Abdallah, Mohammed; Stamm, Jürgen

Evaluation of Sudanese Eastern Nile Reservoirs Sedimentation

Evaluation of Sudanese Eastern Nile Reservoirs Sedimentation

Mohammed Abdallah
Jürgen Stamm

The aim of this paper is to evaluate, estimate and predict the Sudanese Eastern Nile reservoirs sedimentation, thus, inflow analysis and sediment estimation for Roseires and Sennar reservoirs on Blue Nile and Girba reservoir on Atbara river have been carried out, a series of bathymetric survey data and operation policies of the three reservoirs were analyzed, afterward, two grey system prediction models, namely Discrete Grey Forecasting Model “DGM (1, 1)” and Verhulst Model, were applied. The study found a good agreement between observed and simulated reservoirs sedimentation and the models predictability tends to increase with time.

Keywords: Reservoir sedimentation, Grey system, storage capacity.

1 Introduction

River basin systems are normally balanced in terms of erosion and sedimentation processes; therefore, constructing dams will dramatically alters this balance by creating an impounded reaches characterized by low flow velocity and high sediment deposition. These reaches accumulate sediment and consequently reduce the reservoir’s storage capacity which will finally eliminate the storage volume for flow regulation benefits such as flood control, irrigation demands, hydropower, environmental flow, etc.

As reservoir’s operation time and sediments continue to accumulate, severe problems arise and cause serious impacts affect the operation and functionality of the reservoir such as, storage loss, delta deposition, abrasion of hydropower facility, energy loss, and blocking intakes and outlets, therefore, estimation of reservoirs sedimentation is an important issue to improve the system operation in order to meet the design objectives of the structure. Generally, that can be achieved by three main approaches: (1) applying mathematical modeling, (2) empirical trap efficiency, (3) using storage-level relationship to predict the capacity change. The first two approaches need an adequate and accurate data to have precise results, while the last approach is relatively simple and can be abstracted from the available bathymetric survey data.

When data is scarce or inaccurate, it’s important to look for new approaches that could handle this uncertainty problem properly, hence, Grey System Theory can be an appropriate approach due to its ability of dealing with dynamic uncertain systems , information incompleteness, and inadequacy which are typical features of Blue Nile and Atbara river systems in addition to their highly sediment deposition rate -estimated by 140 Million Ton per year- that affected the reservoirs systems, Sennar and Roseires on Blue Nile, Girba on Atbara river, and decreased their storage capacity to be less than 15%, 65% and 47% respectively from their design storage capacity with annual sedimentation rate of more than 40 Mm^3 which impacted severely the system’s reliability to meet the design objectives, where irrigation land has been reduced by 30% besides significant uncertain generated hydropower that have influenced directly the country economic efficiency as most of water resources projects in Sudan are situated at those two rivers region.

For these reasons, the purpose of this paper is to investigate and evaluates the Eastern Nile reservoirs storage capacity. Sediment load has been estimated in both river, then comprehensive analysis of reservoirs storage using the bathymetric survey data in order to extract the storage-level correlation parameters, afterwards, two grey system models namely DGM (1,1) and Verhulst model have been used to simulate the storage parameters in order to predict the future storage decreasing, finally model verification and validation have been conducted using different sensitivity analysis to check the model performance.

2 Reservoir Sedimentation

Reservoir sedimentation is the process of sediment deposition after dam completion and operating, globally, the overall annual loss rate of reservoir storage capacity due to sedimentation is estimated as 1to 2%of the total storage capacity *(Yoon, 1992; Yang, 2003)* which can be attributed to many factors such as: Capacity to Inflow Ratio (C/I), sediment content in the water , texture and size of the sediment, trap efficiency (Te) of the reservoir, and the method of reservoir operation *(Arora and Goel, 1994)*.

