

Kenneth E Hirvonen

Sediment Balance in the Upper Nam Ngum

Modeling the hydrological response to climate change and developmental scenarios for guidance in hydropower asset management

Helsinki Metropolia University of Applied Sciences

Bachelors of Science

Environmental Engineering

Thesis

21.3.2016

Author(s) Title	Kenneth Hirvonen Sediment balance in the Upper Nam Ngum
Number of Pages Date	61 pages 21, March, 2016
Degree	Bachelors of Engineering
Degree Program	Environmental Engineering
Specialization option	Energy
Instructor(s)	Ari Kostinen, Faculty Supervisor Marko Kallio, Modelling Specialist Jorma Koponen, Model Developer
<p>Exploitation of hydropower in excess of 1.3 gigawatts is under development in the Upper Nan Ngum watershed. The infrastructure is expected to continue functioning well after control transfers to the government of Laos. Hydropower is regarded as renewable, reliable and timeless; stores of potential energy, requiring only regular maintenance.</p> <p>This paper examines a creeping affliction, sedimentation which consumes reservoir volume and inevitably invalidates dam infrastructure. It focuses on the differential sedimentation found in hydrological modeling of climate change, land use change and dam operation. The findings illustrate a continuous relationship which maps sedimentation to regional change and predicts infrastructure senescence.</p> <p>Based on the findings and according to operational objectives, no justification could be made for mitigation infrastructure. Social and ecological factors are not considered. The mechanistic response from climate change and land use change has been documented and quantified. A novel metric has been proposed for measuring reservoir sedimentation based on relationships found to exist in the modeled space. This instrument has the potential as a robust metric in hydropower capacity monitoring.</p>	
Keywords	Sediment Balance, Upper Nam Ngum, Dam senescence, Watershed sediment response with respect to Climate, Development and Hydro-electric dams

Contents

Tables	2
Figures	2
1 Justifications	3
2 Theory and Background	4
2.1 Fluvial sedimentation	4
2.2 Points of reference, the region and the model	8
2.2.1 Nam Ngum River Basin	9
2.2.2 Building the case for modelling with IWRM	10
2.2.3 Cascade	16
2.2.4 IWRM software	19
2.3 Experimentation, Scenario Building	22
2.3.1 Dams	25
2.3.2 Climate change	28
2.3.3 Land use	30
3 Analysis	31
3.1 Excluding Cascade	31
3.1.1 General discussion of metrics	33
3.1.2 Tracking sediment movement	36
3.1.3 Tracking sediment volume	38
3.1.4 Summary of Sediment Observations	39
3.2 Incorporation of Cascade	40
3.2.1 General discussion of metrics	41
3.2.2 Sediment Density	41
3.2.3 Sediment mobilization through impounds	44
3.2.4 A case for sediment weir mitigation	46
3.2.5 A case for compound metrics	47
3.2.6 Connecting the dots	51
3.2.7 Comparison to more traditional metrics	52
3.2.8 Infrastructure Senescence	53
3.2.9 Summary of sediment observations considering infrastructure	54
3.3 Hydropower	55
3.3.1 Sorting the mess	56
3.3.2 Another look at Senescence	59
4 Conclusions	61
5 Research suggestions	64
References	64

Tables

Table 1 Upper Nam Ngum reservoir data	17
Table 2 Factorial experimental design array	24
Table 3 Baseload objectives	28
Table 4 Combined strategy objectives	28
Table 5 IWRM UNN, various metrics	32
Table 6 IWRM UNN, Summary Volume and Mass Illustration.....	39
Table 7 IWRM UNN, Specific Density Calculation.....	43
Table 8 IWRM UNN, Fractional Specific Density Calculation	43
Table 9 Fractional Sediment Analysis Worksheet, Iwrn.....	44
Table 10 IWRM UNN Sedimentation figures	45
Table 11 IWRM UNN, Reservoir Sedimentation Statistics Initial Phase Scenario +-..	49
Table 12 Sediment rate 40-50 year selected scenarios.....	51
Table 13 IWRM UNN, Node Specific Annual Deposition as % of Volume	52

Figures

Figure 1 Upper Nam Ngum region	9
Figure 2 IWRM UNN, Land use and Soil type statistics.....	12
Figure 3 IWRM UNN, River and grade statistics	13
Figure 4 IWRM UNN, Downstream Profile UNN watershed V1	15
Figure 5 IWRM UNN, FFT of Precipitation 1995-2007	15
Figure 6 IWRM UNN, Autocorrelation Precipitation 1995- 2007	16
Figure 7 Example of flow curve objective	27
Figure 8 IWRM UNN, Proportional Metrics.....	34
Figure 9 IWRM UNN, Nodam Precipitation and Flow	35
Figure 10 IWRM UNN, Sediment figures	37
Figure 11 IWRM UNN, Sediment Load and River Discharge, various assumptions	39
Figure 12 IWRM UNN, Sediment figures.....	42
Figure 13 IWRM UNN.vmp +++	46
Figure 14. IWRM UNN, Cumulative Sediment Volume	47
Figure 15. IWRM UNN, Cumulative Sediment load.....	47
Figure 17. IWRM UNN, Baseline Deposition Ratio.....	48
Figure 16. IWRM UNN, Climate change deposition ratio.....	48
Figure 18 IWRM Deposition Rate and Ratio	50
Figure 19 IWRM UNN Cascade Node Energy Capacity	55
Figure 21 IWRM UNN Node-Specific Cascade Production	56
Figure 20 IWRM Annualized Cascade Production	56
Figure 22 IWRM UUN Selected Water Level Graphs	57
Figure 23 IWRM UNN Monthly Nodal Production at 10 and 50 Year Timeframe.....	58
Figure 24 IWRM UUN, +-0 NN3 Water Volume	60

1 Justifications

Environmental engineering is a specialized field focused on managing or mitigating the impacts of anthropogenic activities. The field is still defining itself; by category, such as air, water and soil, or by industry, such as regulatory compliance, water treatment or energy industry waste mitigation. This thesis combines categories and industries; a study of soil transmission through a natural watercourse modified by energy infrastructure.

It has been suggested that the present geological era be deemed The Anthropocene. This term, attributed to Nobel Prize winner Paul Crutzen in 2000, distinguishes human activity as the primary driver of environmental change. In the geological timeframe, the shift from one climate regime to another is imperceptible. The gradual change is a property of a system always in balance and at equilibrium. Anthropogenic forces, notably emissions of carbon dioxide from extensive use of fossil fuels, have resulted in a state of flux, and the resulting change to the climate will be unpredictable. (IPCC 2013, Meybeck 2003)

Modifications, or improvements to Continental Aquatic Systems (**CAS**) disrupt an equilibrium which likewise results in a state of flux. Riparian phenomena are anchored to the geology and hydrology which are measurable and systematic. The improvements initiate specific changes to the water course which are also measurable and systematic. The system as it moves from one state to another is in flux, but it is possible to make inferences based on the end states about the interim behavior. (Meybeck 2003)

Few major CAS are free from anthropocentric modifications and sediment balance is a common topic of concern. Dam reservoirs are one of man's mightiest creations, and sediment is their natural enemy. Managing the threat posed by sedimentation can extend dam lifetimes, increase dam profitability and mitigate the dam risk. (Morris 1998, Meybeck 2003)

Nam Ngum River Basin (**NNRB**) In Laos PDR is undergoing a process of improvements which began in 1970 with the installation of Nam Ngum 1 (NN_1) hydro-electric dam. In 2020 there will be 3 additional hydro-electric dams upstream of Nam Ngum 1. This cascade of reservoirs provides power to Laos and its neighbors. The benefits of the improvements will contribute to the Laos strategy of alleviating poverty and providing modern services to its people. (Resources 2011, Shannon 2008, Lao People's Democratic Republic 2001)

In their Social and Environmental Impact Assessment of Nam Ngum 3, Snowy Mountain Engineering offered criticism of several aspects including that of sedimentation. This criticism focused on the use of solely empirical methods and cite the wide deviation in results and the non-correlation with other, more thorough results in similar regions. This disregard for environmental issues is a common theme in developing nations. (Snowy Mountain Engineering Corporation 2001)

This study applies a distributed physical model to address these concerns and to functionalize all the available data. Climactic changes in precipitation, population induced land use change and strategic utilization of the water resource are roughly estimated and applied to the model. Sediment accumulation rate within the cascade is compared in various scenarios.

The objective is not to predict actual sedimentation at discreet points in the future, but instead to measure individual and combined effects of changes which span a practical range. The results may be useful in choosing a particular sediment mitigation strategy or contrasting the costs of proactive vs reactive measures.

2 Theory and Background

2.1 Fluvial sedimentation

The evidence of human activity on the ecology, geology, hydrology and atmospheric chemistry mark the boundary in the archive of the earth lithosphere (Crutzen and Stoermer 2000). Unlike the previous eras which are delineated by a clear boundary recording a single cataclysmic event, the Anthropocene boundary is graduated by the evidence of human development. Impacts from population and technology mark the profile which tracks local and regional change specifically and global change more generally. (Meybeck 2003)

Continental aquatic systems (CAS) are central to many natural earth processes. As the primary arteries delivering nutrients, minerals and organics from the inner regions to low-land deltas, they redistribute the wealth of terrestrial regions. Connecting distant geological areas, they allow for complex aquatic lifecycles to exist. Situated between the major geological phases, they exhibit a significant contribution of water to the atmosphere and to the lithosphere. Though stable from a human time scale, they are dynamic systems continually approaching equilibrium. (Morris 1998, Meybeck 2003)

The anthropocentric value, traditionally halieutic resources, logistic utility, agricultural and domestic demand, more recently, recreational and hydroelectric potential motivates strategic modification. Diversion and impoundment are active improvements to CAS done intentionally and at great expense to control natural fluctuations and develop additional value to riverine systems. Emission of chemical, biological, nutrient or thermal pollution from industry, agriculture or urban runoff can be intentional or unintentional pressures on the natural system with potential long term consequences. Despite their subjugation to our collective will, CAS inevitably continue to perform at least some of their natural processes. These natural processes must be balanced in designing sustainable artificial systems. (ICEM 2013, Meybeck 2003)

The natural process of erosion is a fundamental force, building mountains and cutting them down. Organic material and decomposed minerals, dislodged by impact or traction, released from a stable state to one dictated by the properties they inherit upon combination. Frost, wind or rain can initiate the process and provide a medium for mobilization. The particles begin a journey driven by gravity forever down until finally the energy of the medium spent, it settles and is trapped. In time, the natural cycle of ebb and flow peaks, and it may be picked up to continue farther along or it may remain. At rest it is blanketed under an increasing burden, a lead blanket of matter squeezing even water from its shroud. Together with its blanket of earth, the material will one day rise up strong and proud to face the world as stone, to begin the cycle over again. (Morris 1998)

Sedimentary rock is evidence of this cycle and evidence that can be used to deduce the events of the distant past. The detectives examining the evidence are like cartographers making maps of the ancient CAS. The strata, layering of matter according to size and composition defines an individual periodic cycle. Like counting the rings of a great tree the age of a strata can be estimated by the number of cycles of deposition that lie upon it. (Morris 1998)

The chemical as well as physical properties of water are critical in the formation of strata. The process, formation of strata, is known as sedimentation when it takes place in water impoundments or reservoirs. Particles below a threshold size are dissolved solids, kept in suspension by the molecular motion within the water, they are transported as clay. Above that threshold, like the grape rolling to a stop, they gradually drop out of suspension, settling as silt deposits. The largest particles are rarely suspended but instead dragged along the river bottom in the powerful turbulent currents. The sand and gravel

score the clay and silt deposits as they pass; they smash into one another, are chiseled round and polished smooth, or they are lodged into the substrate and held firm. (Morris 1998)

These components make up the alluvium, or in rivers, the fluvial sediment. Fluctuations in the water flow periodically brush away the excess, like a diner cleaning up after a meal, but channel geometry dictates how effectively this takes place, and where the materials end up. Impoundments, natural and artificial slow the current of water. This drop in kinetic energy reduces the carrying capacity and the current sequentially drops its baggage. The sand and gravel comes to rest first, followed by silt then eventually some part of the clay. At the mouth of a river, the fan shaped profile of sediment spreading into the water body like a slow worm is known as a delta, and it is the natural enemy of the hydroelectric reservoir. (Morris 1998)

Sediment is categorized into size fraction. Course fractions are known as sand or gravel. Fine fractions are known as silt and the ultrafine fraction is known as clay. The transport and deposition of these fractions is distinct from one another. The Brune curve generalizes deposition considering water velocity as well as size fraction. (Morris 1998)

Coarse fraction sediment or sand is separated from the finer fractions by the boundary of 62 μm , the finest fraction that can be sieved mechanically. It is transported as bedload, scoring the water channel. Sand deposition are representative of the parent materials from which they originate. (Morris 1998)

Fine fraction sediment or silt has diameters of 62 to 4 μm , smooth to the touch, but having a gritty texture to the teeth. It remains suspended in moving water but in still water it settles in minutes. Upon deposition, silt particles trap water and occupy a large volume. (Morris 1998)

Clay is the ultrafine fraction consisting of colloids with diameter of greater than 2 μm . It engenders a plastic quality to soil with addition of water. The clay fraction is the most chemically complex, it precipitates at different rates based on the ion concentrations in solution. In quiescent solution with low ion concentrations, it can remain in suspension for weeks. Clay platelets are composed of microscopic disks of silica tetrahedral chemically bound to alumina octahedral microcrystals. They coalesce into colloids due to ionic and Van-Der-Wahls forces. Due to the large surface area of clay colloids, surface tension

has many times the effect of gravity which accounts for the low precipitation rates. Adsorption of pollutant ions can increase deposition rate and sequester the harmful chemicals. (Morris 1998)

Mineral fractions in water are generally not smaller than 2 μm ; thus, below this size the particulate is known as non-clay. It is composed of organic material, microbe bodies and ions. They interact with the clay fractions, acting as catalysts or inhibitors for colloid formation. (Morris 1998)

Sediment generated by erosion in a watershed is transported in riverine channels by discharge and deposited in impounds. The parent material undergoing active decomposition by frost and friction is large and heterogeneous. Soluble components decompose in the stream resulting in a silicate / feldspar ratio which reflects the parent material. Silt, composed of the finest sand component and colloids of clay deposit rapidly in still water. Clays settle at low rates in still water and forms solid deposits which resist remobilization. (Morris 1998)

The rate of sediment entrapment is the speed at which a reservoir ages, or its senescence. It typically is not the infrastructure that ends the life of an impoundment. Morris has suggested 3 phases of reservoir life defined by sedimentation. (Morris 1998)

The first stage is pre-impoundment characterized by periodical fluctuation of sediment flow in a natural riverine channel. This near equilibrium has developed based on the meteorology and hydrology of the region and is stable from period to period. This phase is concluded at dam construction and subsequent filling. (Morris 1998)

The second stage is the main operational life of the dam and is characterized by continuous sediment trapping. Detainment reduces the water velocity and the sediment entering the upper reach is deposited in order of size. The bed load; consisting of sand and gravel, and some part of the silt form a delta, the clay and other suspended solids are carried further before precipitating. The clay deposit is well mixed and distributes evenly resulting in fairly uniform deposition. This stage of the reservoir life concludes with the sedimentation of the dead pool and the encroachment of floodplain conditions from upstream affecting the usability of the plant. (Morris 1998)

It is noteworthy that the large fraction of the incoming sediment is deposited in the delta, and thus predominantly consumes active pool volume. In subsequent flood peaks sediment and debris is deposited over the delta causing aggradation. The elevated alluvium at the mouth is ideal for scrub vegetation which accelerates the capture in subsequent flood peaks and has a dramatic impact on evapotranspiration. This is an important consideration when predicting hydro power capacity or estimating the useful lifetime. (Morris 1998)

The third stage of the lifecycle is characterized by sediment balance, and is very similar to the first stage, with periodic fluctuations of sediment transport depending on flow through the water channel. The new near equilibrium will be different than that of the natural system, with occasional irregular releases from the unstable newly formed floodplain. A reservoir in this phase of life no longer provides any hydropower or flood protection but instead represents a flood risk. This stage concludes with dam breach, by design or by natural causes and results in a large sediment release to the water channel. (Morris 1998)

2.2 Points of reference, the region and the model

A rain drop is born in a bank of moist, dense air compelled by imperceptible currents, ever seeking peace and stability as it drifts through the space above the hectic tumult of land and sea. Pierced by diffuse sunlight, composed of countless prisms of condensation and de-sublimation man perceives the geography of the heavens. The condensate; crystals drawn from the ether, bound to a particulate body, destined to fall, to be an element of destruction and an element of creation. Destined to affect change, ultimately destined to transpire, dissociate to atmosphere and repeat, ad infinitum.

A generation of dew rapidly accelerates through space, descending into the atmosphere subject to increasing resistance. Buffeted by the air, they combine and are ripped apart again, a process which results in a uniform cohort of droplets moving at speed straight to earth.

Approaching earth, the air warms up, and turbulent winds drive biases, shifting the whole population and redistributing the drops. Careening to the surface, the drops impact and dislodge solid materials from their scaffold. The liquid adsorbs to the materials and imparts new properties. As the materials saturate, the liquid phase combine in depressions and flow in miniscule rivulets and rills.

Moving across the surface and combining with other rivulets, the collective body transports more and heavier materials. Fluid running along established channels, dragging with it a host of dissolved and suspended solids. Like splayed fingers, spread across the landscape, it scratches its initials as it moves to the sea.

A river channel is carved into its watershed by the force of erosion, mobilizing surface runoff, sediment, pollutants and organic debris. Established channels deliver seasonal discharge with a fluctuating load of detritus. As seasons and geography change load is picked up and released in a hydrological cycle endlessly approaching equilibrium. Figure 1 depicts the dynamic nature of the region, the rugged terrain along which the river flows and the hydropower cascade nestled among the geography of mountains, foothills and plains.

