low and can reach to peak during wet seasons due to excessive precipitation and rainfall intensity.

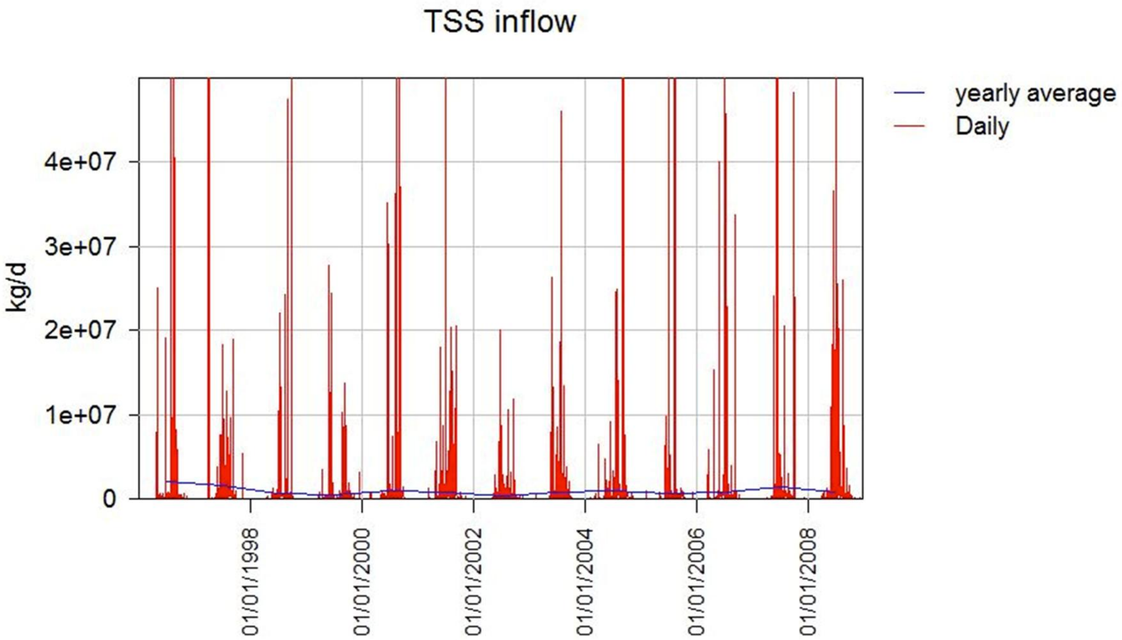

Figure 23: Sediment inflow to Nam Ngum reservoir for year 1996-2008.

The cumulative total inflow sediment load was then determined for the period of 1996-2008. (Figure24)

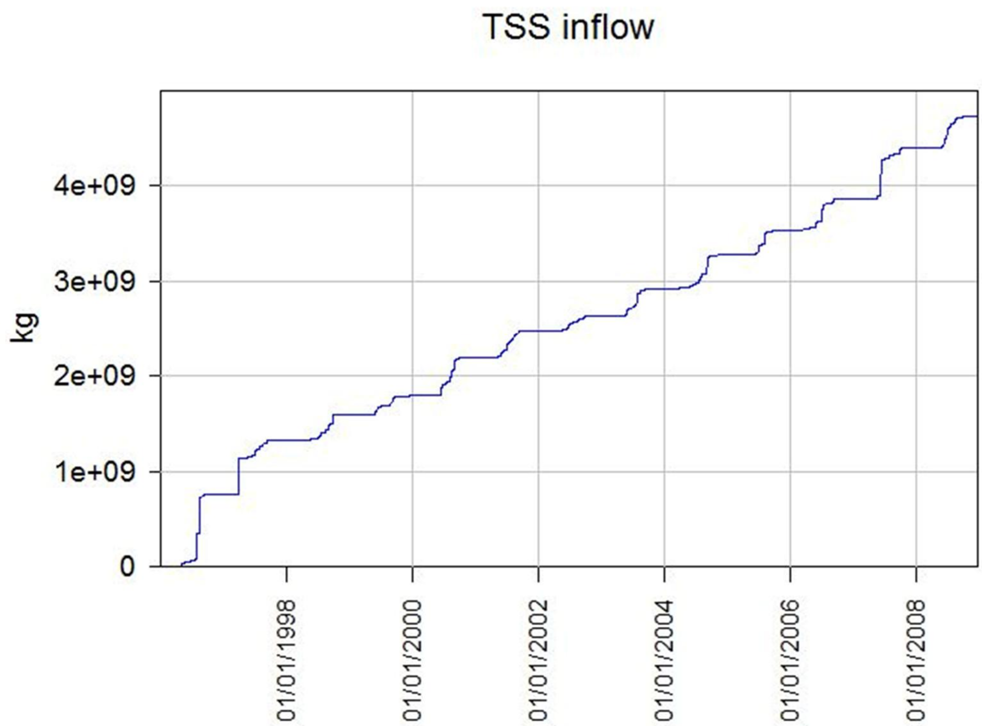

Figure 24: Cumulative sediment inflow to the reservoir for years 1996-2008.