Prediction of reservoir sedimentation is one of challenging tasks due to the complex and dynamic nature of sediment transport; broadly, reservoir sedimentation estimation can be divided into two classes: (1) Mathematical modeling,

(2) Empirical methods such as Trap efficiency and storage-level approaches. Empirical methods are normally built on a fair correlation and understanding of physical phenomena through comprehensive data analysis, while mathematical models are normally based on analytical solution of the hydraulic and sedimentation process. The storage-level method adopted in this paper, according to *(Yevdjevich, 1965)* based on the relation between the Storage volume *S* as a function of both; reservoir elevation *H*, and time *t*, and can be approximated by the following function:

$$S = aH^{m} \qquad (1)$$

Where, *a* and *m* are functions of time resulting from sedimentation process. When bathymetric survey data are available, a storage-level can be correlated and used to fit the *S-H* relation to obtain the values of *a,m* parameters in order to be used as a prediction parameters of storage volume through different reservoir's operation time. Storage-Level method is normally simple and direct method to estimate reservoir sedimentation and can obtain a good results if bathymetric survey process conducting regularly with accurate reservoir storage-level schematization data, nevertheless, the technical and financial constraints limit the opportunity of doing a frequent reservoirs bathymetric survey particularly in developing countries.

Identifying uncertainty to reduce the system's complexity and increase the performance becomes very valuable as future is uncertain due to lack of knowledge or natural variability or both. *J.Deng* developed Grey Systems Theory in 1982 as a new methodology that focuses on the study of problems involving small samples and poor information that are difficult for probability and fuzzy mathematics to handle. It explores and uncovers the realistic laws of evolution and motion of events and materials through information coverage and through the works of sequence operators. Grey systems deals with uncertain systems with partially known information through generating, excavating, and extracting useful information from what is available. So, system's operational behaviors and their laws of evolution can be correctly described and effectively monitored *(Liu.S and Lin.Y, 2010)*.

Despite the fact that probability theory, fuzzy mathematics and grey theory models are deal with small or incomplete data; the focus of grey systems emphasizes on investigation the systems that have a process of clear extension and unclear intension which is quite different from fuzzy mathematics where the theory focus on a systems that have a clear intention and unclear extension.

Grey prediction is originally a system analysis method based basically on understanding of uncertainty characteristics of the systems under the conditions of incomplete information and uncertain cause-effect relationship by making use of sequence operators on the original data sequences in order to generate, treat, and excavate the hidden laws of systems evolution so that grey system models can be established and the future predicted *(Liu.S and Lin.Y, 2010)*.

In reservoir systems, the major sources of uncertainty are; data availability; data error; accuracy and imprecision of measurement and observation; sampling uncertainty, including the choice of samples and appropriate sample size; selection of an appropriate probability distribution to describe the stochastic events; and estimation of the hydrological and statistical parameters in models. Therefore, grey system theory can fit appropriately with such kind of systems to simulate and predict the required parameters.

3 Study Area and system Description

Blue Nile and Atbara River originate from Ethiopian plateau as shown in *Figure (1)*, and consider the main contributors to River Nile discharge by more than 70% of total Flow. Blue Nile is the main tributary, with total catchment area of about 324.500 Km^2 lies in tropical zone and characterized by seasonal rainfall in the period July-September, therefore, the river reaches its peak discharge $6000m^3/s$ within this time while from October the flow falls sharply to be less than 100 m^3/s by April with average annual flow of 50 billion m^3. *Figure (2)* shows the Blue Nile flow measured at Eldiem (*the key station located at the Sudanese-Ethiopian boarder*). Sennar and Roseires reservoirs constructed in 1925, 1966 respectively as a multipurpose reservoirs to irrigate over 1.5 million hectare, generate hydropower, and control flood.

The Atbara River basin lies in Ethiopia has a catchment area of 100.000 km^2 and characterized by highly seasonal as flood peak occurs on August with average of 2000 m^3/s and almost dry during summer months (April-May) with total average annual flow of 13billion m^3, as shown in *Figure (2)*. Girba reservoir has been constructed in 1964 to control the river, store water to irrigate New Halfa scheme, generate hydropower, and control flood.