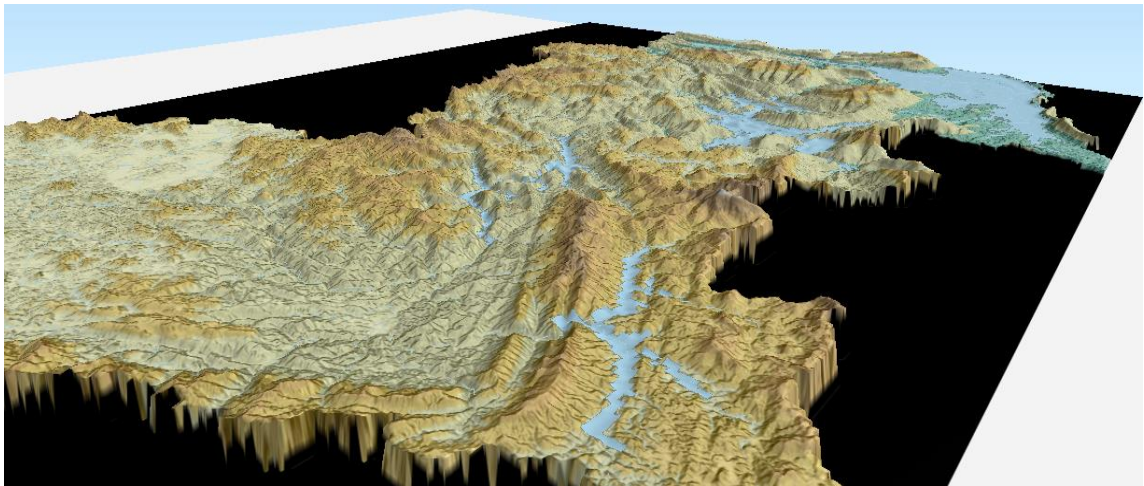


Figure 1 Upper Nam Ngum region

2.2.1 Nam Ngum River Basin

NNRB, the 5th largest watershed in Laos sports a mountainous drainage covering 16 906 square kilometers with elevation ranging from 2684 to 6 masl (WREA, Sector Assessment 2011). Average annual rainfall fluctuates 1.3 to 3.5 meters. On an average year, approximately 37 billion cubic meters of water move through this basin as flowing water, seeping aquifer or evaporating vapor. According to ADB estimates, annual evapotranspiration of 1.06 to 1.36 meters, measured as liquid water, escapes as vapor. Rivers discharge 22 billion cubic meters into the Mekong river. (Kaluarachch 2013, Bartlett, ym. 2012)

Sub-tropical rainforests clad the karst topology. Steep mountains hedged with deep water courses, carved into the severely weathered geology. The shallow sea Mesozoic sedimentary substrate has been carved into dramatic vistas, canyons, pillars, sinkholes, caves and well defined waterways by distinct monsoon meteorology. Public statistics of the region indicate as of 2007 land cover consisted of 47% forest, 34% shrub land, 8% agriculture, 7% grassland, 3.98% and 0.02% developed urban space (WREA, Water Resources and Environment Administration: Nam Ngum River Basin Pro- 2008, Bartlett, ym. 2012, WREA, Sector Assessment 2011, Phommakaysone 2011).

Water utilization in the region as of 2009 was 0.9 billion cubic meters (BCM), or 0.4% of the annual flow. Agriculture is the primary user, accounting for 0.89 BCM or 99% of the extracted water. Agricultural abductions are predominantly from lower reaches, below Nan Ngum 1 dam and the capital city of Vientiane. Urban demand is 4.5 million cubic meters (MCM) or 0.52% of the extracted water and industrial demand is 0.72 MCM, or 0.08% of the extracted water. (WREA, Water Resources and Environment Administration: Nam Ngum River Basin Pro- 2008, Bartlett, ym. 2012)

Nam Ngum has been the subject of much scientific and socioeconomic attention as the ongoing development of hydropower infrastructure begins to affect the regional ecosystem and local population. (Lao People's Democratic Republic 2001, Bartlett, ym. 2012, ICEM 2013)

2.2.2 Building the case for modelling with IWRM

The Nam Ngum river drains the entire Nam Ngum River Basin into the Mekong River. This paper studies sedimentation rates in reservoirs built on the watercourse. Below is a brief evaluation of the catchment and justifications for utilizing the IWRM model.

The rate and mobility of sediment in a fluvial system depends on many environmental and hydrological characteristics. In order to accurately simulate real phenomena, it is necessary to categorize and quantify the catchment and the environmental and hydrological factors and relate them to experimentally verified hydrological mechanics. (Morris 1998)

The hydrological mechanics are generally well known, but applying them on the scale of Nam Ngum River Basin is challenging. In addition, it is not possible to make solid predictions when the underlying morphology changes, for example in the case of reservoir construction. (Morris 1998)

IWRM modeling software is a product of EIA Centre of Finland. It distributes hydrological mechanics at discrete intervals across the region of study. Historical meteorological data provides input to the mechanistic components and observations of phenomena calibrate them. One may then extrapolate by changing the underlying morphology, flow patterns and even climate and still have some confidence in the model results. The application of IWRM has a 20-year precedent in the region having been used in decision support by the Mekong River Commission (**MRC**). (WREA, Water Resources and Environment Administration: Nam Ngum River Basin Pro- 2008, WREA, Sector Assessment 2011, Korhonen 2008, Resources 2011)

Physical modeling of hydrological phenomena, such as sedimentation relies to a great extent on knowledge of the region. This geographic data is built into the IWRM geographic information system raster files. Historical data, meteorology and sampling records are available from EIA Center of Finland. (Korhonen 2008)

The following section includes statistics extracted from the data set with Riverlife GIS, a component of the IWRM suite of programs. It provides a picture of the setting and context for modeling results.

Study Area, Upper Nam Ngum

The Upper Nam Ngum (**UNN**) is an 8126.25 km² subset of NNRB which terminates in Nam Ngum1 east of the capital city Vientiane. It encompasses the watershed feeding the network of impounds, Nam Ngum 1, Nam Ngum 2, Nam Ngum 3 and Nam Ngum 5. Annual rainfall ranging from 1.3 to 2.6 meters translates to 10.6 to 21.2 BCM of water. This is comparable with the 427 m³ mean annual flow reported in the EMSP 2011-2012 report if one allows for evapotranspiration and infiltration of 60%, as was calculated from WREA 2008. (WREA, Water Resources and Environment Administration: Nam Ngum River Basin Pro- 2008, WREA, Sector Assessment 2011)

Land use and ground cover have an effect on erosion by intercepting falling water and inhibiting sediment transport. Figure 2 communicates these regional statistics. Deciduous forest and shrub land make up 85% of the ground cover. Water and coniferous woodland cover 9 and 2 % respectively. Agriculturally managed land only covers 0.5 % and urban areas less than 1 per mille. Floodplains found in the northern plateaus and at the southern NN1 delta account for 0.01%. Parametric values associated with each class modify the effects of precipitation in the hydrological model.

Sediments, originating from the soil are detached by precipitation and mobilized by surface flow. They continue to move towards the sea unless they are deposited. Soil composition in Upper Nam Ngum is predominantly Acrisols and Lithosols. Acrisols are old, typically late Pliocene era alluvia with clearly defined A and B horizon and pronounced illuviation which is evidence of periodic saturation. Lithosols are coarse grained, devoid of horizon and typically devoid of weatherable material. Both soil types make poor agricultural land and are prone to rill and gully erosion when disturbed. These soil types as well as the geological evidence indicate that sedimentation rates may be considerable. (Vattenfall Power Consultant AB. 2008)

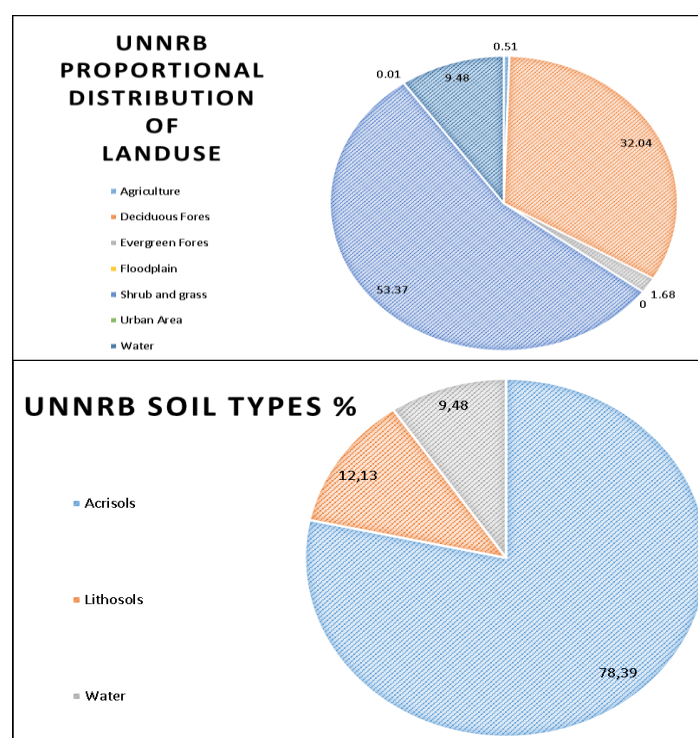


Figure 2 IWRM UNN, Land use and Soil type statistics

The volume and velocity of surface runoff has a pronounced impact on its sediment saturation limit, or carrying capacity. Surface runoff moves more quickly down steep inclines carving rills which erode to form gullies. Mountain slopes over 43 degrees make up a relatively small portion (~8%) of the land area, but contribute significant amount of sedimentary material. Wet season erosion as mentioned, but also dry season wind erosion deposits fine fraction silts in valleys. 83% of the land has less than 15-degree slope and sediment mobility is heavily dependent on land-use class. In the model space, precipitation defines water delivery to the surface and inclination defines the flow velocity.

The region is mountainous with a saddle contour splitting the northern reach. To the northeast, expanses of flat farmable land above 1000 masl drain into a channel hedged by rolling hills, the buried peaks of future mountains. Each node of the cascade is connected by the Nam Ngum and contributes to the flow by channeling the precipitation from its specific catchment into a single location. Figure 3 summarizes statistics extracted from the model software regarding slope and river characteristics.

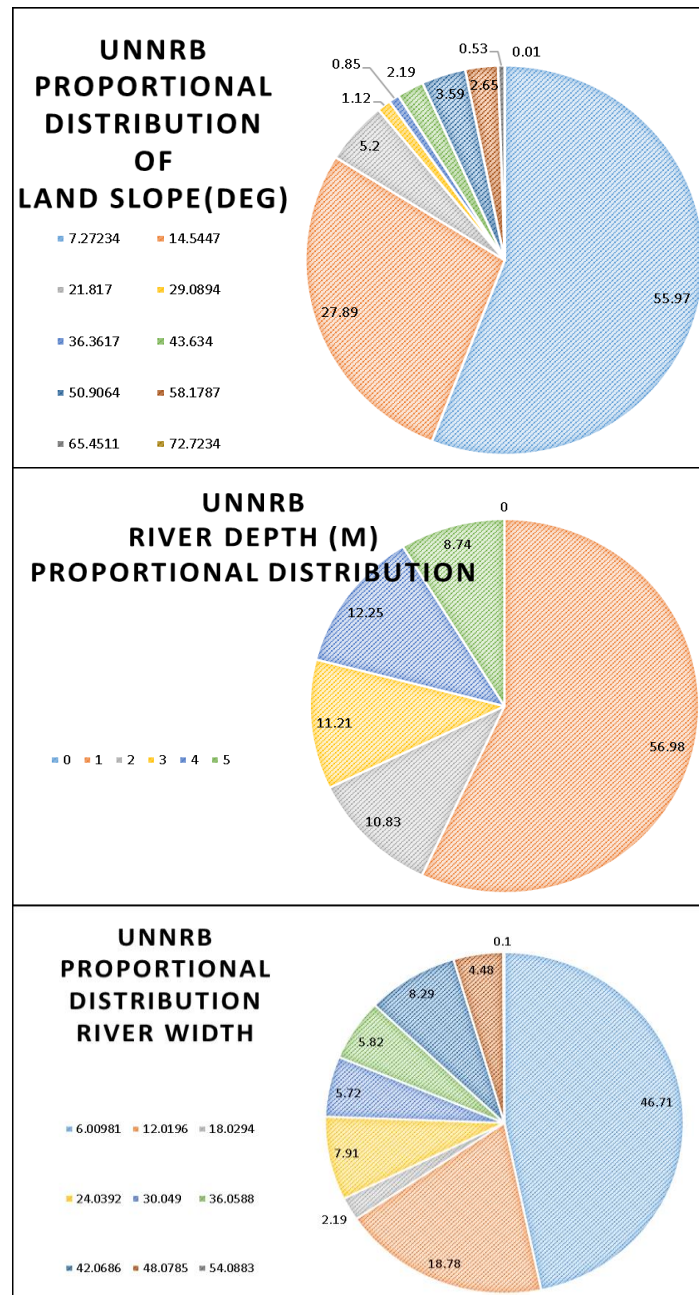


Figure 3 IWRM UNN, River and grade statistics

In the northwest, Nam Ngum 5 reservoir is secluded amongst the deep gorges and high peaks extending well over 2000 masl. Over 70% of the specific catchment lies above 1100 masl. The long narrow 14.6 km² impoundment with a full capacity elevation of 1100 masl is filled at an annual mean rate of 17 m³/s by the 390 km² catchment. At a mean depth of 21.8 meters, the 314 million m³ reservoir is recharged in approximately 217 days. Two francis turbines with a rated capacity of 120 MW at 337-meter head and a load factor of 90% deliver 507GWh electric power to Xieng Khuang transfer station to supply the local market and Vietnam.

Nested in the saddle seat, Nam Ngum 3 retains water in a canyon impound with a full capacity level of 720 masl. Nearly 95% of the specific catchment lies above the full capacity elevation. The steep walls and deep bottom store 1.32 billion cubic meters at an average depth of 51 meters in the 25.6 km² reservoir. It accepts the drainage from the northeast plateaus and consequently has the largest specific catchment in the cascade of 3888 km². Combined flow from the specific catchment and NN river of 110.8 m³/s displaces the total volume in 138 days. Since 2014 the rockfill concrete face dam has delivered 305-meter head to 4 francis turbines, supplying 440MW capacity, 2128 GWh to supply the Thai electric market.

Following the river south, the mountainous aspect persists as the mean elevation drops. In the rugged, weathered topography, stream-beds cut deep and wide provide the 6.8 billion cubic meters Nam Ngum 2 impoundment. 87% of the catchment lies above the full capacity elevation of 380 masl. The 87 km² reservoir accepts an average inflow of 193.5 m³/s from Nam Ngum river and the 1804.5 km² specific catchment. Annual average inflow recharges the reservoir in 405 days. Nam Ngum 2 is rated at 615 MW and delivers 2200 GWh annually to the Thai market in 3 Francis turbines operated under an average head of 159 meters.

At the southern reach, with its mouth only 6 km down-stream from Nam Ngum 2 powerhouse, a giant body of water covering 360 km² at full capacity surface height of 212 masl and surrounded with the ruined remains of mountains. Nam Ngum1 retains over 7 billion cubic meters of water from the rolling, farmable land covered by grass and shrub or leafy forest. The 2617.5 km² specific catchment and Nam Ngum river supply an annual mean flow of 427 m³/s. At a mean depth of 19 meters the reservoir is recharged every 129 days. Annual production from Nam Ngum 1 and the connected Nam Lik diversion is 1025 GWh from the 155 MW powerhouse. 5 Francis turbines with a combined load factor of

75% working at an average 50-meter head provide power supplying the capital city of Vientiane and the local grid.

The modeled UNN watercourses originate from depressions in the elevation raster. The

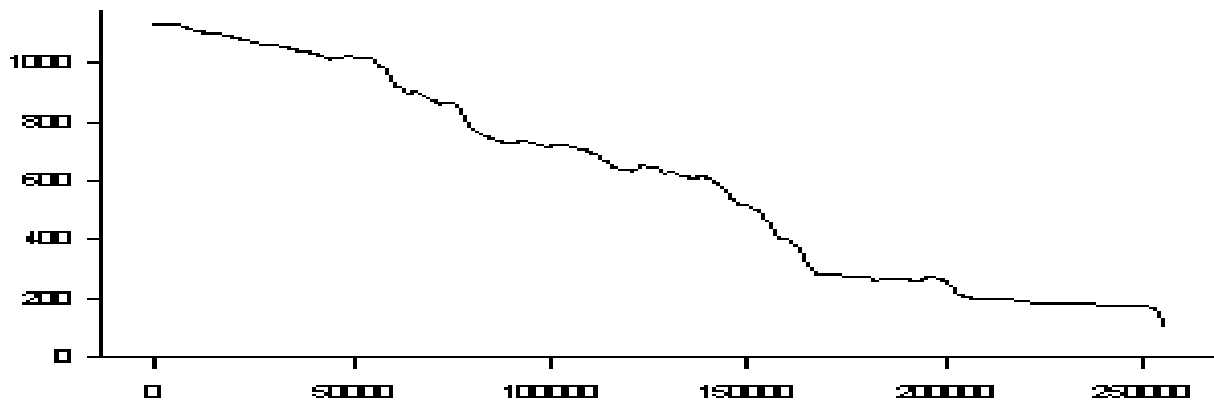


Figure 5 IWRM UNN, Downstream Profile UNN watershed V1

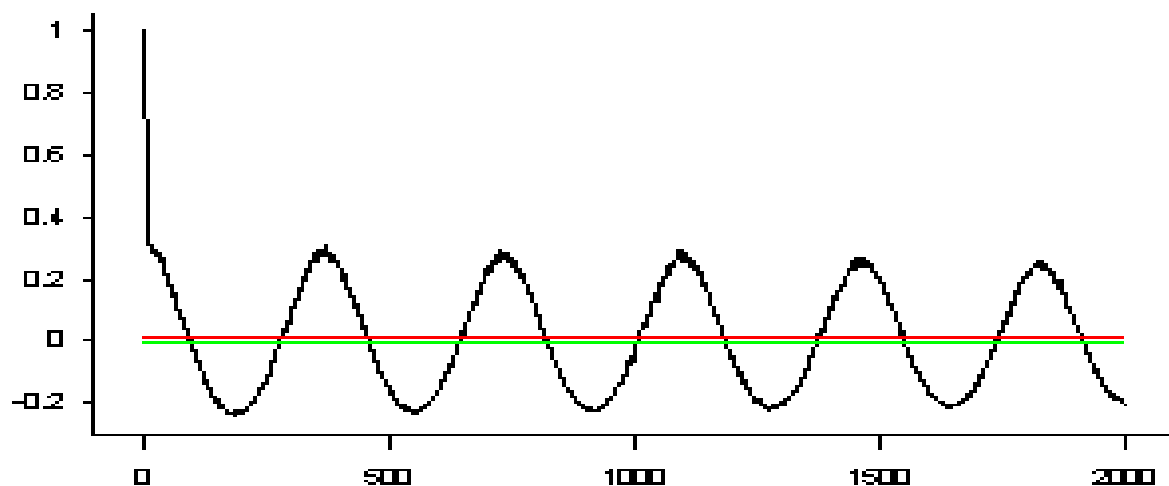


Figure 4 IWRM UNN, FFT of Precipitation 1995-2007

mountain streams combine to fill the Nam Ngum river. Figure 5 shows the height profile of the watercourse from the northern plains to the Nam Ngum 1 tailrace. This is the river elevation and does not portray the water elevation at reservoirs. The reservoirs Nam Ngum 3, 2 and 1, through which this profile passes, would inundate the land at elevations 720,380 and 212 respectively.

Figure 4 and Figure 6 present seasonality through fast Fourier transform and an upward trend from autocorrelation analysis.