Here, sediment inflow is high and is in the range of 4.7 x 10^9 kg (4.7 million tonnes) during the twelve year period. Thus, the average annual sediment inflow to the reservoir was determined to be 0.392 million tonnes.

5.3 Theoretical Trapping efficiency using Brune's Methood

The retention time for the reservoir was determined by using volume and flow data guided by the reservoir operational procedure for the period from 1996 to 2008. The average monthly outflow from the reservoir and the average monthly volume were used to determine the retention time, and Brune's method was used to determine the trapping efficiency of the Nam Ngum reservoir. The Trapping Efficiency calculation results are presented in Table 6.

Table 6: Trapping efficiency calculation

Year	Volume	Volume	Total yearly flow	Total flow	Retention Time	Trapping Efficiency
	(Million liters)	(km^3)	(m^3/S)	(km^3/S)	(yr)	
1993	2214170	22.14	2064.7	65.113	0.340	0.914
1994	3169830	31.70	3020.7	95.262	0.333	0.913
1995	4125500	41.26	3669.4	115.718	0.357	0.916
1996	5081160	50.81	4196.5	132.342	0.384	0.919
1997	5124420	51.24	4229.5	133.382	0.384	0.919
1998	5255130	52.55	4320.8	136.261	0.386	0.919
1999	5298130	52.98	4348.1	137.121	0.386	0.920
2000	5373630	53.74	4391.0	138.473	0.388	0.920
2001	5427950	54.28	4418.2	139.333	0.390	0.920
2002	5508870	55.09	4453.4	140.444	0.392	0.920
2003	6030200	60.30	4645.3	146.494	0.412	0.922
2004	6442340	64.42	4767.6	150.351	0.428	0.924
2005	6478000	64.78	4775.6	150.603	0.430	0.924
2006	6505680	65.06	4779.7	150.733	0.432	0.924
2007	6600670	66.01	4786.8	150.956	0.437	0.924
2008	7003990	70.04	4786.8	150.956	0.464	0.927
					Average TE	0.920

The theoretical values of TE vary from 0.61 to 0.66 for large reservoirs ($10^7 m^3$< volume >10^9 m^3) and from 0.66 to 0.92 for very large reservoirs (volume >10^9 m^3). For the Nam Ngum reservoir, TE is greater than 90 % at any time [12]. Hence, TE calculations show that 92% of the sediment inflow to the reservoir is trapped in the reservoir.

5.4 Trapping efficiency by Sediment Trapping method

Sediment trapped in the reservoir was determined by calculating the difference between inflow TSS load and the outflow TSS load of the reservoir. The average yearly TSS outflow and daily TSS outflow from the reservoir during the period of 1996-2004 are presented in Figure25.

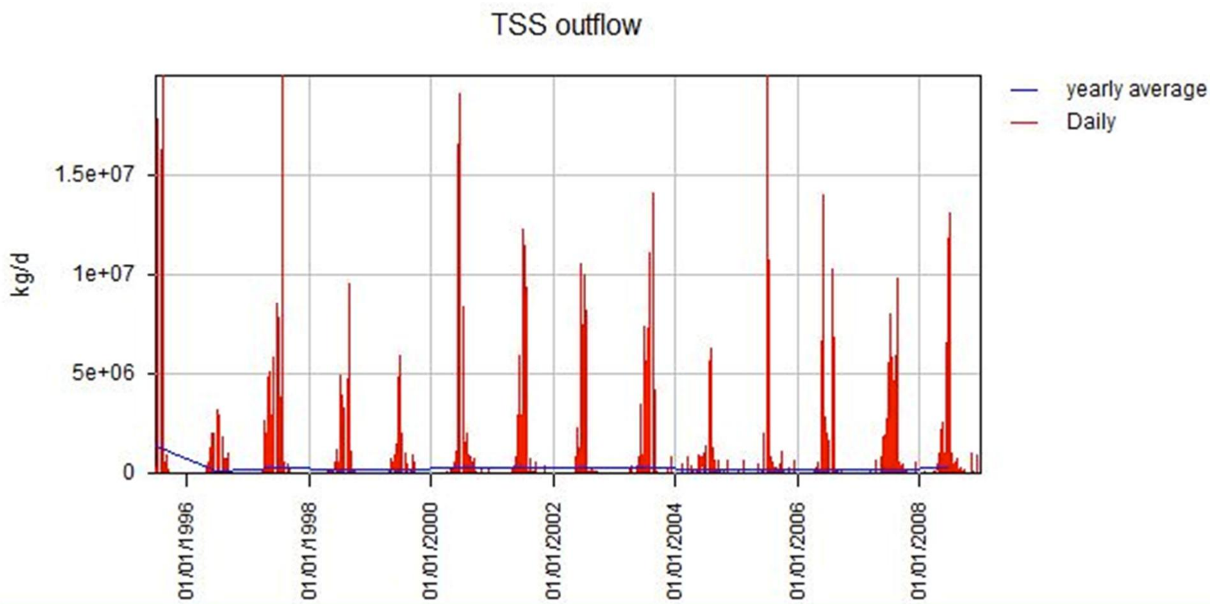

Figure 25: Daily and yearly average TSS outflow from the Nam Ngum reservoir for the period of 1996-2008.