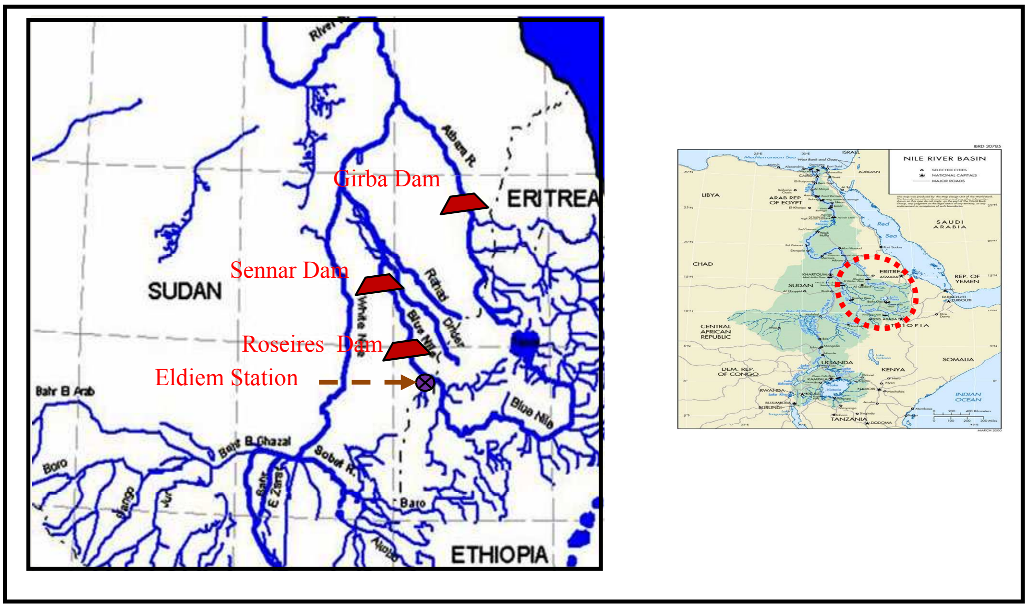

Figure 1: Blue Nile and Atbara River

Blue Nile and Atbara River carry big amount of sediment during flood season (July-September) and are predominantly carried in suspension varies from 4000 PPm to 6000PPm with insignificant amount of sediment during the rest of the year. The approximated average volume of 140 million ton per year as shown in *Figure (3)* is estimated as measured in Eldiem and upstream Girba dam on Blue Nile and River Atbara respectively where some of scattered suspended sediment of years (1970,73,75,93,94,2000-2009) are available.

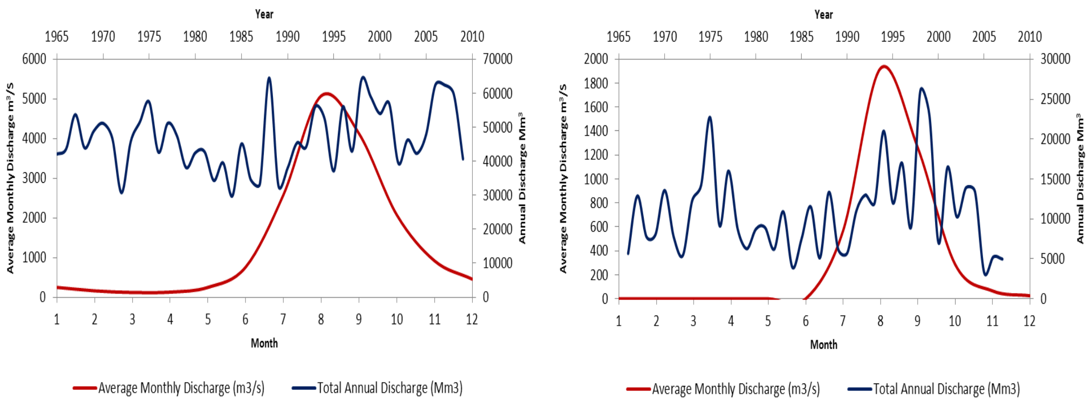

Figure 2: Blue Nile and Atbara River Hydrograph

According to *Siyam, et.al (2005)*, the mean annual water flows were equal to or greater than the long term mean which should produce results with maximum error of 20%, therefore, the values of 122 and 17 Million tons for long-term suspended sediment inflow at Eldiem and upper Girba dam stations are likely to be represented, even though, due to the absence of regular measurements makes this value questionable.