The contribution of each consecutive specific watershed combine to produce an increasingly large volume of water. The modeled space accounts for rivers with over 50 tributaries, however 56% of them are less than a meter in depth, and 45% are less than 6 meters wide. Larger rivers are mostly found in the south. 21% are over 3 meters deep and 35% are over 18 meters wide.

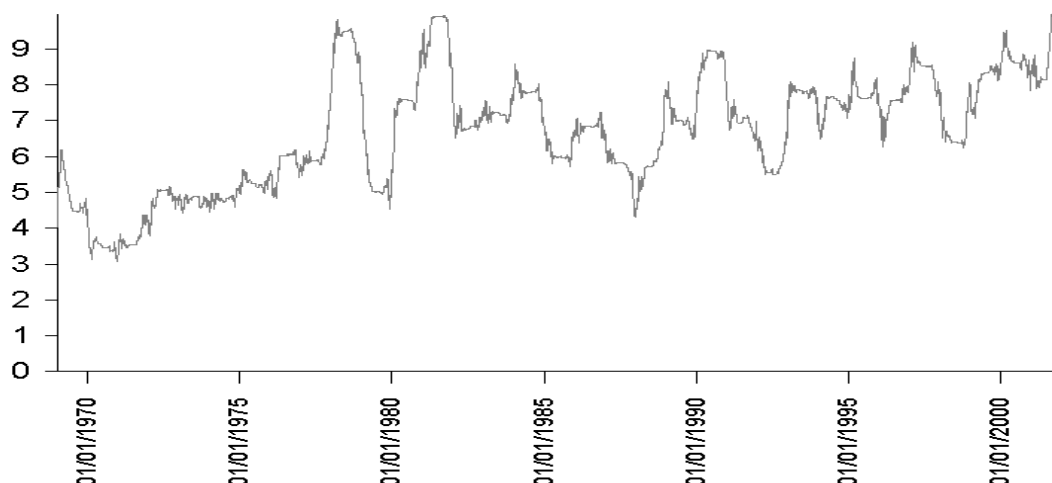


Figure 6 IWRM UNN, Autocorrelation Precipitation 1995- 2007

Regional weather data provided with the model software comes from monitoring stations in the region. The monitoring stations in NNRB have precipitation records from 1995 to 2008. Autocorrelation indicates smooth annual periodicity. The annual average daily precipitation increases at approximately 0.2 mm per year at the Vientiane observation station series from 1970. According to this data, average rainfall has gradually increased from 1.5 to 2.7 meters per year. Average temperature over the 15 year daily observation period is 25.9 degrees Celsius with a standard deviation of 3.6 degrees. 35 degrees was the highest temperature achieved march 19th 1998.

Note: All figures from region dataset, provided by EIA Center, and extracted using IWRM Riverlife data viewer.

2.2.3 Cascade

Table 1 summarizes information from various sources including EIA publications, public records, news articles and company websites. Reliability is based on 3 categories in decreasing order:

- source,

- age of publication
- repetition

Table 1 Upper Nam Ngum reservoir data

Class	Nam Ngum 1	Nam Ngum 2	Nam Ngum 3	Nam Ngum 5
Production				
Rated capacity	155 MW (148.7)	615 mw	440MW	120
annual production (GWh)	1025, (1006)	2220, 2300	2128, (2077)	507
Turbine Rating (MW)	3-40, 2-17.5	3- 205	4- 110	
Turbine Type	francis	Francis	francis	Francis(x2)
Transmission length (km)		95	180	
Transmission type (kV)	115kv	230/500	230	
load factor	75 %			90
Location				
Coordinates, utm48n	241122.196 2050701.724	48 N 265790.589 2076317.932	276785.111, 2111395.972	48 N 250688.557 2142536.907
coordinates	18.531048, 102.547742	18.9213,102.7404 (102.778272, 18.765281)	102.878517, 19.0833	19.361472, 102.626603
location	<u>Vientiane</u>	Vientiane	130 km north of Vientiane	Vientiane and Xieng Khuang
design date	1964	1994		
Construction start	1971	2004	2014	2007
completion date	1971,78,81,96	2011	2018	2012
Dams				

D Type	Concrete Grav- ity	Concrete Rock Fill	Face	CFRF Dam	RCC
D length (m)	468	470		460	237
D Width (m)	6				
D Height (m)	75	185 (181)		220	99
head (m)	25,00	159 (146)		305	337
headrace l (m)				11000	8917
headrace di- ameter (m)				7,5	4,2
penstock length (m)				150	2443
penstock di- ameter (m)				3,2	3,8
Tailrace length (m)				930	68
spillway cap (m ³ /s)	4900	9000			
Average depth (m)	18,95	77,67		51,56	21,78
Elevations					
Full Elevation FSL (m)	212	375		720	1100
Dead storage Elevation (m)	196	345		660	1060
Storage					
Gross stor- age (Bm ³)	7.03	6.77		1.31	0.448
Dead Storage (Bm ³)	2.33	2.42		0.979	0.196
Active stor- age (Bm ³)	4.7	4.23		0.337	0.252
Areas					

	Dead Storage Area (km2)			15,124115	
	Surface area at FSL (km2)	370 km2 (400)	100 (7.5)	25,50	15
	Catchement A (km2)	8460 km2	5640 km2	3888	483
	Flows				
	Average rain-fall (mm)	2000			
	mean annual inflow (Mm3)				22,8
	annual mean flow (m3/s)	300-1500	193,5	98	21,14
	Flow/a (Gm3)	22	6,2	3,09	0,67
	Hydraulic size (C:I)	0.467	0.00103513	0.00060087	0.013365

2.2.4 IWRM software

IWRM is a physically based, distributed GIS 2.5 d model. It is a powerful tool which compensates for weak data with physical computations and parameter calibration. At heart, it is composed of 4 separate components each a collection of causal relationships formulated mathematically. The components work in concert to estimate complex hydrological phenomena.

The grid is composed of GIS raster-map overlays each containing specific data. A raster is a digital image; each pixel value represents specific information. At minimum IWRM requires a raster with elevations, land use, soil type and river information. These contain the basic information for the model components. The 50 m raster sets provided by EIA Centre of Finland were reduced to 500 m resolution in order to facilitate rapid computation.

Individually the model components describe surface flow, water quality, weather and crop productivity of the gridded study area. The weather algorithm interpolates temperature and precipitation from observations and distributes it according to elevation. The surface model allocates the precipitation; assigning it to the surface, subsurface or evaporation based the grid and weather data. The water quality model estimates ion concentrations, pH and sediment based on information from the previous sets. The crop model estimates agricultural crops response to the combined set of data. Each component operates simultaneously outputting discrete time series responses at each geographic point in the grid.

In addition to the grid data, the components of the model require meteorological input. This is in the form of time series precipitation, temperature, river flow and other information. These data, provided by EIA Centre of Finland are from measurement stations in the region. The locations are fixed on the grid and the weather model distributes extrapolated values across the region.

It has been described as a 2.5 d model, this can be understood as a Cartesian plane with elevation parameters associated to each cell. Height and time are not true dimensions in the model. Phenomena such as inter-cell flow is derived from elevation of adjoining cells. One set of outputs is produced for each set of inputs and so phenomena that takes place in time can only be studied if there is a series of inputs representative of the period. In prediction of future phenomena, one must first calibrate the hydrological parameters then apply a representative input series.

Model weaknesses

In general, modeling is affected by two key weaknesses, data quality and mechanistic resolution. Physical models such as IWRM compensate for a degree of data weakness, but accuracy and reliability suffer. Model designers strike a balance between computational complexity and resolution. The inputs and formulas are chosen to achieve particular objectives. IWRM is a generally applicable hydrological model that can be run on low resource computational systems.

The data quality from Laos is poor, in fact, every study conducted in the region cite several classes of weaknesses, inconsistent reporting with weeks or months of unreported data at stations, abnormal jumps in established trends with no indication of change of

sampling methodology or merit, disjointed records with respect to upstream or downstream flows, rainfall and river flow data which rise and fall independently and in some cases completely opposite of intuition. These well documented accounts need not be evaluated further. Instead, the weakness is noted and an interested reader may refer to practically any other study of NNRB for more details. (Snowy Mountain Engineering Corporation 2001) (Bartlett, ym. 2012, ICEM 2013, Resources 2011)

A specific example of weak data at play in this set of experiments is the sediment calibration observations. In calibrating sediment in the model they must fit observations, both quantity and quality count. In this case, there are only two one year sets of observations and they are composed of monthly values of averaged spot samples with no documented description of method, time or frequency. The trend of sediment concentration fits well, but the observations themselves are questionable.

Weak data injects two types of uncertainty; initial and cumulative. The values fed into the model affect the dynamics of the output. Uncertainty cumulates within the simulation each time step, as a result of each inaccuracy, assumption or approximation. The model component accuracy is proportional to the underlying data, so the results present a range of possible outcomes.

Mechanistic resolution refers to the ability for the model components to reproduce phenomena at an appropriate scale. The formulas in the model may be insensitive to complexity, and unable to capture nuances. Alternatively, it may be overly sensitive and functionalize relics or random variability. In either case, the model results may be compromised.

Two examples of this are specific deposition and erosion. Both exhibit causal behavior, which can be described with detailed knowledge of the system. The knowledge is not refined enough to apply functional relationships. And if it were, it would be far too computationally demanding to be modeled on a desktop computer. In lieu of using formulations of these complex relationships, calibrated parameters of linear combinations establish the general erosion and sedimentation is distributed evenly across the reservoir.

The case of soil depth illustrates a linear solution for lack of data which can be calibrated, but represents an undefinable amount of uncertainty. Soil depth data is not available for incorporating into the grid. The software assigns an adjustable group parameter for all

the depth related components. The depth can be calibrated to fit hydrograph observations, but the local variability is absent.

Calibration of the model components with IWRM indicates a discrepancy between the grid and actual region. Literature provides component parameter values which are hydrologically accurate, but the representations only approximates the complexity of the system. Calibration provides an adjustment factor to fit the empirical values to observations.

Calibration is modeling. In order to deliver particular information, the model must be forced to mimic that behavior. To make progress, the accuracy of other phenomena is ignored. When there are two objectives to calibrate to, one may have to compromise accuracy with both.

An aspect that cannot be calibrated pertains to dam parameters. Hydro-electric dams are complex mechanisms and morphologically difficult to simulate. The IWRM reservoir module has limitations with respect to intake specifications, low level outlet capability, environmental flow settings, outlet specifications, rule curve settings and turbine efficiency. These prevent the model from making sediment predictions with much precision. Instead, some part of the sediment is released per Brune equation based on the fractional concentrations at the dam location and intake elevation and power is evaluated according to the hydraulic potential at the dam location.

Regardless of the many sources of uncertainty and inaccuracy and the limitations as to hydraulic power production, the model is a useful tool. Making predictions is difficult, especially about the future, but the test set predictive power of this model was reliably found with a Nash Sutcliffe Coefficient to be over 0.65 in calibration runs prior to experimenting.

2.3 Experimentation, Scenario Building

The Upper Nam Ngum region presents a particular challenge to computational modeling. Though only some 8000 km², there exists a wide range of varying geography ranging from mountain peaks and high elevation plateaus to flat plains. There may be significant variation which the model is simply not sensitive enough to capture. Calibration has been made from points in the plateau and again in the foothills. It follows the trend well, but the observation set is very limited, only one year of monthly measurements.

Modeling combines and functionalizes information enabling the experimentalist to track changes to actual metrics under simulated scenarios. Modeling is the preferred method to study complex subjects such as hydrology. The information can be observations or physical relationships. Information collection can be decoupled from analysis and the experimentation efforts can be compartmentalized to improve quality and productivity and reduce cost. Computational models make it possible to test specific assumptions in rapid succession to determine and forecast relevant phenomena. (IPCC 2013)

Because of the ease of experimentation with computational models, scenario building is an important element of the process. IPCC for example has an array of development scenarios to which approved climate change models conform. The assumptions implicit in the scenario are under evaluation, more than the actual predictions.

In more traditional sciences, a well-designed experiment tests a hypothesis based on a theory. The result proves or disproves the hypothesis and thus the theory. The proof or disproof distinction does not exist in modeling experiments. Models make a prediction based on the assumptions specified by the scenario, the results of which are evaluated based on statistical accuracy when compared to independent observations. The predictive power of a model is a normalized summary metric such as R^2 or Nash Sutcliffe Coefficient. (Kaluarachch 2013, Massart 1988)

The parametric value of the summary metric varies. Nash Sutcliffe Coefficient, for example lies between - infinity and 1 which constitutes a perfectly determined relationship between observations and modeled values. In evaluating hydrological models, Nash Sutcliffe is insensitive to small magnitude fluctuations. It is more useful in determining the general dynamics of the system. Debate exists over what constitutes a useful score. According to many in the field, a score higher than 0 has predictive power and is useful, others assert that anything less than 0.9 embodies excessive uncertainty. (Krause 2005, Kaluarachch 2013)

Modeling results are forecasts and the results embody the accumulated uncertainty of the observations and the equations that they feed. Therefore, the precise state of a system cannot be determined with any real confidence. The trends in forecasts, though, do have meaningful implications with respect to the inputs. By adjusting input factor levels from one experiment to another, characteristic reflections of the input may be measured from the results.

Experimental design is a procedure enabling researchers to extract more information from a set of experiments. It involves using a structured methodology to set independent factor levels. This project involves sedimentation of reservoirs, and independent factors such as operations schedules, land-use change or climate change will surely have an effect on the sedimentation rate. Making accurate predictions of specific factor levels at some point in the future is beyond the scope of this project. By using experimental design and setting levels that span a possible range for each factor, the researcher can have confidence that the actual response is within the continuum described by his array of results. In addition, the impact of each individual factor expresses the relative importance with respect to the response. (Massart 1988)

The results from an experimental array quantify the relative importance of the factors. It can also be seen if the factors interact in characteristic ways. Factors used in this study include precipitation rate, an approximation of climate change, objective based flow curves and land use change to account for population growth.

The design is based on fractional factorial k^n design, named because of the binary expansion of the number of experiments. The superscript indicates the number of variables, or factors under evaluation. The base indicates that each factor has k levels. In order to test every permutation of factors, there will be k^n experiments. (Massart 1988)

Table 2 lists the experiments performed and the factor levels applied in each one. Symbolic code is used for clarity. The symbology is defined below.

Table 2 Factorial experimental design array

Operational strategy	Land use change	Climate Change
-	-	-
-	-	+
-	-	0
-	+	-
-	+	+
-	+	0
+	-	-
+	-	+
+	-	0
+	+	-
+	+	+
+	+	0

Land use change

- - Existing land use data
- + Expanded urban and agricultural classes

Climate Change

- - Existing precipitation data
- + RCP 4.5 scenario A
- 0 RCP 6.0 scenario B

Impoundment status

- - No artificial impoundments
- + Ruled release

2.3.1 Dams

Hydro-electric infrastructure has two main advantages. It is dispatchable within minutes of demand and reliable year over year. Operators can utilize these factors to design a rule curve to cater to the unique needs of the local consumer. The grid is a dynamic structure and hydro-electric power can stabilize supplies or compensate for peak demands. Dam operators make contractual commitments to grid operators to guaranty a certain amount of power at particular times. (Shannon 2008)

In order to satisfy the objectives defined by the commitments, operators store a volume of water suitable to account for a certain degree of seasonal variability. The release schedule is known as a rule curve or flow curve. The timing and dynamics of the rule curve disrupt the natural flow in the river.

The choice of rule curve has an impact to people along the water course. One which stabilizes the flow throughout the year prevents seasonal floods and provides for irrigation of dry season crops. One with erratic or unpredictable fluctuations increases the risk to fisheries and the local population. This social aspect is not taken into consideration in this project. (Bartlett, ym. 2012)¹

Historical weather records can be coerced to present several useful nuggets of information. For example, the normal standard deviation of the monthly precipitation gives a range of preparedness for each reservoir. Seasonality offers the potential to periodically flush sediments if the dam is equipped with a bottom drain or to sustain large magnitude production in the lead up to the wet season. ²

¹ Development of rule curves accounting for social considerations

² Application of seasonal flush strategy to remove sediment deposits

The rule curves have been built to represent different operational strategies. IWRM software determines sediment deposition under each scenario over a fixed period of time. The results indicate which strategy is the most sustainable in terms of infrastructure longevity.

Dam Operation

Real dams provide base and peak load by ramping flow in response to grid demand depending on the local production mix. The scenarios provided here are proposed as purely hypothetical strategies with specific objectives as described. If certain operational strategies have more pronounced sedimentation it will inform management and operations in the actual infrastructure. (Krause 2005)

In developing the flow curves, environmental flow is held constant and evaporation and rain fall for the period are extracted from IWRM calibration runs meteorological data. The resulting geographically averaged parameters are representative of the Upper Nam Ngum for the period January 2001 to December 2008. Environmental flow is additive from upstream reservoirs with individual contributions based on the size of the specific catchment.

Equation 1 is an optimization model adapted from various sources including Morris, MIT linear programming and several YouTube videos. Equation 1 can be used to propagate volume at time with a rule curve. Optimization takes place when the equation series is fit using least squares to an objective series of volumes.

The model produces a time series of volumes and can be optimized in excel using solver. Unfortunately, this method, was not capable of delivering working flow curves. There is a discussion of several operational strategy factor levels in the following text, but only a combined strategy was used in experimentation.

The (-) dam operational strategy is actually a misnomer, because there is no dam! The sediment is tracked at the location of each node of the cascade. It is done to establish a basis of comparison. The (+) operational strategy utilizes a rule curve, taken from EIA Center of Finland, conforms to the regional data and approximates contractual grid commitments.