TSS outflow is significantly high in the wet season due to the fact that more flow is available to flush sediment out of the reservoir during the wet season and also TSS inflow is high during the wet season. The total sediment outflow from the reservoir and its comparison with sediment inflow during the period of 1996-2008 is presented in Figure 26.

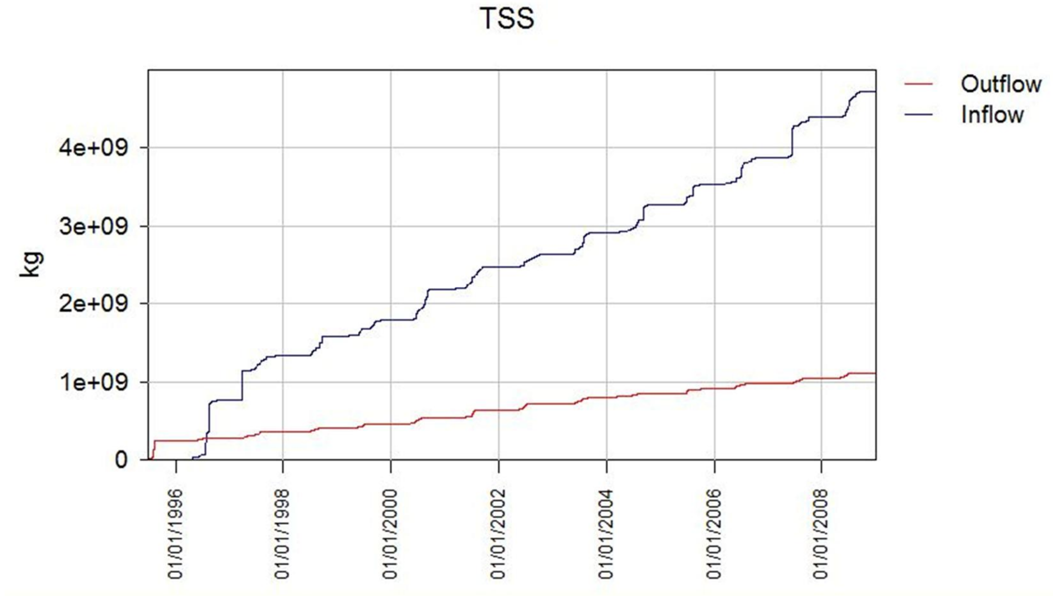

Figure 26: Cumulative total sediment inflow and outflow from the reservoir from 1996 to 2008.

Now, when TSS inflow is subtracted from TSS outflow, cumulative TSS trapped in the reservoir is obtained. This is presented in Figure 27:

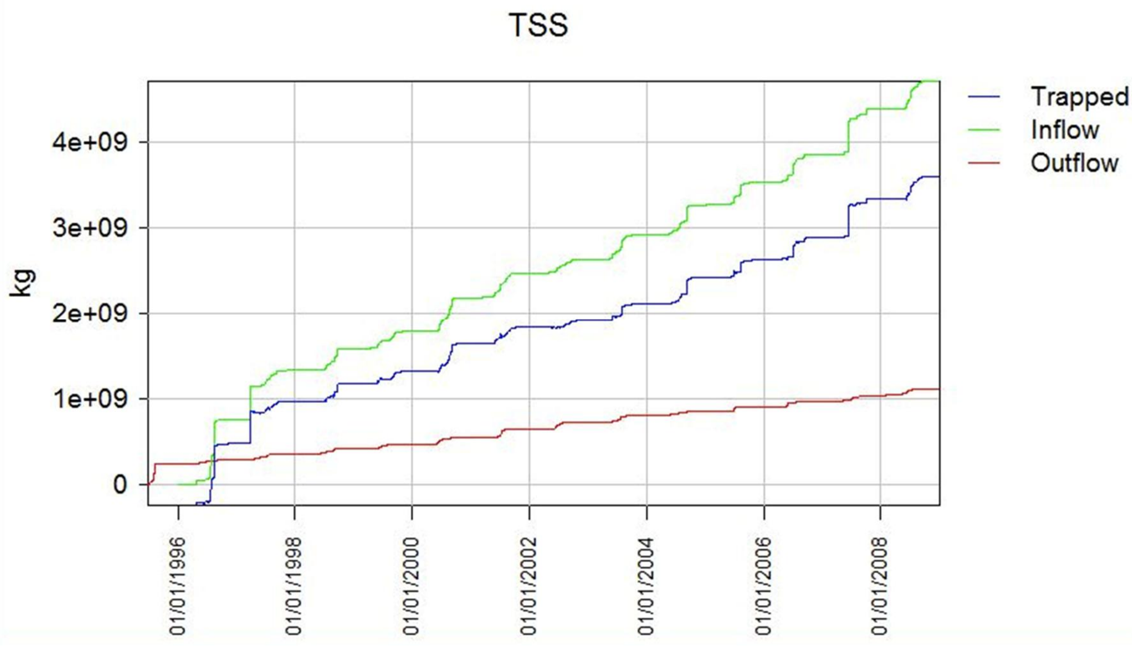

Figure 27: Estimated Sediment Trapped in the Nam Ngum reservoir for the period of 1996-2008.