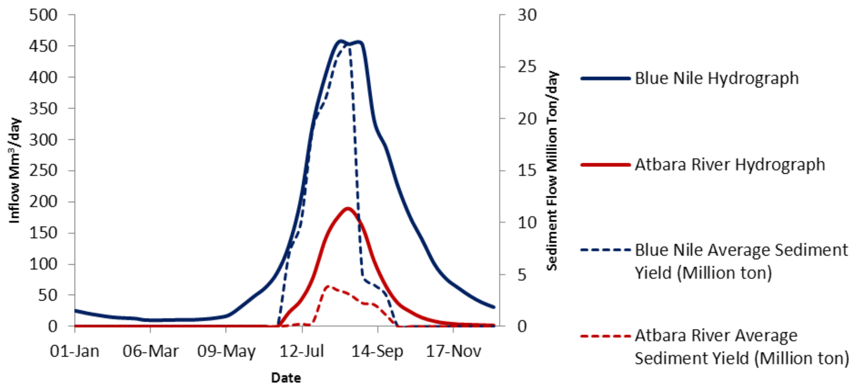

Figure 3: Blue Nile and Atbara River sedimentation

The Sennar, Roseires, and Girba dams are the major Sudanese reservoir in eastern Nile; Analysis of bathymetric survey data shows a sedimentation rate between 9-35 million/ton per year which reduced the total reservoirs storage dramatically by more than 50% from above $5.2*10^9$ m^3 at 1966 to less than $2.7*10^9$ m^3 in 2010 as shown in *Table (1)* and *figure (4)*.

Table 1: Main Reservoirs Characteristics

Dam	Construction Year	Design Capacity (Mm^3)	C/I	Mean Annual rate of sedimentation (Mm/yr)	Hydropower capacity (MW)	Storage Losses (%) (2010)
Sennar	1925	930	0.06	9.25	15	85%
Roseires	1966	3100	0.02	34.35	240	35%
Girba	1964	1300	0.11	17.9		53%

The general operation policy of these reservoirs are based on storing water during flood period and use it later, therefore, the hydrological year can be divided to four periods:

(1) 1^{st} to 31^{st} July - rising period;
(2) 1^{st} to 20^{th} August - period just before peak;
(3) 21^{st} August to 30^{th} September - peak period;
(4) 1^{st} October to 30^{th} June - recession and low flow periods.

During the flood period, the priority is given to fill the reservoir and bypassing the sediment at the same time, therefore, the reservoirs are normally operated at the minimum level at the beginning of flood to pass the sediment and start filling at the end of season.

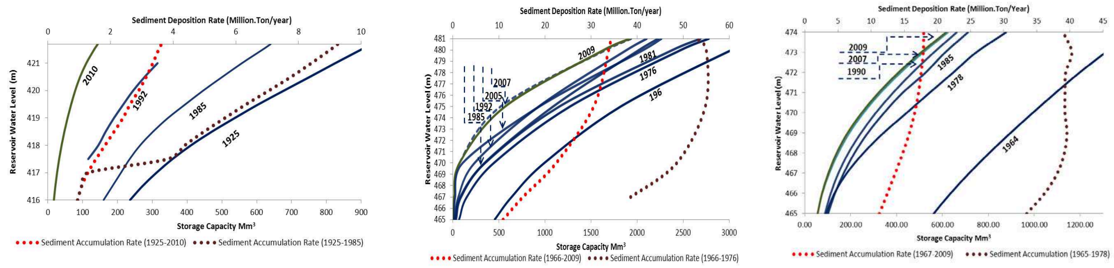

Figure 4: Reservoirs sedimentation and sediment accumulation rate for (a) Sennar, (b) Roseires, and (c) Girba dams.

4 Methodology

Blue Nile and Atbara River flows, Bathymetric survey analysis, and sediment sampling measurements have been used to estimate reservoir sedimentation and extract *a,m* parameters as shown in *figure (5)* . For Blue Nile sedimentation *Hussain(2005)* formulas found to be the most applicable which divided the flood season into two periods:

1-Rising Flood Stage:

$$Q_s = 4.286 * 10^{-4} Q \quad (2)$$

2- Falling Stage

$$Q_s = 1.837 * 10^{-4} Q^2 \quad (3)$$

While for Atbara River, *Moussa et.al, (1991)* has been applied:

$$Q_s = 297.114 * 10^{-6} Q^{1.092} \quad (4)$$

Where Q_s is daily sediment flow, Q is daily discharge.

Two Grey system prediction models have been applied to simulate the *a,m* parameters, of which DGM(1,1) and Verhulst Model, afterwards, the obtained results are compared with observed one to verify and update the model. Finally, a sensitivity analysis have been conducted to check the convergence of simulated values and in order to use them in future reservoir storage prediction. Three evaluation methods- (i) Nash-Sutcliffe efficiency (NSE), (ii) percent bias (PBIAS), (iii) ratio of the root mean square error to the standard deviation of measured data (RSR) - were applied as expressed in equation (5), (6), and (7) respectively.