Flow curve development occupied a substantial portion of the early project and though the curves were not used in the modeling, there still is room for discussion of the procedures, presumptions and progress. Figure 7 has a flow curve plotted against time. Equation 1 is the rule curve optimization model, adapted from various sources:

$$V_{t+1} = V_t + Q_t(\pm SD * Fp) - M_t - Hp_t - S_t - E_t \quad (1)$$

Where:

- V_t = Volume at beginning of period
- Q_t = Inflow for period
- SD = Monthly standard deviation
- Fp = Flood pool proportional to active
- $M_t = A_{V_t} * PET_t$
- A_{V_t} = Reservoir area
- PET = Evapotranspiration
- Hp_t = Turbine discharge
- S_t = Spillage for period
- E_t = Environmental q^3

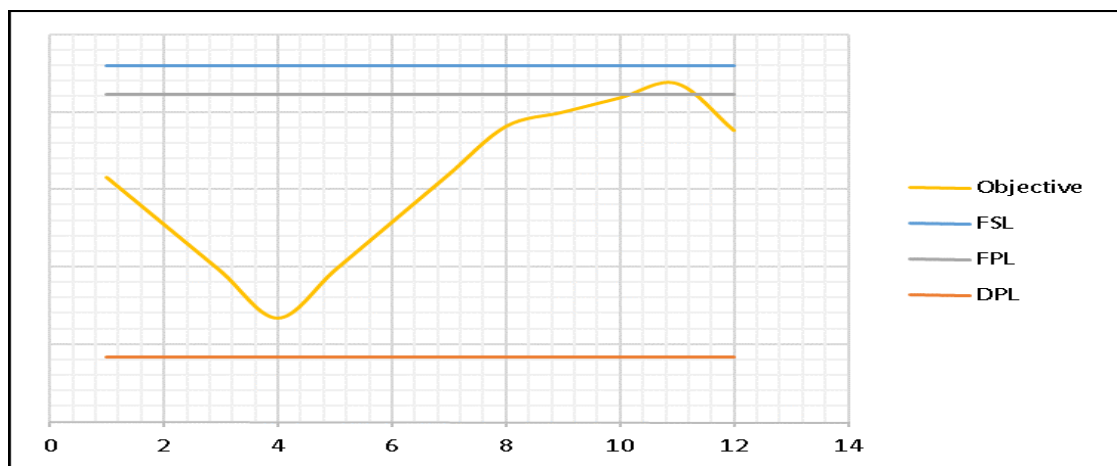


Figure 7 Example of flow curve objective

Baseload electrical demand is stable, fluctuating around daily and seasonal means. Water flow to the powerhouse is constant and reserve volume accounts for historical sea-

³ Environmental flow is primarily established to provide access to the upstream spawning beds for migratory fish. Drawn from the reservoir, the artificial water course takes a path around the dam and discharges into the natural course downstream. It is noteworthy to mention that a riparian diversion may play a role in an active sediment mitigation strategy. Depending on the location of the bypass, some part of the incoming sediment will be prevented from depositing in the reservoir. This has not been considered in this study, though it warrants research.³

sonal variation, measured as standard deviation. The rule curve that correlates to baseline operational strategy maintains the highest and most uniform flow for every given period. Table 3 summarizes the optimization criteria.

Table 3 Baseload objectives

V_t	Minimize accounting for standard deviation of inflow
Hp_t	Minimize flow variation (ideally one single flow throughout year)
S_t	Minimize

A combined operational strategy balances the steady release of a baseload strategy and the greatest possible reserve volume. The rule curve optimization maximizes volume, environmental releases and spillage maintain constant flow to in the water channel. Table 4 summarizes the optimization criteria.

Table 4 Combined strategy objectives

V_t	Maximize for potential, minimize for evapotranspiration
Hp_t	Maximize sum of flow allowing free range of variability
S_t	Minimize spillage

The results of these strategies are summarized in the Tables 3 and 4. This topic is handled very lightly, but a more comprehensive development of rule curves is beyond the scope of the study. A more complete study of this topic would provide more detailed information. The work done here would provide an excellent starting point. ⁴

2.3.2 Climate change

The **IPCC**, Intergovernmental Panel on Climate Change is a **UN**, body consisting of World Meteorological Organization (WMO) and United Nations Environmental Program (UNEP) staff, but functioning independently with elected leadership. **IPCC** is responsible for developing scientific consensus on climate change research. The organization publishes assessment reports (AR) summarizing the estimates and defining methodological criteria. (IPCC 2013)

In order to be recognized by the **IPCC**, research or models built on environmental datasets must be peer reviewed and conform to certain standards. Models recognized by

⁴ Suggested research: Objective based rule curves for cascade hydropower

the **IPCC** are considered reliable estimates of future climate, to such an extent that modeling has become an integral component of the strategic framework government and business use to plan for the future.

The General Circulation Model (GCM) accounts for meteorological and ocean behavior over time. Complex material and energy flows are approximated by mathematical functions. The experimentalist feeds the model historical data and the model extrapolates system behavior into the future. The general circulation model provides a poor resolution picture of future climate. (IPCC 2013)

Downscaled CC data

This study tests the effect of CC on the rate of sedimentation with specific attention to hydropower capacity. The projected temperature and precipitation is downscaled from a global circulatory model (GCM) based on regional weather patterns. The choice of GCM is made based on how well the downscaling fits historical meteorology.

Downscaling data from GCM is beyond the scope here, however downscaled data sets have been provided which have been used in The **USAID Mekong ARCC Climate Change Impact and Adaptation Study for the Lower Mekong Basin**. That project evaluated climate change with 7 accepted downscaling models, and found 2, CGCM3.1 and ECHAM5 most representative of the region. (Cai et al. (2009) and Eastham et al. (2008)). (ICEM 2013)

The data is based on RCP 4.5 and 6.0 which correlate with the B1 and A1B storyline detailed in IPCC AR4. It represents radiant atmospheric forcing 4.5 and 6 times greater than 1750 levels. IPCC AR4 defines radiant forcing:

Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. In this report radiative forcing values are for changes relative to preindustrial conditions defined at 1750 and are expressed in Watts per square meter (W/m^2). (IPCC 2013)

A1B scenario assumes gradual declines in greenhouse gas emissions, stabilization around 2100 followed by decreasing concentrations. Industrialized nations remain wealthy and as population growth continues there is a movement to renewable energy and nuclear power. Poor nations continue to rely on fossil fuel resulting in environmental decline and social economic hardship and increased war and famine.

B1 storyline is more optimistic, considered the low -emissions scenario where concentrations of greenhouse gasses stabilize mid-century followed by gradual declines. Global outreach

programs share technology and wealth between rich and poor countries. Population stabilizes, democracy spreads peacefully around the world and everybody eats closer to the earth.

In downscaling, the GCM trends are converted to weighting factors which are then applied to local meteorological data. This statistical method is well developed and discussed in depth in the **USAID Mekong ARCC Climate Change Impact and Adaptation Study for the Lower Mekong Basin** methodology section.

For the purpose of this study 11 meteorological monitoring stations have been chosen to represent the differing elevation and geology of the region. Records at some stations go back to 1970, but the period 1998 to 2008 was well represented at all 11 sites.

IWRM Software has a built-in tool to apply statistical scaling. GCM weights are applied to the existing monitoring station data to represent the climate scenario 50 years in the future. This is a useful method of experimentation because the underlying weather dynamics remain the same in each scenario. The changes in the results are due strictly to the changes in climate assumptions.

2.3.3 Land use

The land-use change assumptions are informed by two global trends. Urbanization and population growth. Public records on the Lao PDR governmental statistics hub indicate that they are taking place within the region. The scenario applied to modeling is not based on specific information.

UNN has two active urban regions. In the scenario, urban areas have expanded into the most viable grid squares based on land slope and road access. Dense populations in urban areas draw more fruit and fiber from the surrounding countryside. The agricultural areas surrounding the cities have increased to account for the increased demand. (WREA, Sector Assessment 2011)

Under Land-use change assumptions, Urban space is doubled and the agricultural land in the proximity of the urban space is doubled. This corresponds to urban area change from 1 ‰ (per mille) to 3 ‰ of the total area, and agricultural land area changing from 3.4 % to 17.12 %

3 Analysis

3.1 Excluding Cascade

Modeling makes it possible to evaluate the Upper Nam Ngum under conditions which are not possible in reality. This section focuses on various metrics under the fictitious assumption that there are no impoundments in place. The results are illustrative of natural cycles and the magnitude of the impact owing to climate change and land use assumptions.

Model calibration remains the same throughout all experiments, this 'no-dam' set establishes an index for comparison. *Table 5* presents deviation in hydrological or meteorological metrics according to their correlation with the baseline. This set of experiments are performed as a precaution against the extraneous variability which may confound the results if there are nonlinear relationships between the factors. Maintaining a single model calibration is a further precaution to eliminate hidden variables from having an effect.

$$Corr(x, y) = \frac{\sum \left(\frac{x_i - \mu_x}{\sigma_x} \right) * \left(\frac{y_i - \mu_y}{\sigma_y} \right)}{n} \quad (2)$$

(3)

$$Proportional \ values = \frac{X_{baseline} - X_{scenario}}{X_{baseline}}$$

The correlation coefficient measures how the time-series compares to the baseline. The scale goes from 1 to -1 with a score of 1 indicating perfect correlation and -1 being a perfect negative correlation. A score of 0 indicates no discernable relationship between the sets. It is of importance to note that due to the formulation of the correlation coefficient, linear combinations are identical, so magnitude is not under evaluation.

Table 5 IWRM UNN, various metrics

	Land-use Change	CC A	CC B
Precipitation	1	0.9360816	0.9489351
Change, mag.	No Change	192.6 %	188.5 %
Change, SD	No Change	115.7 %	109.2 %
Sediment (L)	0.9982455	0.2939813	0.3226479
Change, mag.	148.1 %	201 %	240 %
Change, SD	163 %	188.6 %	145.6 %
Sediment (C)	0.9994237	0.181533	0.1962763
Change, mag.	145.4 %	130.5 %	136.9 %
Change, SD	141.7 %	-3.3 %	-1.3 %
Sand (L)	0.8708172	0.0018696	0.0021253
Change, mag.	126.1 %	237.5 %	213.7 %
Change, SD	128.8 %	378.3 %	269.1 %
Sand (C)	0.8485008	-0.16448	-0.016634
Change, mag.	122.5 %	196.3 %	156.6 %
Change, SD	121.4 %	275.27 %	171.9 %
Silt (L)	0.9639823	0.930052	0.9270859
Change, mag.	152%	227.4 %	271.4 %
Change, SD	152.1 %	214.2 %	246.1 %
Silt (C)	0.9893805	0.8455846	0.8350649
Change, mag.	149.1 %	142.9 %	150.8 %
Change, SD	148.8 %	121.6 %	127.2 %
Clay (L)	0.961302	0.1399992	0.1485882
Change, mag.	128.6 %	-24.3 %	-9.3 %
Change, SD	133.3 %	-78.6 %	-74.9 %
Clay(C)	0.9862962	0.1227096	0.1274395
Change, mag.	125.8 %	-39.8 %	-36.6 %
Change, SD	126.7 %	-88.1 %	-87.2 %
Flow	0.9767002	0.9541175	0.9544023
Change, mag.	-1.0%	174.3%	194.9%
Change, SD	102%	165.1%	186.9%

The coefficients are a normalized measurement of squared residuals from the baseline values for the given series. This is not a measurement of magnitude and one may not make claims based on correlation that one scenario has greater or less of the metric under consideration, only the dynamic similarity of the time series.

Standard error is an estimate of the measurement variability based on a sample of replicate measurements. It assumes normal distribution about an actual mean and random variation in measurements so its usage here is perhaps unconventional. It is reported in Table 5 but it is applied later in the development of an approximation.

3.1.1 General discussion of metrics

Abnormally high sediment values in the wet season of 2005 – 2008 found under Baseline and Land-use change but not climate change assumptions may be relics from input data. They correlate with high precipitation events at a single weather measurement station. The climate change scenarios are produced with statistical scaling. It would seem that the high precipitation events are not robust enough to translate into the scaled climate change weather sets which explains why the events are not evident in either climate change scenario. With these events excluded, the scenario responses are more in line with the other observations and therefore used for the following discussion. This exclusion is tantamount to removing obvious outliers or errors from a training set.

Precipitation in the model is based on historical records from measurement stations throughout the region. At no point did the temperature drop below 0 Celsius; there was no snow or sleet measurements in any model results. Precipitation in the land-use scenario is identical to baseline.

The correlation coefficients comparing climate change to baseline are 93 and 94 indicating a broad similarity though this is to be expected when considering the methodology used in generating climate change meteorology. Indeed, period and duration remain mostly unchanged in both cases.

The scenarios deviate from baseline in magnitude and in variability as depicted in Figure 8. Overall volume of precipitation under climate change assumptions nearly doubles, and standard deviation in mm of daily rainfall changes from 13 to 30 and 29. Although more rain fell in both climate change scenarios, there was 16 fewer rainy days per year.

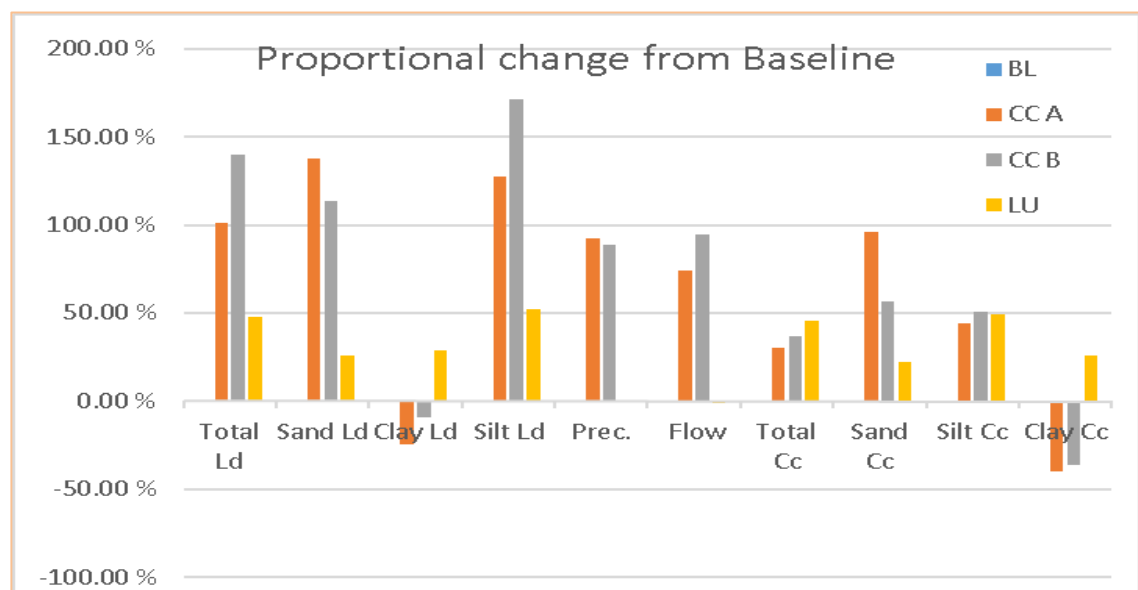


Figure 8 IWRM UNN, Proportional Metrics

Figure 9 presents precipitation and river discharge, measured at the location of Nam Ngum 1 outlet. There is an annual increase of 78 % and 98 % over baseline flow in climate change A and B. In the land-use scenario there is a 1 % reduction of annual flow. This is perplexing because the land-use scenario supposes urban expansion in which increased water flow is expected due to the low permeability of paved and built up spaces. In addition, the land-use scenario supposes agricultural land expansion; this would increase subsurface recharge to the fluvial system. (Kaluvarachch 2013)

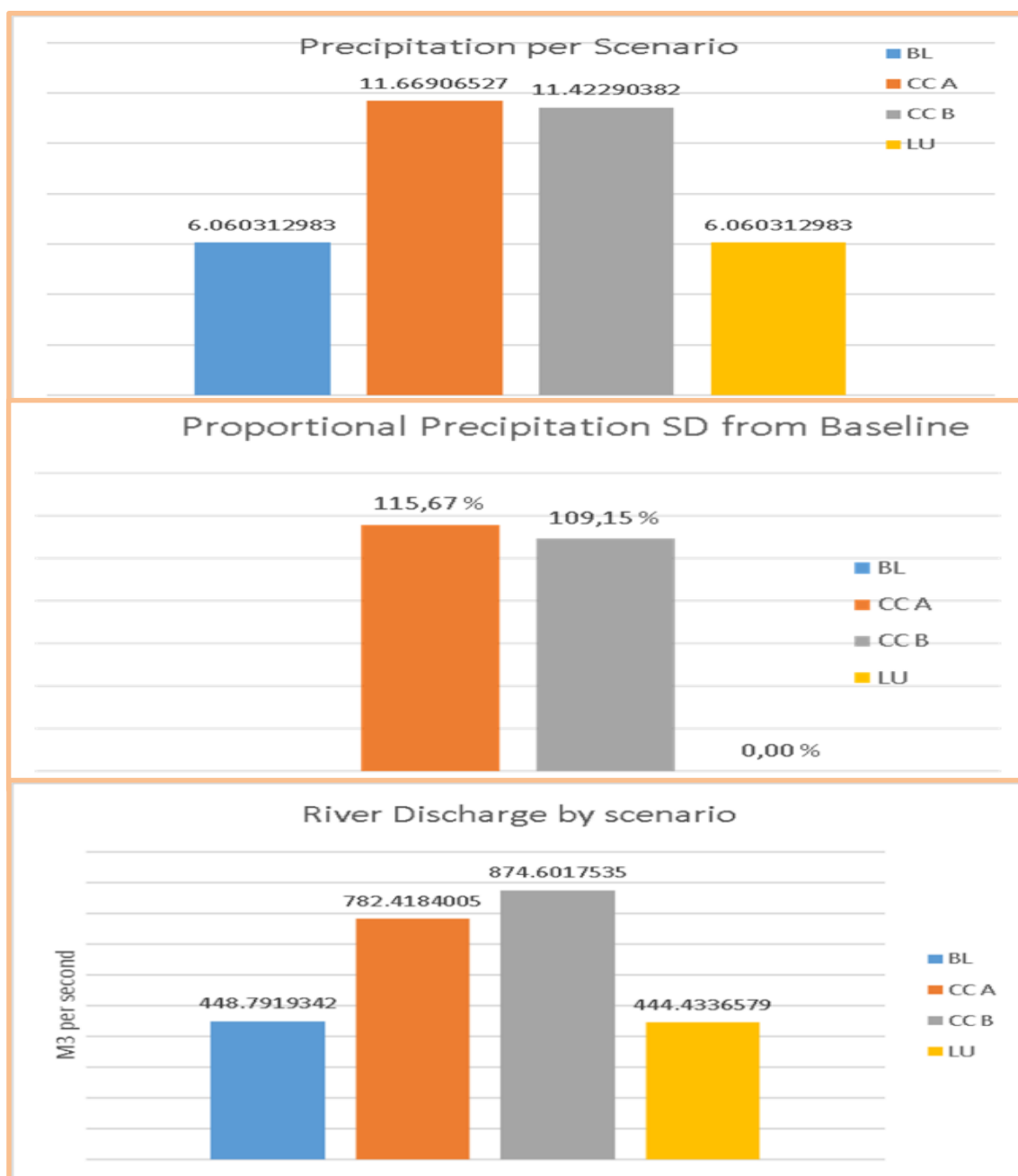


Figure 9 IWRM UNN, Nodam Precipitation and Flow

3.1.2 Tracking sediment mobility

Sediment load described in this section is the average daily sediment mass discharged from UNN. It is expressed in dry weight units, tons per day. The sediment load under land use change assumptions correlate well with the baseline while those incorporating climate change assumptions correlate poorly. In fact, the climate change seems to have an impact which affects some fractions to greater extent than others. Under the baseline assumption, the annual average sediment load is 436 tons per day. Under land-use change assumption, it increases to 646 tons and in the climate change A and B assumptions it increases further to 877 and 1048 tons per day.