From Figure 27, the maximum TSS deposited in the reservoir was determined to be 3.7 X10^9 Kg (3.7 million tonnes) over the period of twelve years. Thus, average sediment trapped in the reservoir was determined to be 0.308 million tonnes per year. TSS values were used to determine the trapping efficiency (*TE*) of the reservoir as follows:

$$TE = \frac{TSS_{in} - TSS_{out}}{TSS_{in}}$$

$$TE = \frac{0.308}{0.392}$$

So, TE = 0.785

Thus, trapping efficiency of Nam Ngum reservoir was determined to be 0.785 by sediment trapping method. In other words, 21.5 % of sediment is discharged from the reservoir.

In Brune's Method, the volume of the reservoir is taken into account, but the distribution of volume could differ. Although volume could be same for shallow and deep parts in the reservoir, settling of sediments is more in shallow than that of deeper parts. This difference in the settling of sediments affects the TE of the reservoir although volume might be constant.

Daily TSS flux through the dam (Figure 28) was determined by subtracting daily TSS inflow from TSS outflow.

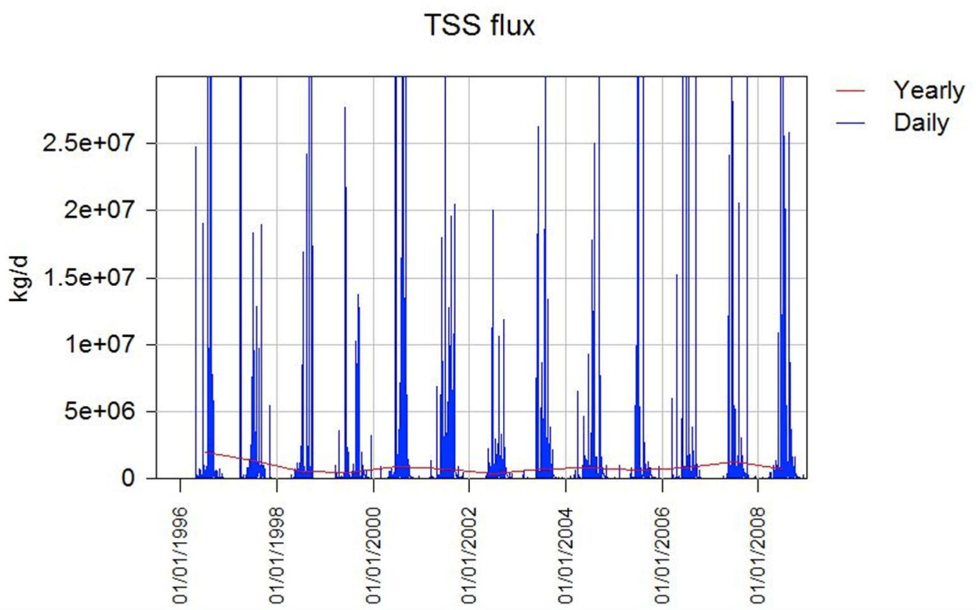

Figure 28: TSS flux.

In Figure 28, average TSS flux is very low as TSS transported downstream is very low and much of the TSS is retained by the reservoir.

5.5 Comparison of results with measurements

In April 1991, sediment cores were sampled in the Nam Ngum reservoir by a Swedish team and annual mean sediment inflow was determined for the period of 1972 to 1989. According to calculations, the annual mean inflow of suspended inorganic sediments to the reservoir was determined to be 1.4 million tonnes for the period of 1972-1989. Also, the sediment yield for the Nam Ngum catchment area was determined to be 140 tonnes/km^2. The study emphasises that the results are ”very uncertain, since they are based on many assumption”. [17]. The monthly sediment inflow measured at Ban Na Luang in the Nam Ngum reservoir (Figure 29) shows a peak in sediment inflow in month of July and August.

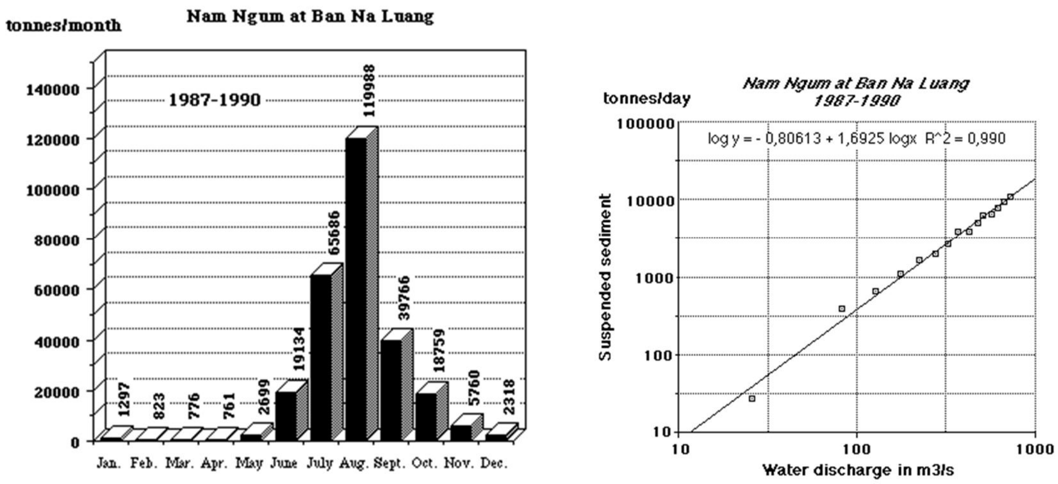

Figure 29: Monthly mean sediment inflow at Nam Ngum reservoir and sediment rating curve for year 1987-1990 [17].

From the study and Figure 29, estimated yearly sediment inflow to the reservoir was 1.4 million tonnes that includes bottom and organic sediment load.

Simulated annual TSS load to the reservoir was 0.39 million tonnes corresponding to 39 tonnes/km^2 sediment yield. The differences in the computed and estimated values may stem from the uncertainties in the estimate.

Further, TSS inflow when plotted with water inflow provides a sediment-rating curve (Figure 30).

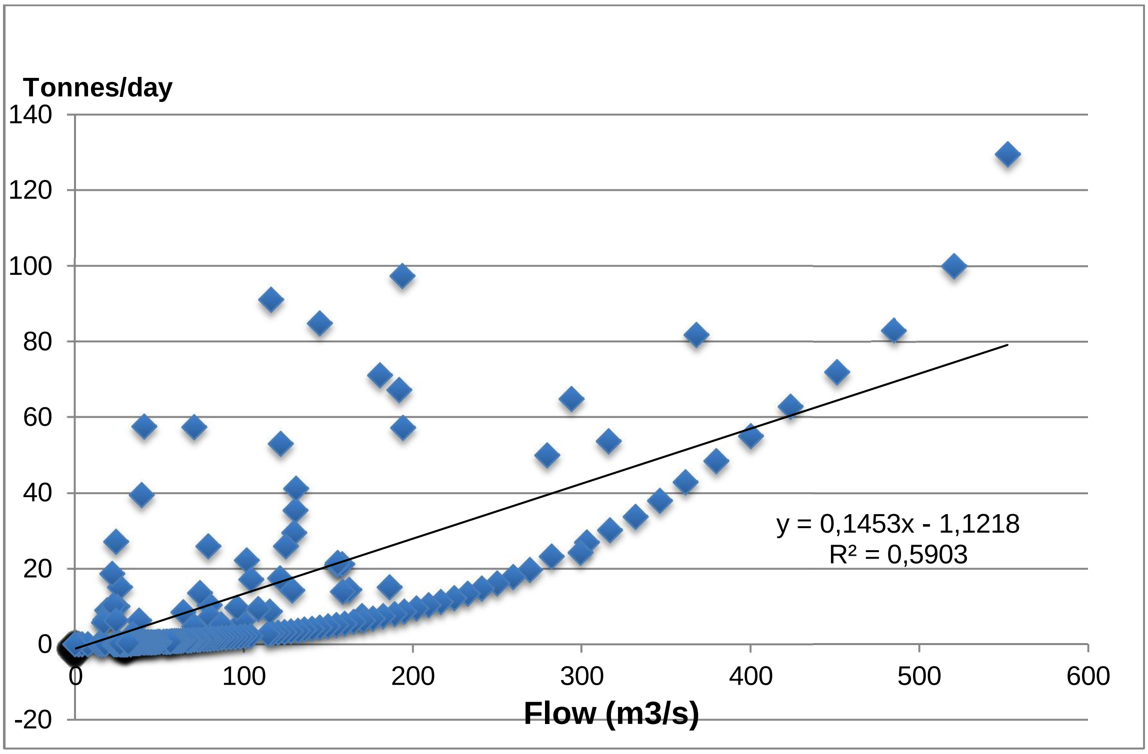

Figure 30: Sediment rating curve for the Nam Ngum reservoir from simulated values.

According to the Swedish study, during the period of 1987-1990, about 20% of incoming sediment load was discharged out of the reservoir [17]. This sediment load discharged was approximately the same when compared with the model-calculated sediment discharge of 21.5%.

5.6 Downstream effects

The presence of the reservoir can have significant downstream impacts. Over a long period of time, the reservoir affects the natural flow pattern of the river and sediment transported downstream.

For determining the difference in flow and sediment load patterns, a simulation was performed with controlled outflow from the reservoir and with natural flow without any reservoir. Results were then compared on the Ts point downstream of the reservoir. The difference in the flow pattern due to presence of the reservoir is presented in Figure 31 below. Here, dry season flow with the reservoir is significantly higher in comparison to dry season flow without any reservoir.