Sediment concentration is a combination metric which accounts for sediment load and river flow. It is measured in mass per volume of water. There are important consequences in ecology and agriculture when changes to sediment concentration take place. Land-use change assumptions have the strongest impact on the sediment concentrations. There are 45% increases in annual concentration and 42% greater variability in day to day concentration. The CC A scenario has a 30 % greater average concentration, but the variability is reduced by 3%. The CC B scenario has 36% greater average concentration with only 1 % greater variability.

The changes to sediment concentration, owing to its formulation as a two component metric, may be due to changes in sediment mass or water volume. Under land use assumptions, the meteorological conditions are identical and the river flow is very nearly the same, so the change must be due to agricultural land erosion. Climate change assumptions result in increased precipitation and decreased regularity. Runoff laden with sediment from the more intense rainfall is delivered to water channels and, compounding the problem, fluctuating discharge within the channels preventing an equilibrium from being formed with respect to erosion.

The climate change assumptions have a dynamic impact on wet season sediment load. It enters rivers mostly from saturated surface runoff, or flood. As the ground becomes saturated, surface, rill and gully erosion contribute to greater extent. The sediment load in wet season climate change scenario is over two times the baseline wet season and this represents a drastic departure from the preexisting sediment balance.

Sediment fractions originate from the same sources, but are found in different proportions under climate change assumptions. The fractional concentrations can be described

by the same two characteristics which affect total concentration. The fractional changes are due to different erosion forces and differing flow conditions in the channel.

Figure 10 presents sediment figures from the region with no hydropower cascade. The changes to sediment fractions show how dynamic and unpredictable the effects of climate change can be. Silt-fraction wet-season concentration are 400% of baseline while dry season only have a 30% increase.

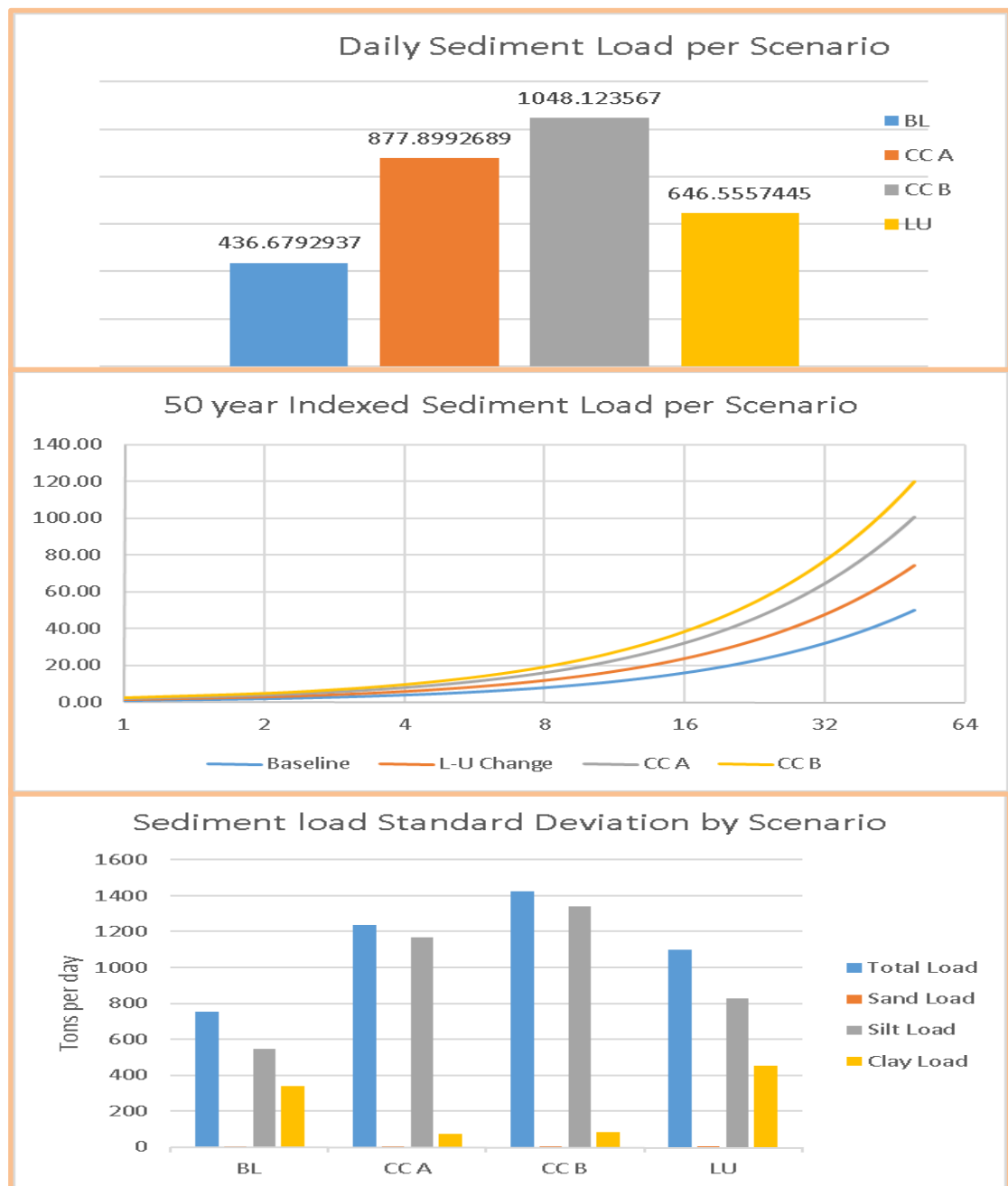


Figure 10 IWRM UNN, Sediment figures

Clay fraction wet season concentration decreases 13.8% and 5% from baseline while dry season has increases of 58% and 56% (CC A,B). Sand fraction wet season concentrations are 500% and 900% of base line while in dry season there are only increases of 22% and 14% (CC A, B).

The magnitude of the change is a striking result. Average wet season load is 125 % of baseline under climate change A and 137 % under climate change B. Average sediment load in baseline is 436 tons per day. In the land-use change assumptions, it increases to 580 tons. Under climate change assumptions, it increases to 1010 and 1060 tons per day. In scenarios incorporating both land use and climate change assumptions, the rates of sediment load climb to 1450 and 1520 tons per day.

These results, striking as they may be, are self-consistent. Each component of the change can be traced back to a specific assumption and that assumption results in a characteristic specific change.

3.1.3 Tracking sediment volume

The river flow and sediment load monthly values under baseline and climate change assumption are depicted in Figure 11. This series is measured at the single point outlet of UNN region where the Nam Ngum release would be if the modeled space included dams. Most notable is the dramatic increase overall in both metrics under climate change assumptions. Seasonality, seen in the prominent peak in Fall and the deep valley in Spring, is preserved but distinctly different than baseline.

Increased precipitation due to climate change has a strong effect on sediment load. There is evidence of 3 erosion phenomena which helps to explain the effects. The rain is more intense and less frequent. Interception is dependent on drop size and density, as the precipitation increases there is greater erosion and more surface runoff entering the channel. Silt fraction load is disproportionately high in both climate change assumptions. Silt size material accumulates in the absence of rain and is mobilized rapidly upon wetting. Channel erosion, bed load and carrying capacity are proportional to water velocity, and the modeled velocity must rise to account for the added volume.

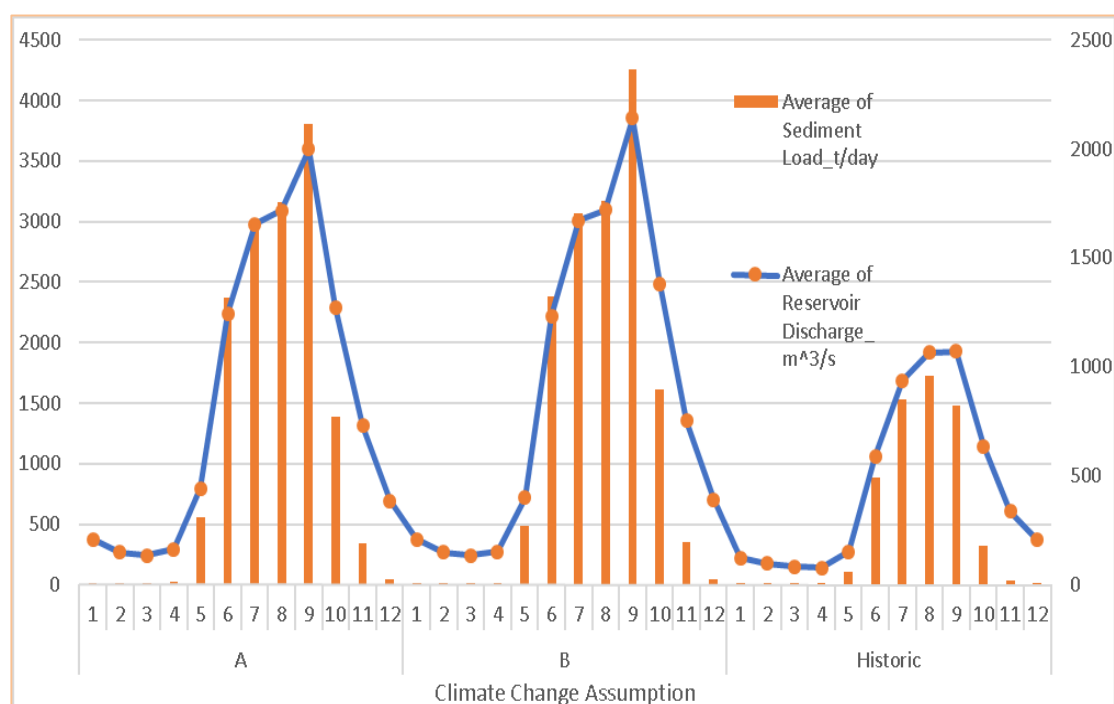


Figure 11 IWRM UNN, Sediment Load and River Discharge, various assumptions

Table 6 has sediment load extended to one year and to the lifetime. Volume is estimated assuming a sediment specific density of 2.65 ton/m³. (Morris 1998) The last two columns give perspective to the volume of sediment expressed in 50-year lifetime. Football field meters is the depth of a football field sized area that would have an equal volume to the sediment estimated in the scenario. NN1 gross volume units is the ratio of sediment from the scenario estimate and the gross volume of Nam Ngum 1 reservoir.

Table 6 IWRM UNN, Summary Volume and Mass Illustration

	Baseline	Land-use	CC A	CC B
Ton per day	450	600	950	1 000
Volume per day (m³)	170	220	350	400
Ton per year	165 300	211 400	353 600	371 000
Volume per year (m³)	62 400	79 770	133 500	140 000
Ton over 50 y (m³)	8 266 300	10 569 600	17 682 500	18 549 200
Volume over 50 y (m³)	3 119 350	3 988 500	6 672 600	6 999 600
Football-field meters	300	400	600	650
NN1 gross vol. units	0.00044	0.00057	0.00095	.001

3.1.4 Summary of Sediment Observations

One puzzling finding concerning accuracy has arisen in the course of analysis. Over a modeled period of eight years, only 0.044% of Nam Ngum 1's volume of sediment passed through UNN. Extrapolating from this, the reservoir could trap all the sediment

and still have a useful lifetime of 2200 years. This author's suspicion is that the source and the solution of the questionable sediment numbers is in calibration. Unfortunately, there are scarce few sediment observations in the region to choose from.

Land-use and climate change have self-consistent, quantifiable effect to sediment generation and transport. These experiments, made excluding the cascade give an impression of the individual impact owing to each assumption. The characteristic change can be generalized as properties associated to each assumption.

Land use change has a property associated to sediment load concentration and variability. They increased by about half the levels found in the baseline. The change is a result of 2 % increase to the urban space and 3.74% increase to agricultural area representing a sum 3,75% change to the region. Since the land use change assumption is otherwise identical to the baseline, the changes to sediment must be entirely due to the change to the region.

If we assume that the land-use behaves linearly between these two states, we can make an approximation from these results. Two qualifying conditions must be met; that the proportional change in land-use conforms to the given assumptions and that the change takes place in similar proximity to the reservoir. Satisfying these criteria, every percent change to land use, will have a 13% increase to the sediment Load.

The primary climate change related effect is increased precipitation; magnitude and variability. These changes can be handled as measurement error to derive a similar rule-of-thumb to that made with land-use. The average change in precipitation is 62 %. The corresponding average increase in sediment load is 120% with a 45% increase in sd err. Making the linear assumption and simplifying, for every 2 percent increase in precipitation there will be 4 percent greater sediment load and 3 percent greater fluctuation day to day.

3.2 Incorporation of Cascade

This discussion focuses specifically on the impact of dams to the routing of sediment through the modeled Nam Ngum river. The same metrics are monitored under precisely the same conditions except for the implementation of the 4-reservoir cascade.

3.2.1 General discussion of metrics

Climate and Land-use change increase sediment generation and the subsequent sediment load, as seen in the previous analysis. Later, Table 7 and Figure 12 indicate that impoundment has a mixed effect, reducing the apparent load carried alluvially and changing the proportions. But despite the lower concentrations, strong evidence indicates that more sediment is mobilized under the impoundment conditions.

Impoundments decrease the sediment load by retaining and selectively releasing pure water. Sediment load is approximately a third of pre-impound levels regardless of assumptions. The fine and ultrafine fractions show greater reductions.

This, and the observations of increased erosion indicates two significant threats to the sediment balance. Impoundment results in lower load observed leaving the region. The correction factor is sediment deposition; the difference must remain in the impoundments. Secondly, the cascade selectively captures fine fractions changing the water quality downstream.

3.2.2 Sediment Density

The sediment density estimated from data recovered from reservoir sediment volume and load. Sediment volume is available as a time series variable in IWRM. The difference between the cumulative load up and down stream of a dam assigns a mass in tons for the sediment volume. Taking the average of the ratios of these values gives an estimate of density. Figures are presented in Table 7 from a three-year model of the baseline scenario.

The figures in Table 8 are derived similarly to those in Table 7 except the mass is refined into fractions and regression coefficients corresponding to the fractional specific volume, the inverse of which is the specific density. Note that kilo-tons/Ml is the same ratio as tons/m³. Excluding Nam Ngum 2 which presents a negative capture mass, the average sediment density is 2.04 tons per cubic meter which correlates well with literature values, but fraction analysis reveals a significant inconsistency.

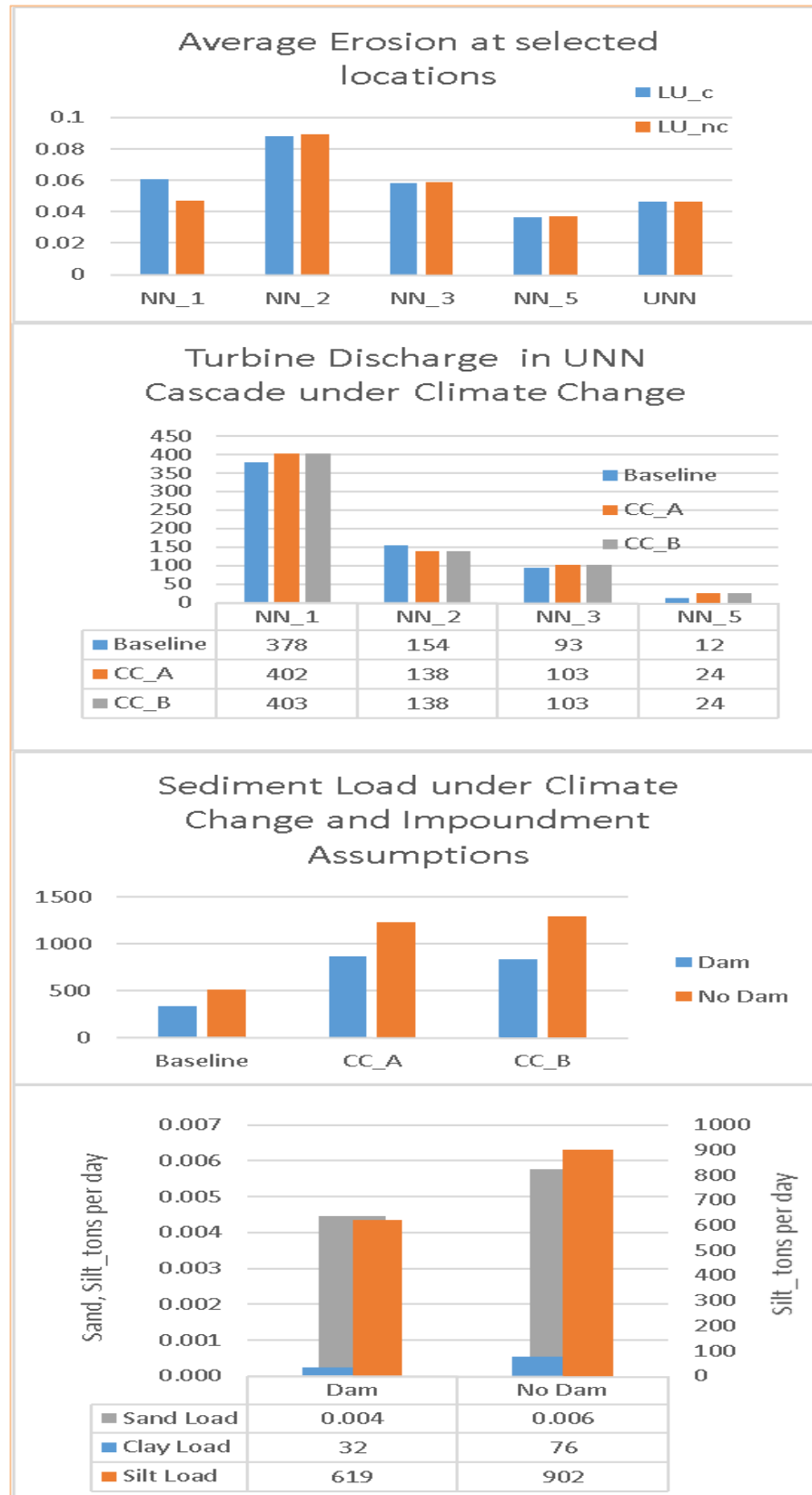


Figure 12 IWRM UNN, Sediment figures

$$\rho_{sediment} = \frac{m_{sediment}}{V_{sediment}} \quad (4)$$

Table 7 IWRM UNN, Specific Density Calculation

	Sed.Vol. (MI)	Sed. Load (kt)	Sed. Load_d_s (kt)	Captured (kt)	Y ⁻¹ (m ³ t ⁻¹)	P (tm ⁻¹)
NN_1	94	205	15.3	190	.50	2
NN_2	136	281	395	-113	NA	NA
NN_3	138	496	181	314	.53	2.2
NN_5	19	51	14	36	.48	1.9

$$V_{sediment} = \vartheta_{clay} * mass_{clay} + \vartheta_{silt} * m_{silt} + \vartheta_{sand} * m_{sand} \quad (5)$$

Table 8 IWRM UNN, Fractional Specific Density Calculation

	CLAY (KT)	SILT (KT)	SAND (KT)	VOLUME (ML)
NN1	22	499	0.004	94
NN2	17	NA	NA	136
NN3	29	832	0.05	138
NN5	2.5	96	NA	19
TOTAL	51	1332	0.054	23

Surprisingly, some of the sediment load fractions downstream are higher than the load in the reservoir. It may not be possible to derive an independent sediment density with this method using the existing computational resolution. Each grid cell is 25 ha and the time-series output represents the whole grid cell. Water properties such as sediment concentration or discharge have a single value based on what enters the cell. The reservoir discharge is no longer representative of the reservoir when it is measured from the grid cell adjacent the discharge location.

The coincidence of finding a sediment density that correlates with literary values is probably influenced by many unidentified factors. In an actual hydropower discharge tailrace, it is likely that the pure water would become saturated rapid before it leaves the cell, shifting the average and confounding the result. In order to salvage some information, the negative values have been excluded from the regression analysis. Regardless, the solution is nonsensical, with a negative coefficient (specific volume) for sand.

3.2.3 Sediment mobilization through impounds

Implementation of hydropower infrastructure on the Nam Ngum river dramatically reduces sediment load measured downstream from each node and results in unnatural sediment profiles. Table 9 shows loads and fractional loads due to assumption and changes due to impoundment.

Table 9 Fractional Sediment Analysis Worksheet, lwrn

SEDIMENT LOAD			
CLIMATE ASSUMPTION FRACTION	No Impounds	Cascade Impoundment	Change due to Impoundment
BASELINE TOTAL	510 (t/d)	335.3 (t/d)	- 34 %
SAND	2.4 (kg/d)	2.1 (kg/d)	- 14 %
SILT	457 (t/d)	318 (t/d)	- 30 %
CLAY	54 (t/d)	16.4 (t/d)	- 69 %
CC A TOTAL	1232 (t/d)	869.0 (t/d)	- 29 %
SAND	5.4 (kg/d)	5.9 (kg/d)	- 10 %
SILT	1154 (t/d)	826 (t/d)	- 28 %
CLAY	77 (t/d)	42 (t/d)	- 45 %
CC B TOTAL	1288 (t/d)	837.9 (t/d)	- 35 %
SAND	6.9 (kg/d)	4.7 (kg/d)	- 33 %
SILT	1207 (t/d)	797 (t/d)	- 34 %
CLAY	81 (t/d)	41 (t/d)	- 50 %

A logical assumption would be that this proportional change represents a capture rate and that the sediment load reductions are equal to the sediment captured. The extension of this assumption would be that any additional sediment would have to represent additional sediment generation between nodes within the cascade. Note that this is not the same as the density analysis, the scores are not extracted from downstream, they are from parallel model runs.

Ultra-fine, clay fraction sediment shows the greatest proportional change. This indicates that clay would be the primary sediment fraction captured within the cascade. This is truer in larger reservoirs with larger recharge rates.

Table 10 IWRM UNN Sedimentation figures

Sediment Volume at 8th year

Node (MI)	Calculated Volume		
NN_1	381	Baseline,no-dam	452 t/d
NN_2	879	Baseline, dam	579 t/d
NN_3	779	Difference	126 t/d
NN_5	62	8 th year	368528 t
Total	2102	Volume	180 MI

Fine, silt fraction sediment shows the greatest change in terms of mass, and subsequently volume. It is the most mobile of the fractions, and the most effected by erosion. It has a particularly negative effect on dam capacity because it precipitates rapidly in quiescent reservoir conditions.

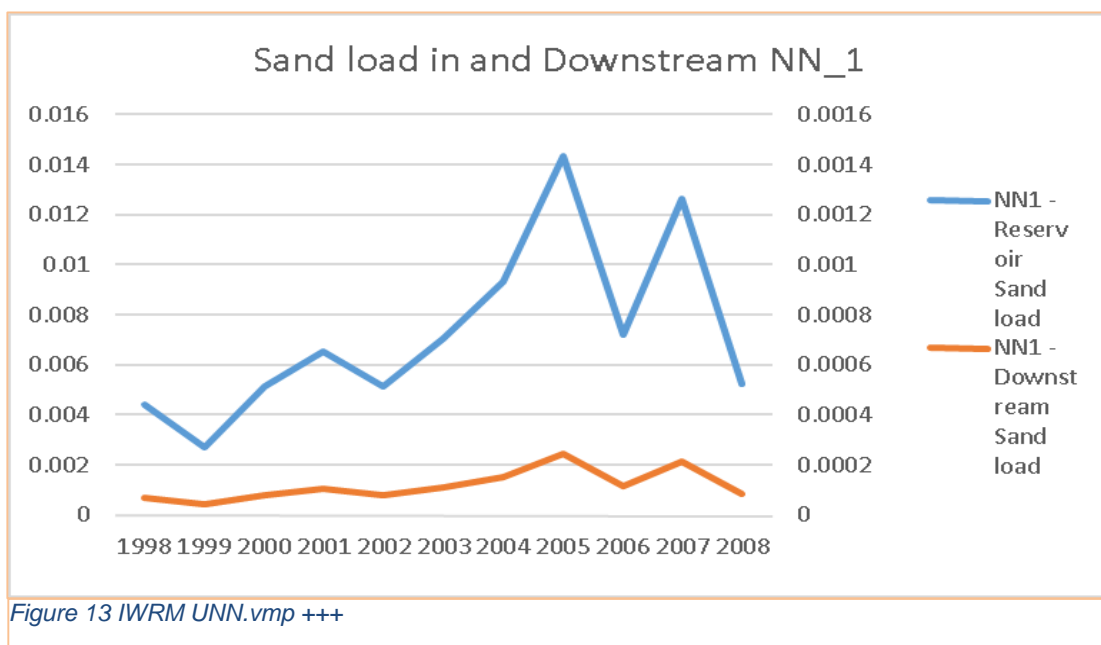
Coarse, sand fraction sediment halts at the headwater of reservoirs and forms the delta deposit. As such the reservoir completely stops the transport of bed load beyond each dam. The sand load measured downstream actually represents additional sand fraction generation immediately after the tailrace. Downstream from impoundments, the distribution of fractions has changed. Sand represents a larger component relative to silt and clay.

In terms of mass, downstream sediment load is about one third of upstream. The difference is retained in the reservoir. At this capture rate, over eight years 368 528 tons of sediment would be stored in the reservoir. At a specific density (derived in the previous section) of 2.04 t/m³ this would occupy 180 million liters of space.

Table 10 presents cumulative sediment volume from an eight-year period under baseline assumptions in each node of the cascade is a reported by IWRM to be 2102 MI. This indicates that eleven times the volume of sediment has deposited than can be explained by proportional reductions alone. The most likely explanation is that channel erosion from the regulated, pure flow from reservoirs is compensating for the discrepancy

3.2.4 A case for sediment weir mitigation

Figure 13 shows modeled annual sand fraction load values, up and down stream Nam Ngum 1 for a ten-year period. The first observation of note is that the sand load is not steady year to year. This indicates that some factor (river velocity, erosion, etc.) is affecting the sand load differentially in separate years. The second and more important observation is that the downstream load is an order of magnitude lower than the upstream observation. Dams typically do not release coarse fraction sediment so the coarse fraction recovers 10 % of its mass immediately after leaving the dam.



This observation, downstream from the dam is illustrative of Brune curve sediment mobilization. Regulated flow from the powerhouse in the model is more steady throughout the year than the natural flow. The average discharge is about the same, but fluctuations are evened out and velocity is normalized. Coarse fraction sediment is mobilized as bed load proportional to water velocity above a threshold. Bed load (sand fraction) would increase significantly should the threshold water velocity necessary to mobilize it be surpassed. This has implications in the design of outlet infrastructure; if the water velocity is controlled, the sand fraction mobilization could be tuned.

The observation may be further generalized. Sediment deposition and composition are characteristic to the properties of the water medium. By designing infrastructure within the waterway to specifically affect the properties of the water, the sediment balance could be maintained and the lifetime of hydropower assets could be extended.

The river may be able to deliver even more benefits by installing specific trap infrastructure. (Morris 1998) Trap infrastructure could provide a sediment bypass, or a convenient dredge location. The sorted sediment has value in construction and agriculture. An analysis of specific deposition, logistics and economics would be very useful in this respect.⁵

3.2.5 A case for compound metrics

A sampling of sediment volume and cumulative sediment load representing a range of assumptions are plotted in Figure 15 and Figure 15. The shapes of the plots are similar suggesting that a fixed part of the sediment is becoming trapped.

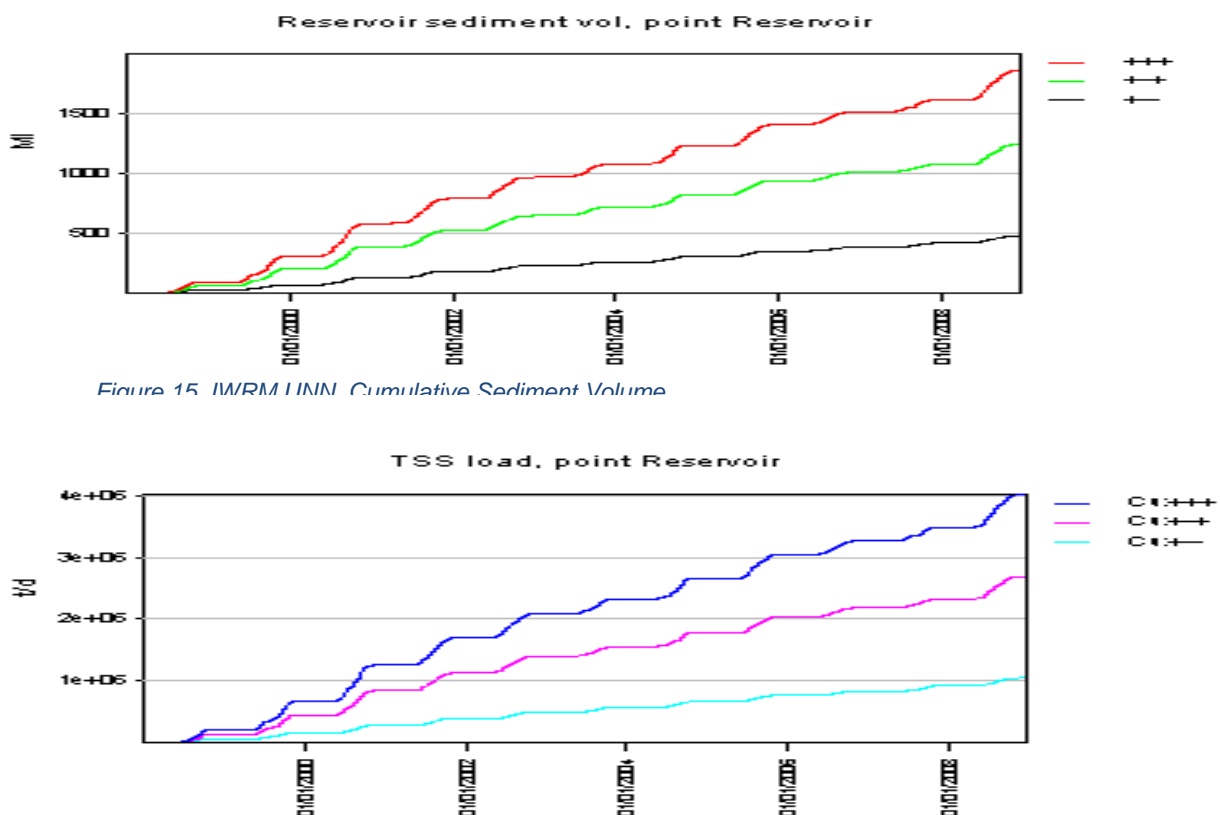


Figure 15. IWRM UNN, Cumulative Sediment Volume

Figure 15. IWRM UNN, Cumulative Sediment load

Examining Figure 17, differentiated sedimentation vs sediment load, referred to henceforth as *deposition ratio*, one can see a stabilization taking place as the ratio assumes a near constant. In numerical examination one finds that the value is in fact gradually decreasing. The ratio shows promise as a convenient measurement reservoir senescence. It allows an indirect estimation of volume based on simple, inexpensive measurements

⁵ Suggested further research: Deposition characterization under 3d modeling to identify natural sediment weirs

of sediment abundance in the water. Figure 17 indicates the inverse relationship with data from Nam Ngum 1 reservoir under baseline meteorological assumptions.

The deposition ratio is representative of the assumptions. Converted to liters per ton load per day, the rate is 205 l to 446 l and 428 l in baseline, land-use and climate change. This indicates that there will be twice as much deposition per unit of sediment load in the water in either change assumption.

The deposition ratio from Nam Ngum 1 under baseline assumptions shows more dynamics than the other nodes. This phenomenon is absent in climate change scenarios where there is greater water volume and greater sediment load. The second phase of life for an impoundment according to Morris ends with dead pool sedimentation and flood plain conditions. Flood plains flush sediment periodically, in flood season. It is possible that Nam Ngum 1, being the oldest and shallowest of the reservoirs in the cascade is exhibiting some of these flood plain characteristics.

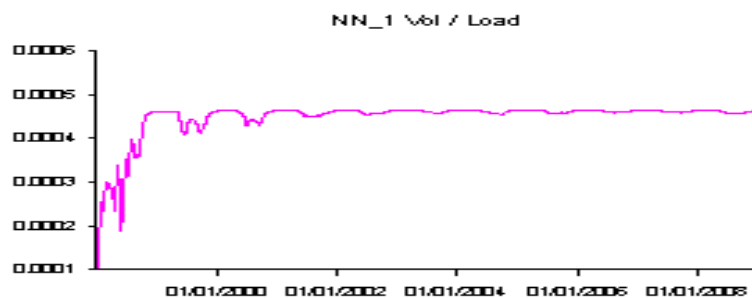


Figure 17. IWRM UNN, Climate change deposition ratio

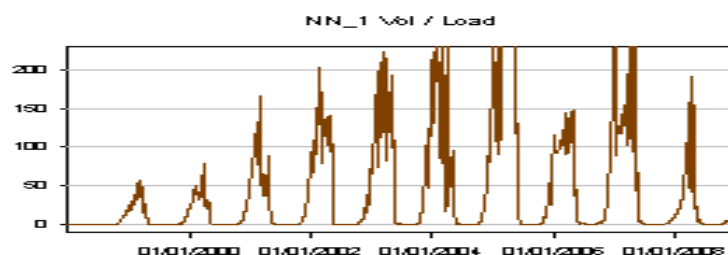


Figure 17. IWRM UNN, Baseline Deposition Ratio

This phenomenon may also be evidence of proper utilization of dam capacity. The rule curve is built to conform to baseline meteorological conditions. Climate change increases precipitation and water levels are higher throughout the year. Since there is less flushing in dry season to mobilize sediment into the dead pool and less turbulence suspending

fine fractions in the epilimnion the deposition would be more uniform. A stable ratio of deposition may be evidence of young or underutilized reservoirs.

This theory is attractive, but, there is evidence that flushing is not actively mediating deposition ratio from two sources. First, the sediment volume plot never decreases in the model. Second, the deposition ratio is never negative. In Figure 17 for example, the ratio resolves to a constant of 445 liters per ton of sediment load in 1 year despite drastic annual fluctuation in water level.

A related ratio can be derived from the data, which offers additional insight. Termed *deposition rate*, it is the daily increase in volume calculated by subtracting each step of the sediment volume time series from the previous entry divided by the daily load. Table 11 presents a sample of deposition rate and ratio as well as two measures of hydrological size, length to width ratio and capacity to flow ratio for the cascade.

Table 11 IWRM UNN, Reservoir Sedimentation Statistics Initial Phase Scenario +--

	NN1	NN2	NN3	NN5
C:I	0.467	0.00103513	0.00060087	0.013365
L:W	34	69	46	73
Dep ratio	445 ld/t	468 ld/t	255 ld/t	370 ld/t
Dep rate	872±705 ld/t	744 ±385 ld/t	8E3 ± 1E4 ld/t	4E3 ± 5E3 ld/t

The deposition rate would be a very useful metric if it could be squared with the deposition ratio because of its simple reliance on historical data of sediment load. It estimates sedimentation in real time and can be adjusted periodically with bathymetric survey results. Reservoir senescence can be determined by examining the mean value over time and the quality of variability. It can be adjusted to correspond to climate change and land use or inversely be used as a metric to measure those changes.

It is clear that something unusual is taking place in the Nam Ngum 3, and to a lesser extent in Nam Ngum 5. Sediment ratio is lower than the other reservoirs, but the rate (from the whole time-series) is an order higher than Nam Ngum 5 and two orders higher than Nam Ngum 1 and Nam Ngum 2. Close examination of the ratio graph reveals that in fact the constant makes three dramatic fluctuations in 2005, 2006 and 2007. These correlate with the extreme weather events which excluded those years from the analysis in the previous section. Removing these cuts the rate by a factor of 6 and places it in

the same order as Nam Ngum 5 but it remains the most dynamic reservoir in the cascade.

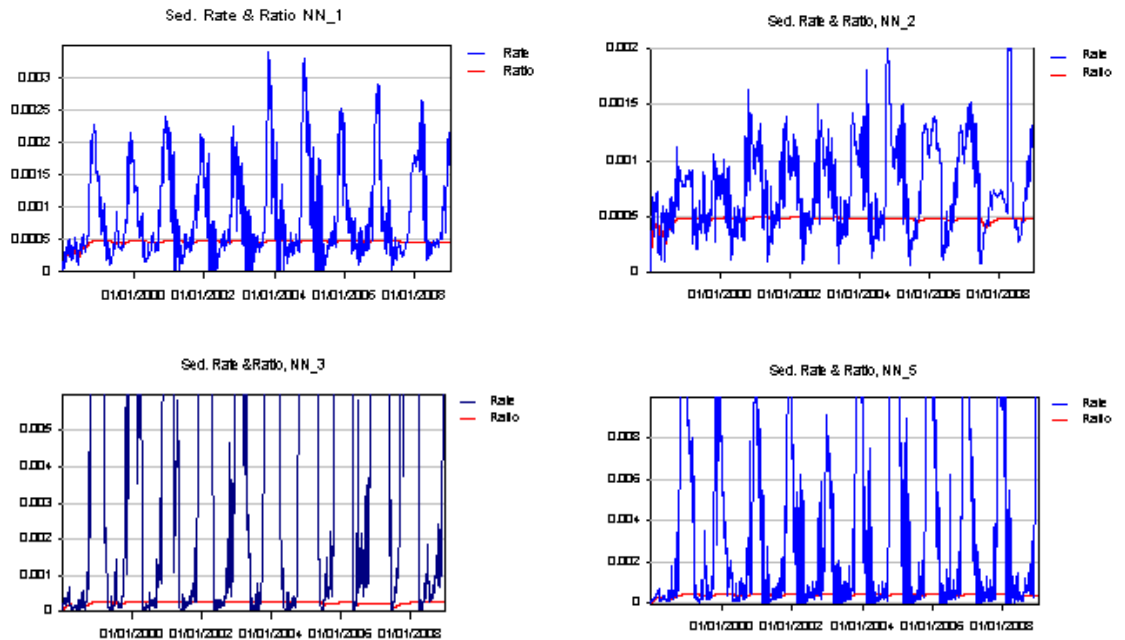


Figure 18 IWRM Deposition Rate and Ratio

The blue lines in Figure 18 graph the deposition rate. Note, this is the change to sediment volume divided by the sediment load per period and has the units $\text{dam}^3 \text{ days} / \text{ton}$. The graph presents a fluctuating rate with a minimum distributed about the deposition ratio, which is the cumulative sediment volume divided by the cumulative sediment load. The graph stops abruptly above 0, and deposition is always positive, indicating that there is no deposited sediment remobilized and fixing the age of the reservoir to operational phase.