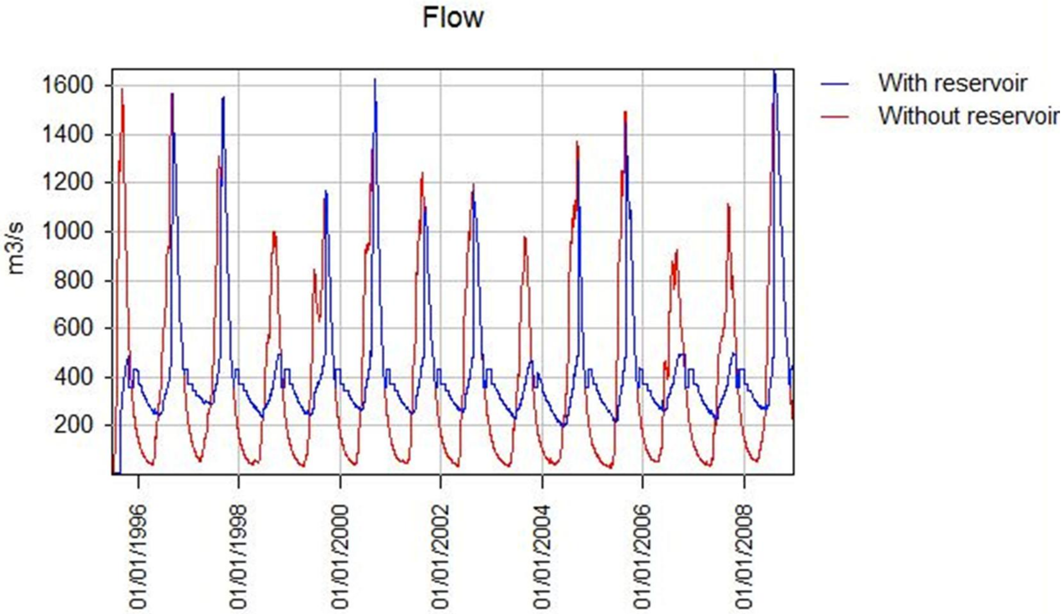

Figure 31: Daily flow downstream with and without the reservoir.

The monthly average of the flow with the reservoir and without the reservoir (Figure 32) shows the major difference in seasonal flow pattern. Although the yearly average flow might remain approximately the same, the monthly dry season average flow with the reservoir is significantly higher than dry season flow without any reservoir. Despite similar wet seasons flow, dry season flow with the reservoir is twice the natural flow.

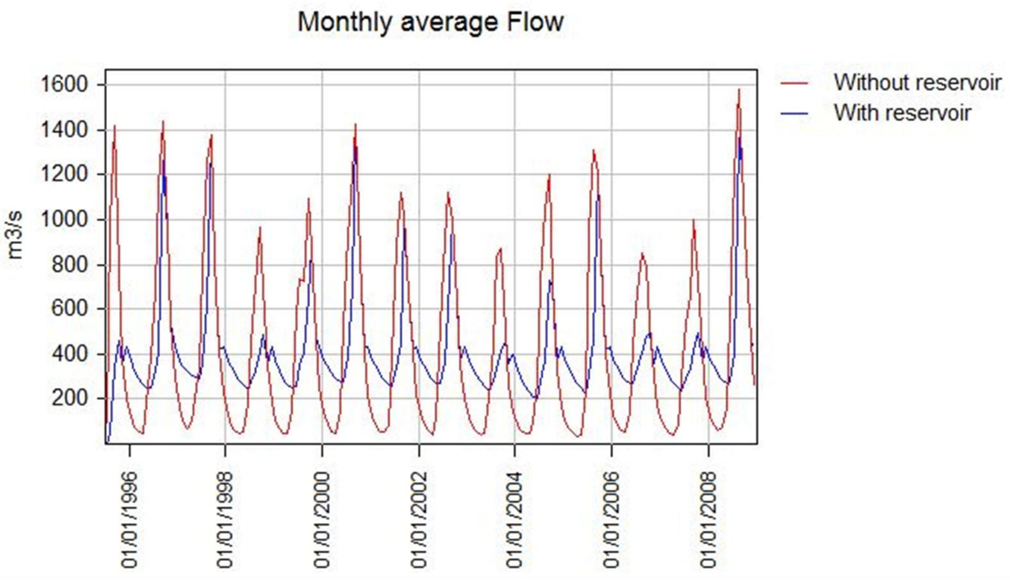

Figure 32: Average monthly flow with and without the reservoir.

The daily TSS load measured downstream with and without the reservoir (Figure 33) shows that total TSS load without the reservoir would have been much higher during any time of the year.