The magnitude of the fluctuation is large in both mountainous reservoirs. Both mountain reservoirs have fluctuation, measured as standard deviation, 20% higher than the average deposition rate. This indicates that, either the daily deposition in these reservoirs is particularly high when the sediment load is low or that the sediment deposition is exponentially related to sediment load. Regardless of the underlying mechanism, the deposition variability seems to be exceptionally high in mountainous terrain.

It becomes difficult to calculate the deposition ratio over a longer timeframe because IWRM resets the sediment load each iteration, but deposition rate can still be calculated. Table 11 shows the rate sampled from various scenarios. Nam Ngum 3 is an outlier again in this analysis. There is simply more sediment entering and becoming trapped in this reservoir.

The average values from Table 12 are solid and represent sedimentation within the cascade based on daily sediment load observations. Now, combining the systemic behavior found in section 3.1, it is possible to predict the deposition rate based on the extent of climate change, and perhaps the climate change based on sediment deposition. The list summarizes the systemic responses:

- **For every percent change to land use, there will be a 13% increase to the sediment Load**
- **For every 2 percent increase in precipitation there will be 4 percent greater sediment load and 3 percent greater fluctuation day to day**
- **The average sediment density is 2.04 tons per cubic meter**

Table 12 Sediment rate 40-50 year selected scenarios

	NN_1	NN_2	NN_3	NN_5	AVERAGES	
					Vol per day	Mass per day
++-	848	770	12146	3764	4382	
+++	958	737	4813	5976	3121	
++0	935	759	3629	5341	2666	
					3389,67	7118,31

3.2.6 Connecting the dots

Two points from the analysis may be consolidated at this point. First, that baseline, present day sediment deposition within the cascade, on whole is 3389 liters, or 7116 kg per day per ton of sediment load found in the river. Second, that sediment load in the reservoir behaves characteristically with increased precipitation. Combining these nuggets, we can develop a general relationship between sediment deposition and climate change.

Sediment deposition within the cascade will be 13% higher for every percent change to qualified land use change. This translates to 440 liters or 925 kg more sedimentation per day. The makeup of the deposit will be predominantly silt, because of the natural abundance of this fraction. Though clay fraction shows the greatest proportional change, sand fraction is completely disrupted. The sediment balance is changed along the river. Sediment is selectively trapped within nodes and additional sediment is generated to account for the discrepancy.

Sediment deposition within the cascade will be 2% higher for every percent change to precipitation. This translates to 68 liters or 142 kg of sedimentation per day. It is unclear what effect the variability will have on sedimentation. The mathematical definition of the deposition-rate has a weakness which can be seen in flood periods. This is due to the dramatic increase in sediment load (denominator). The sediment load becomes large relative to the daily change (numerator). It is not that there is less deposition, only that there is so much more load that the rate becomes numerically small.

3.2.7 Comparison to more traditional metrics

Reservoir lifetime, in terms of sediment volume has an exponential character. Initially, the deposition is constant and proportionally small relative to the overall volume. It is fixed to the physical properties of the water. The physical properties of the water are fixed to the geometry of the basin. As sedimentation displaces free space, the geometry changes and the sedimentation rate changes accordingly. Life stages can be defined in terms of sediment deposition (continuous, deposition and scour, sediment balance) or in terms of morphology (riverine, transitional and flood plain).

According to Morris, the transitional riverine phase of reservoir life is characterized by constant deposition. Sediment volume from the model is essentially the same the results of a bathymetric survey. It is shown in Table 13 (offset) that each node exhibits constant deposition, therefore at 50 years those reservoirs remain in transitional riverine or operational phase.

TABLE 13 IWRM UNN, NODE SPECIFIC ANNUAL DEPOSITION AS % OF VOLUME

	Node	10-y	50-y	Offset	Y ⁻¹	Volume	% y ⁻¹	Life-
		(MI)	(MI)	(MI)	(mm ³)	(Bm ³)		time
NN_1	+++	1860	9301	7441	1.86	7.03 Gross	0.022	3779
	+-+	1242	6212	4969	1.24	2.33 Dead	0.79	1250

NN_2	+++	2393	11847	9473	2.37	4,2 Gross	0.06	1770
	++-	2391	11841	9468	2.37	1.95 Dead	1.21	823
NN_3	+++	2552	13281	10650	2.66	1.316 Gross	0.20	4950
	++-	2540	13220	10601	2.66	0.337 Dead	.788	1270
NN_5	+++	345	1725	1380	3.45	4.48 Gross	0.08	1300
	++-	348	1743	1394	3.45	0.097 Dead	0.04	281

The annual average deposition at 10 years is an accurate estimator of the deposition at 50 years. Annual deposition as a percentage of reservoir dead storage is a common metric used to describe reservoirs. Typical values fall between 0.5% and 2 % with larger values being commonly associated with smaller reservoirs.

Sedimentation as a percentage of volume are within normal values, but lifetime estimates range from 281 to 1250 years. This seems to be justification for neglecting sediment mitigation.

3.2.8 Infrastructure Senescence

According to the results of 50 years simulated dam operation under various scenarios, none of the reservoirs in the Nam Ngum cascade are nearing the sediment balance phase. In fact, even sedimentation as a percentage of dead pool volume is remarkably small. At the present rate, Nam Ngum 1 will take over a thousand years to transition to sediment balance.

Dam lifetime, based on the annual sedimentation in Table 13 ranges from hundreds to thousands of years. These predictions seem abnormally large. Fortunately, the object of this paper is not to make concrete predictions, only to test trends.

At any rate the software has realistically simulated the transition from riverine phase to operational phase. There is a divergence in Nam Ngum 1 under land use change, but strangely not in any other reservoir. Perhaps the trapping is due to the smaller length to width ratio, but most likely it is due to the urban and agricultural modification taking place along the Eastern reach. It seems that the location of the land use change relative to the reservoir has important implications for sediment mobility.

This last point regarding the proximity to reservoirs and land use change impact bodes well for the region. The Nam Ngum river carves a path through rugged mountains where there are few native inhabitants. The trend in Laos has been rural consolidation and

migration into cities where there are greater opportunities. It is unlikely that this trend will reverse, thus the inhospitable land through which the river passes will not experience urbanization. Accessing the land is difficult with poor roads, and the land is not conducive to agricultural development, so there are significant obstacles to farmers contributing additional land use sediment. The plateau has potential for urbanization as well as agricultural development, but it is separated from the main course of the river by hundreds of kilometers of mountain peaks and deep valleys. Development on the plateau will probably not contribute significantly to sedimentation within the cascade.

3.2.9 Summary of sediment observations considering infrastructure

Dams placed on the Nam Ngum river will have a dramatic impact on sediment balance. One third of the sediment load present in the water from the former analysis is unaccounted for when implementing the cascade. Surely it is captured within the impoundments. Yet the volume of sediment within the reservoirs is 15 times greater than this discrepancy. The only robust explanation for this is that sediment generation has increased.

Sediment deposition with respect to sediment load, derived here and coined *deposition rate* is an indirect metric of sedimentation and senescence using primarily turbidity. When paired with the characteristic responses of land use and climate change, it can be used to make predictions of sedimentation in various climactic or developmental scenarios. Once established at a particular reservoir, changes to the deposition rate will indicate measurable changes to sedimentation. In addition, trends to the change in deposition rate has potential as a novel new climate change metric.

Implementation of infrastructure specifically designed to consolidate sediment upstream of the reservoir presents several benefits. Sediment weirs would make cost effective dredging possible, reducing the risk of sediment entering the turbine intake, extending the lifetime and making the sorted sediment available for use in construction or agriculture. It would be an ideal source for riverine bypasses to mitigate ecological concerns and help to stabilize the sediment balance.

The effect of fluctuating water levels in reservoirs appears to positively impact active pool volume by flushing sediment to the dead storage. Therefore, operation has an impact on sediment distribution. Over the lifetime dead pool sediment will undergo greater consolidation, and thus occupy less volume. The rule curve is sensitive to precipitation, and it

is not optimized for the climate change set. The true effects of flushing are therefore not effectively being expressed in the model.

The geography of the region, with impassable mountains and flood washed valleys discourages agricultural and urban development along the bulk of the Nam Ngum above Nam Ngum 1. Land use change impact to sedimentation has been shown to be dependent on proximity to the reservoir. Indeed, the proximity may be used as a weighting factor, though this is unproven. As a consequence, the effect of land use change and population growth will be mitigated by the very nature of the region.

3.3 Hydropower

Figure 19 indicates the power potential available at each node of the cascade. Figure 21 presents samples of potential available under various assumptions.

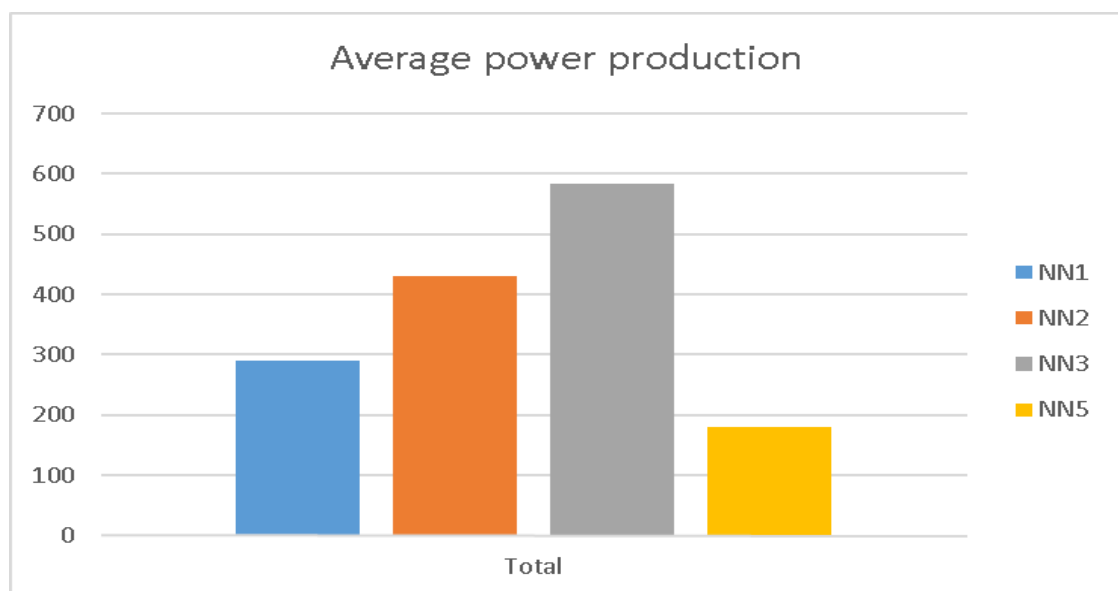


Figure 19 IWRM UNN Cascade Node Energy Capacity

IWRM reservoir module maintains a water level time series, and a turbine release time series. This makes it possible to approximate the hydropower potential for each day of the simulation. The ratings described here are constrained by three points. There are no efficiency reductions being made so the values represent an upper limit or ideal value. The rule curve is not optimized, so there may be significant gains to be made by simply adjusting the flow. The release elevation (h) is evaluated based on the water level as

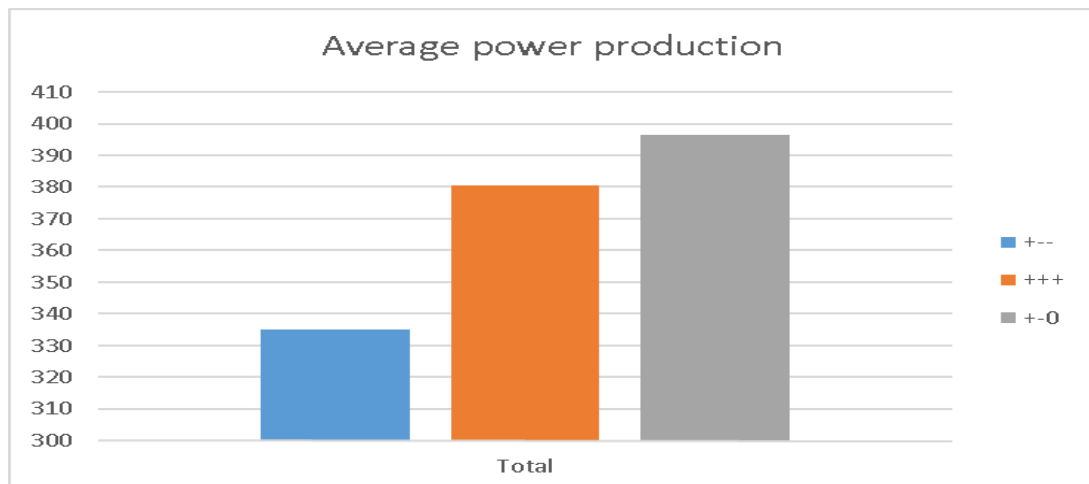


Figure 210 IWRM Annualized Cascade Production

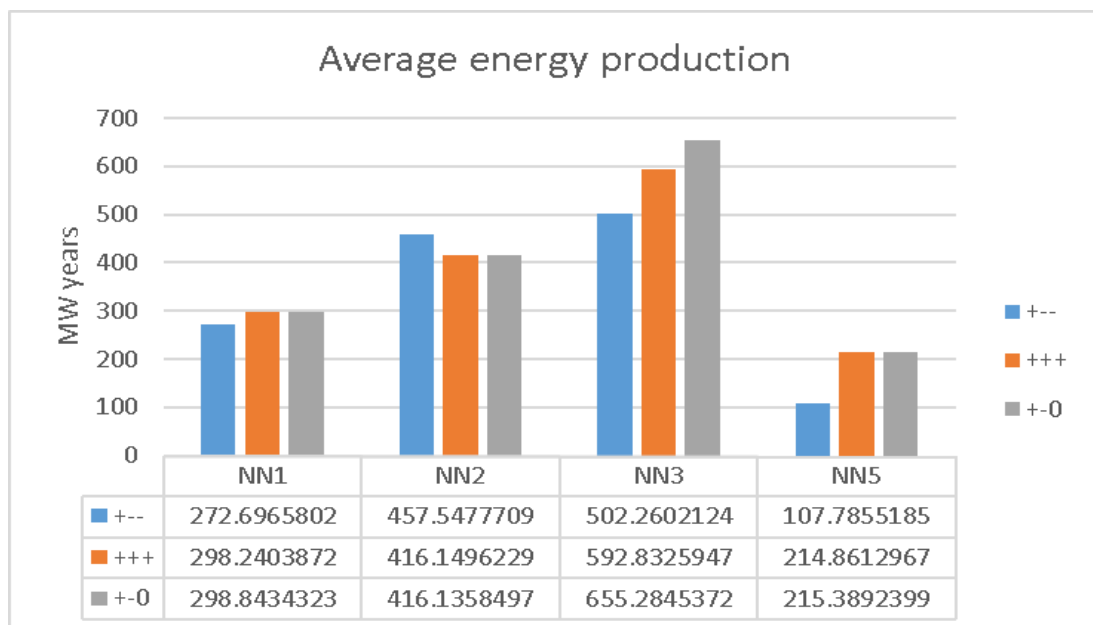


Figure 21 IWRM UNN Node-Specific Cascade Production

compared to the river immediately downstream. There is no setting to account for a remote powerhouse at a lower elevation as is the case with Nam Ngum 2 and Nam Ngum 3

3.3.1 Sorting the mess

Figure 21 showed the annualized cascade production collectively and sorted into specific nodes presenting a sampling from different scenarios to compare the impact of the assumptions. Climate change impacts are most visible in the mountain nodes, with Nam Ngum 5 doubling the potential. This may be due to less than optimal rule curves, because the trend is reversed in Nam Ngum 2 and only just visible in Nam Ngum 1.

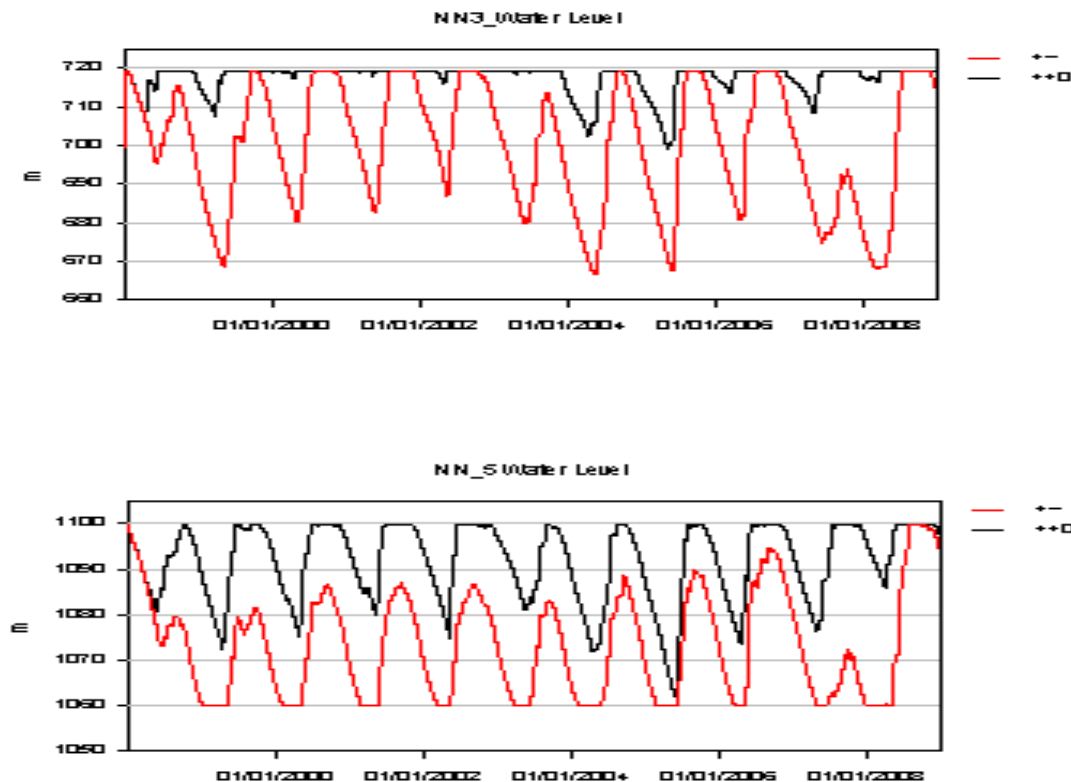


Figure 22 IWRM UUN Selected Water Level Graphs

Under climate change assumptions seasonality has shifted subtly and average precipitation has increased. As a result, mountain nodes maintain a larger storage, as visible from the water elevation plot in Figure 22. This allows for a larger ruled release and greater power production. Indeed, there is greater potential available under climate change.