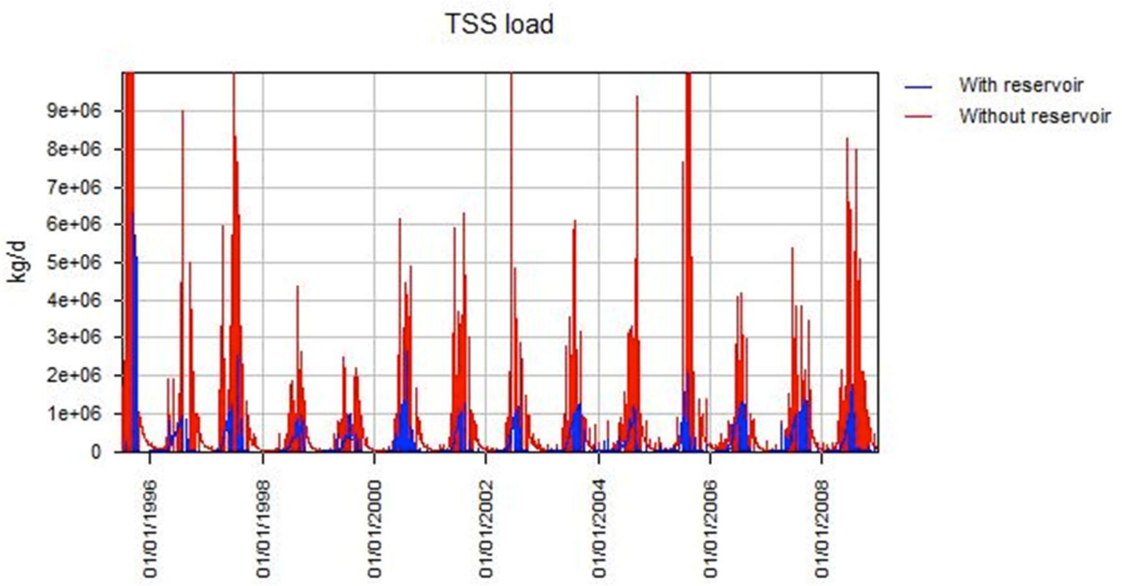

Figure 33: Daily TSS load with and without the reservoir.

Cumulative TSS load simulated in the downstream of the reservoir between 1996 and 2008 is presented in Figure 34.

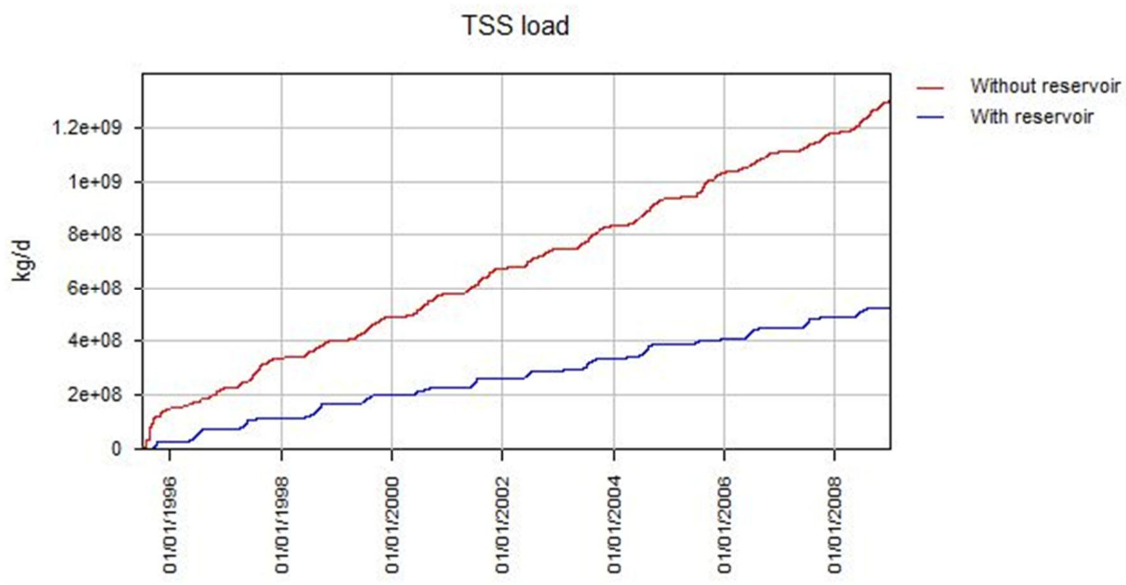

Figure 34: Cumulative TSS load with and without the reservoir for years 1996-2008.

Here, total TSS load is much higher without the reservoir than with the reservoir. This supports the fact that high amount of sediment is trapped in the reservoir; thus, there is less TSS available for downstream users.

In Figure 35, cumulative TSS for the period of 1996-2008 was approximately 5 x 10^8 Kg with the reservoir and approximately 1.3 x 10^9 Kg without the reservoir. This result when used for TE calculation provides a TE of 61% which is 17.5% less than the TE calculated through sediment trapping.

5.7 Morphological impacts of sediment trapping

Dam construction not only has negative impacts on downstream users but also positive impacts.

Positive impacts include increase in dry season flow thus, decreasing the risk of water shortages and the increase in dry season irrigation. Also, on the lower basin, the increase in dry season flow reduces saline water intrusion to agricultural land, thus, benefiting rice farming and fish production. The increase in water level during dry season can lead to an increase in navigational activities in various places.

However, these positive impacts are overshadowed by the negative impacts of dam closure. The negative impact includes change in the natural flow pattern of the river due to controlled flow, effects in physical, biological and chemical properties of water and more importantly fish migration. The increase in dry season flow has a potential for flooding important ecosystem downstream, and a decrease in wet season flow may have an impact on the biological productivity of smaller floodplains. [12]

Normally, a sharp decrease in TSS concentration occurs after the closure of the dam. As most of the TSS is trapped in the dam due to general high trapping efficiency of the reservoir, lower amount of sediment is available for downstream user. Thereby, leads to loss of important biological fertilizers that the river carries as sediment and thus accounting to loss of productivity in agricultural land dependent on the river system. Apart from these, loss of reservoir storage capacity is a major concern due to sediment trapped in reservoir. As hydropower development already has high social, economic and environmental cost, loss of storage capacity causes additional economic and environmental costs for the reservoir operation. Also, hydropower production and flood control effectiveness decreases due to the decrease in storage capacity. Further, the downstream impact of sediment trapping by the reservoir is more severe than the corresponding upstream impact. The downstream flow with low sediment concentration when combined with natural erosive force of the flow of the river creates erosion in the form of a widening and deepening of the river channels [13]. This flow is in the long run is responsible for the riverbed erosion and leading for coastal erosion on downstream.

After the closure of dam, the sediment transport capacity will exceed the available supply of sediments in both dry and wet season especially close to dam sites. This would lead to downstream impacts like channel bed degradation, textural changes involving coarsening of surface grain size distribution and lateral expansion [12]. Typically, dam changes two critical elements of geomorphic system, the ability to transport sediment and the amount of sediment available for transport [Grant et al, 2003 as quoted in 12]. As the transport capacity exceeds the available supply of sediments, the flow becomes “Sediment Hungry” [7]. The “Sediment Hungry Water” then erodes the riverbed downstream to fulfill the sediment requirement as flow capacity for resuspension and erosion is not reduced. Thus, it provides some compensation for the sediment trapped in reservoir. In the Mekong River, the active bottoms are largely sand and are unable to compensate the portion of finer sediments. Further net erosion cannot fully compensate the decreased sediment input to the system; thus, erosion will decrease with time and finally, the river system obtains the new equilibrium with erosion and sedimentation process. With an increase in water level fluctuations between seasons, wetting and drying of riverbanks and changing ground water levels will stress the riverbank and finally increase erosion [7].

The long-term (more than 20 years) changes of the sediment trapping are visible with changes of river channels and flood plains. In conjugation with bed erosion, bank erosion and change in flow, visible impacts of sediment trapping are seen in aquatic life, irrigation, water quality and fish migration. [14]

6 Conclusion

Creation of model for assessment of sediments provides good insight to possible future complications caused by imbalance in sediment flow. For long-term ecological balance, modeling not only provides overview of different possible environmental challenges but also provides possible solution measures as definitive area for changes could be focused with obtained result. Model developed during this task allows determining the sediment load generated, transported and trapped with possible ecological risks involved. The model also allows visualizing different important hydrological and geographical components such as land use and corresponding effects on the result. Further, results of the model demonstrate possible morphological changes as impacts of the change in sediment flow. Thus, this sediment related issues could be incorporated in the pre-planning process of hydropower dam construction in such a way that sediment trapping has the least possible damage to the downstream environment in the long term.

When relating the modeling result of one particular reservoir with other reservoirs throughout the world, better perspective to the global impact could be obtained. Hence, in overcoming the possible challenges and developing better policy, such model is a useful tool.

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Weather data interpolation

Height correction for precipitation=0.0004 mm/m elevation

Height correction for Temperature= -0,006C/m elevation

Interpolation types are presented in table below:

Type	Interpolation
0	First found
1	Closest, additive height correction
2	Closest, Multiplicative height correction
3	3-point interpolation, additive height correction
4	3-point interpolation, multiplicative height correction

Sensitivity analysis

Parameter	Base Value	New Value	Change	Cumul Flow	Cumul Flow	Base Flow	Base Flow	Peak Flow	Peak Flow	Cumul TSS	Cumul TSS	Base Tss	Base TSS	Peak Tss	Peak TSS
			%	m3/s	%	m3/s	%	m3/s	%	kg/d	%	kg/d	%	kg/d	%
Rainmult	1	1,3	30	305137	13,20	477	13,00	2641	13,48	2,85E+09	6,00	4,46E+06	6,04	1,27E+08	4,43
Petcorr	0,8	1,2	50	250591	-5,69	392	-5,87	2223	-2,79	2,66E+09	-0,72	4,16E+06	-0,72	1,21E+08	-0,48
Laimax	5,1	7	37	178395	-48,47	279	-48,75	1748	-30,72	3,36E+09	20,20	5,25E+06	20,21	1,91E+08	36,43
Ksd	0,27	0,54	100	264857	0,00	415	0,00	2285	0,00	4,10E+09	34,69	6,42E+06	34,69	1,36E+08	10,98
Tau0	0,3	2	567	264857	0,00	415	0,00	2285	0,00	2,68E+09	0,03	4,19E+06	0,00	1,21E+08	0,00
Ker	0,02	0,1	400	264857	0,00	415	0,00	2285	0,00	2,68E+09	0,00	4,19E+06	0,00	1,21E+08	0,00
Pcanopy	0,8	1	25	264857	0,00	415	0,00	2285	0,00	2,69E+09	0,39	4,21E+06	0,39	1,22E+08	0,33
Cerosion	0,5	1	100	264857	0,00	415	0,00	2285	0,00	2,68E+09	0,03	4,19E+06	0,03	1,21E+08	0,01
Rrough	25	50	100	264857	0,00	415	0,00	2285	0,00	2,68E+09	0,03	4,19E+06	0,03	1,21E+08	0,01