Sedimentation continues at a constant rate as is expected in the operational phase of reservoir life cycle. This will generally continue as the reservoir dead pool becomes filled with sediment. The exception will be in the delta deposit which will consume primarily active pool volume. Unfortunately, this is not visible in the model due to the lack of deposition resolution, a sacrifice made to allow the software to run on low resource computational platforms.

The comparison of monthly production capacity is presented in Figure 23. Nam Ngum 2, fall and early winter production presents more evidence of the poor rule curve. The ruled

release in these periods is conservative to allow for regular release throughout the dry season. In dry years, the rule doesn't allow any flow for week-long stretches during these months.

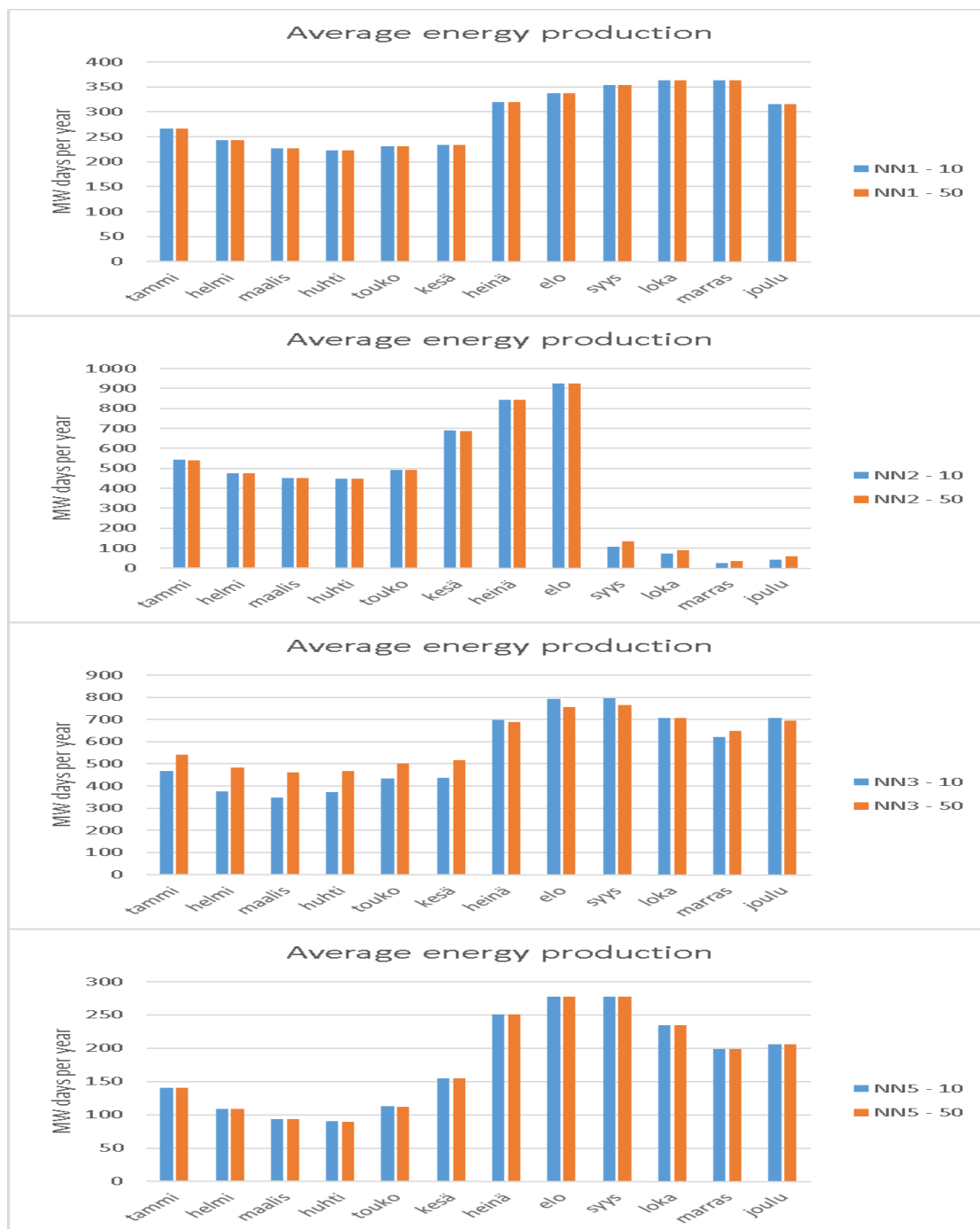


Figure 23 IWRM UNN Monthly Nodal Production at 10 and 50 Year Timeframe

3.3.2 Another look at Senescence

Figure 23 is a series of bar graphs depicting monthly electric capacity averaged from ten years as derived in Equation 6. The blue columns represent the initial period, year 1 through 10 and the orange columns represent the advanced period, year 40 through 50. Both periods are ruled by the same curve so sedimentation over the period is the only assumption under examination. The graph is produced from the scenario incorporating land use change and climate change (A), but lower bound references are taken from the baseline.

Climate change presents additional precipitation which correlates to a greater average flow of water. The increase is on order of 40 %. Hydropower potential is simplistically presented in Equation 6. The potential is directly proportional to flow so 40 % increased flow would result in 40% greater potential.

$$E_p = \rho_p q_p h_p g \quad (6)$$

Nam Ngum 1 and Nam Ngum 5 electric production are essentially unchanged after 50 years. According to the sediment volume, these reservoirs will range from 0.01% to 0.4% and 0.02 to 1.8% respectively of dead pool volume. They are still young reservoirs with hundreds of fruitful years ahead.

Nam Ngum 2 is producing at a slightly higher capacity in the advanced series wet season. This increase is due to the minor accumulation of excess water volume over each annual period gradually shifting the ruled release to higher categories.

The conservative rule curve certainly stabilizes dry period volume in Nam Ngum 1. Day to day fluctuations of hundreds of cubic meters per second water imply that river flow is not stable. It ranges from 0,1 to 2500 m³ /s in most years. The water velocity is remarkably stable speed ranging from around 2 m/s minimum to 5 m/s maximum. Even at the lower velocity, Brune curve predicts unconsolidated sediment would be mobilized.

Nam Ngum 3 presents a more complicated situation where the advanced time frame dry season production has increased but the wet season has decreased. This node has the greatest sediment deposition rate. The rule curve remains the same, with flow specified per season depending on water elevation. Sedimentation displaces water storage capacity. In the advanced time frame, a smaller volume of water would result in a greater

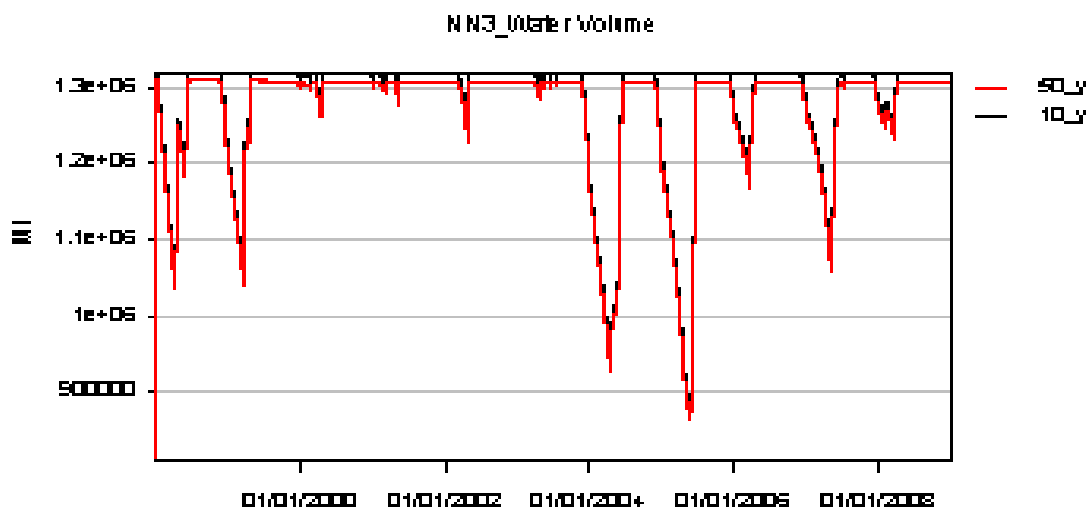


Figure 24 IWRM UUN, +-0 NN3 Water Volume

elevation. Dry season production would increase because of the additional height; wet season would decrease due to the reduced volume.

Figure 24 shows a 10-year sample of water volume under climate change assumptions, with the present land use assumptions at initial and 50-year timeframes. There is clearly decreased volume in the 50-year sample, and that must be due to sediment accumulation. In fact, the difference in average volume from the two samples is very nearly the same as the average sediment volume from the 50-year series.

The 10000 MI of sediment correlates to about 40 meters of sediment deposited in the dead pool covering 0.7 km². This only accounts for 0.06% of the reservoir volume and 1.3 m of water height at the crest. Certainly the added elevation would result in additional energy production, but 1.3 meters is fairly insignificant. There must be some other phenomena playing a role in the dry season power production in Nam Ngum 3 in the advanced time frame.

Little more can be extrapolated from the hydroelectric analysis of upper Nam Ngum cascade without undergoing thorough optimization of rule curves. This would be a very productive exercise, and would result in a much more holistic impression of sedimentations

effect to hydro power. Also the cost and benefits of mitigation could be compared to make an argument as to the wisdom of neglecting this in the planning.

4 Conclusions

According to the analysis of scenarios representing land use and climate change calibrated to correlate with Vattenfall's 2008 data, there is no risk of sedimentation interfering with dam operation or profitability in the foreseeable future. This finding is in line with lifetimes of other comparable dams. Hoover dam, in the United states, for example is expected to continue operating for 10000 years. Despite this, it is very likely that the limited calibration simplifies erosion and sediment transport in the differing terrains found in Upper Nam Ngum.

Climate and land use change have been found to have characteristic effects to the sediment balance in the region. Qualified land use changes result in 13% higher load per 1% increase in agriculture and urban space. Climate induced precipitation change were found to affect a 2% gain in load for every 1% of added precipitation. These provisional findings warrant further study. If a systemic relationship between these phenomena indeed exist, it would be a powerful tool for decision makers and the natural sciences.

The application of this systematic relationship in combination with the *deposition rate* metric shows the utility of the findings. The metric is simple; it describes the specific sedimentation as a proportion of sediment load, resolved over a representative period of time. Since sedimentation is predicted from sediment load or concentration; it is bound by the systematic relationship found to exist with respect to climate change and land use change.

Consequently, the inverse should also be true, trends in deposition rate should indicate climate and land use change. In combination with public records, meteorological monitoring and local calibration this may be an elegant climate change metric with relevance on the regional scale.

The deposition rate metric, provides a context through which sedimentation could be estimated based primarily on turbidity. Impoundment lifecycle is measured in terms of lost capacity so this enables an indirect measurement of senescence. It provides economic benefits, in reduced reliance on bathymetric surveys in lieu of inexpensive turbidity

monitors. Furthermore, it would be affected by certain pollutants so environmental monitoring may incorporate it as a metric for tracking water pollution from industry upstream.

In terms of hydropower, there seems to be a host of benefits from climate change. Power production is proportional to flow and climate change estimates range from 28 to 42% above present day levels. The great majority of this potential could be captured for electric production by optimizing the ruled release. The stabilization of dry season flow through the cascade maintains higher water levels in the low-land reservoirs, thus allowing more production throughout the year.

Land use had no impact on hydropower in this analysis, incorporation of agricultural commitments to the rule curve was not practical within the model. Agricultural and urban water abductions would have been minimal and subsurface migration and changes to evapotranspiration would have counteracted the effects, but the impact to sedimentation is significant. This impact seems to have a linear relationship with proximity to the water body. This makes sense; the further sediment has to go, the less likely it will make it.

Sedimentation did not interfere with normal operation in the economic lifetime of the cascade, and it is predicted to have minimal effect on the functional life time. The composition of the sediment load, and therefore sedimentation is clearly different when the impoundments are in place, but making specific deposition predictions is beyond the capabilities of the model and beyond the scope of the project.

Empirically, complex systems bare many striking resemblances. Some aspects of this topic have been reminiscent of other activities or processes. Taking an unconventional perspective can sometimes help to fully understand a subject. For example, rule curve optimization has a parallel in the tax system or economic policy with release schedules analogues to progressive rates and categories or prime rate and representative GDP. Sediment deposition has a parallel with lifetime having clearly defined phase and with sedimentation being analogous with heart disease and the agglomeration of plaques. Working through the analysis and connecting points is very much like putting a large puzzle together and scenario building has a parallel in creative writing, where imagination is as important as technical skill.

Exploration of the system using alternative mechanisms which are implied by the empirical similarity would be a very productive exercise. It may be that some unrelated subject has the proper tools to analyze hydrological systems already developed. Alternately, the

study of hydrological systems may be applicable in other fields, for example weight management or traffic light timing.

This analysis is brief and lightly touches on many topics, but from the results, no clear economic justification for sediment mitigation can be made. This statement is based solely on lifetime and power production. The social and ecological benefits of sediment weirs and riverine bypasses are clear in terms of fish migration, sediment transport and the value of the dredged material.

No attempt is made to quantify the cost of inaction but at a glance it seems substantial. Without a fish ladder or riverine bypass, it is expected that two endangered fish species will die off. Without a sediment bypass, nutrients transported by the river will be trapped in reservoirs and erosion will destroy agriculture along the riverside. Without sediment weirs the whole sand fraction will deposit as delta in the impound, consuming active storage and causing aggradation upstream. By addressing these problems now, the environmental harm could be mitigated, lifetime could be extended and the benefits of the improvements could be more evenly distributed.

The calibration of the model is a source of concern. Though the predicted lifetimes seem realistic, model parameters are fit to a single terrain. Furthermore, the sedimentation is estimated empirically from Brune and Churchill equations and is uncalibrated.

The reservoir module is limited due to computational restraints. At 500-meter resolution a great deal of nuance is averaged away, but at 50 meter the computation is beyond the resources of a desktop computer. Hydraulic intake and outlet geometry cannot be specified and environmental flow is expressed as a linear component of river inflow. The sediment discharge seems unrealistic or overly generalized and there is no obvious way to check the accuracy. Specific deposition is not considered and aggradation or erosion of riverbeds is not accounted for.

Power predictions from the various scenarios is fixed according to the release curve, so they are not representative of the assumptions. It seems that as much as 42% greater potential might be available under the most extreme climate change assumption, but this would be accompanied with a halving of the expected lifetime. The benefit is in favour of the climate change because lifetime would still be counted in hundreds of years.

5 Research suggestions

The following listed research suggestions are footnotes within the paper. Certainly, the takeaways from the project should be independently reproduced in order to provide legitimacy to the findings. In particular, I suggest the estimated lifetime be collaborated across modelling platforms and the sediment rate metric be evaluated against real world observations to confirm the practicality and applicability referred to herein.

- Deposition characterization under 3d modeling to identify natural sediment weirs
- Objective based rule curves for cascade hydropower
- Development of rule curves accounting for social considerations
- Application of seasonal flush strategy to remove sediment deposits

References

- Bartlett, Ryan, Justin Baker, Guillaume Lacombe, Somphasith Douangsavanh, and Marc Jeuland. 2012. *Analyzing economic tradoffs of water use in Nam Ngum River basin, Laos PDR*. Washington DC: Duke University.
- ICEM. 2013. *Mekong ARCC: Climate Change Impact and Adaption Strategies for the Lower Mekong Basin*. Bangkok: United States Agency for International Development by ICEM- international Centre for Environmental Management. Accessed January 22, 2016. www.mekongarcc.net/resource.
- IPCC. 2013. "Summary For Policymakers." In *Climate Change*, by Working Group to the 5th Assessment Report to the IPCC, 3-12. Cambridge UK and USA: Cambridge University Press.
- Kaluarachch, and D.L.Jayasekera. 2013. "Estimating monthly rainfall in rural river basins under climate change." *Hydrological Earth Systems, Science Discussion* 6847-6896.
- Korhonen, Jorma. 2008. *IWRM Help Window*. Espoo: EIA Finland.
- Krause, P., Boyle, D.P., and Base, F. 2005. "Comparison of different efficiency criteria for hydrological model." *Advances in Geosciences* 89–97.
- Lao People's Democratic Republic. 2001. *National Growth and Poverty Eradication Strategy*. Vientian: Ministry of Foreign Affairs.
- Massart, D.L., Vandeginste, B.G.M., Deming, S.M., Michotte, Y., and Kaufman, L. 1988. *Data handling in science an technology*. Amsterdam, Holand: Elsevier.
- Meybeck, Michel. 2003. *Global analysis of river systems: from earth system controls to anthropocene syndromes*. Paris France: The Royal Society.
- Morris, Gregory L. and Fan, Jiahua. 1998. *Reservoir Sedimentation Handbook*. New York: McGraw-Hill Book Co.

- Phommakaysone, Khampha. 2011. *THE GEOLOGY AND MINERAL RESOURCES OF LAO PDR*. Vientiane: Department of Geology and Mineral Resources, Ministry of Natural Resources and Environment, Lao PDR.
- Resources, Dep. of Water. 2011. "IWRM based water planning approach in Lao PDR." *International Conference: Water in the Green Economy in Practice*. Zaragoza Spain: Ministry of Natural Resources and Environment.
- Shannon, Lawrence. 2008. *Power Surge*. Berkely, California, USA: International Rivers.
- Snowy Mountain Engineering Corporation. 2001. *Social Action Plan and Environmental Management Plan*. Dorking, UK: Resource Management and Research.
- Vattenfall Power Consultant AB. 2008. *In support of Nam Ngum 3 Cumulative assessment report, project number 40514*. Lao Peoples's Devmocratic Republic : Sinohydro.
- WREA. 2011. "Sector Assessment." *Water Resources Management in Nam Ngum River Basin*. Vientiane, Vientiane: Asia Development Bank.
- WREA. 2008. *Water Resources and Environment Administration: Nam Ngum River Basin Pro-*. Laos: Prepared Under the Nam Ngum River Basin Development Project.