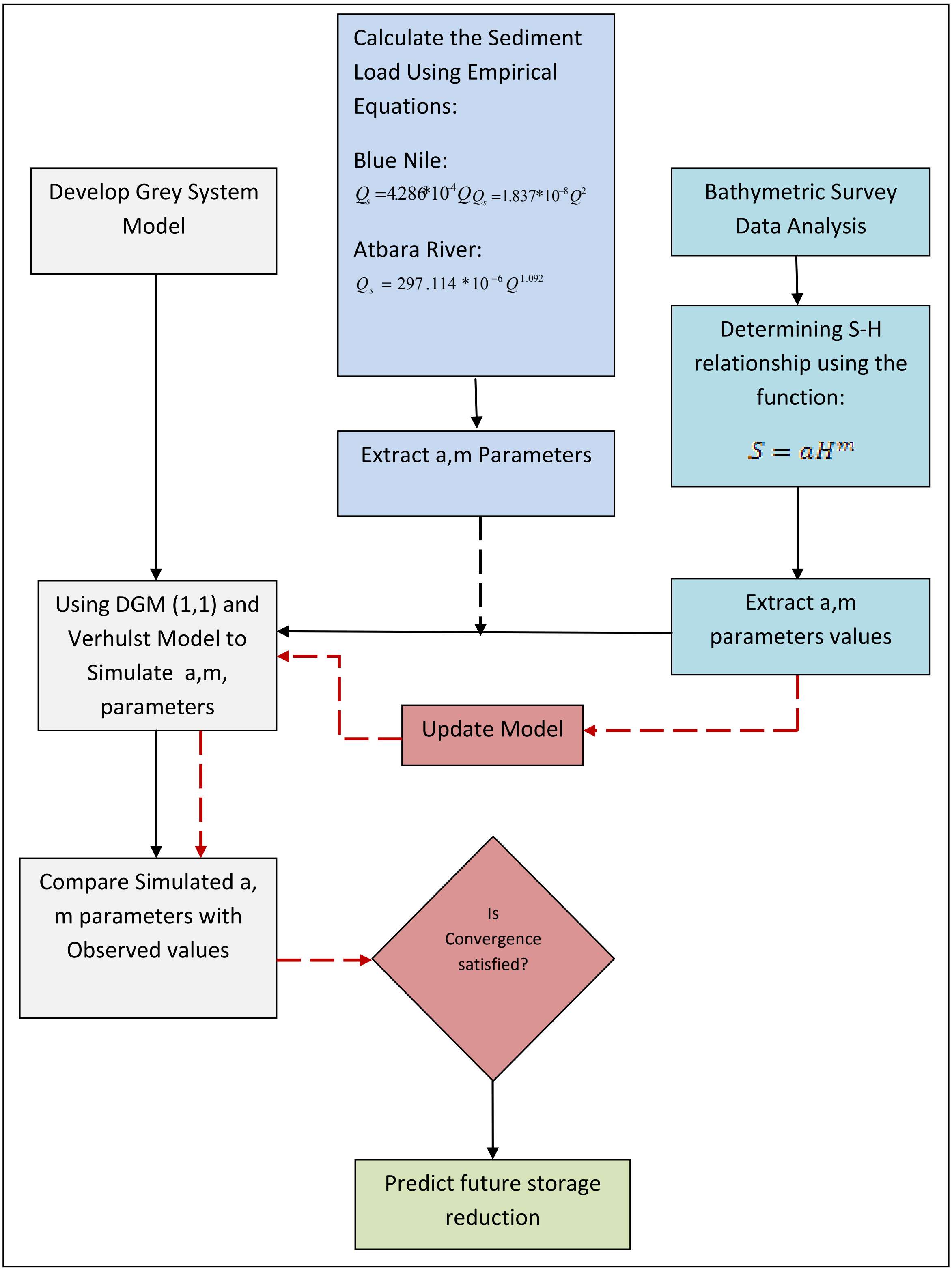

Figure 5: Methodology Flow Chart

$$NSE = 1 - \left[\frac{\sum_{i}^{n} (X_i^{obs} - X_i^{sim})^2}{\sum_{i}^{n} (X_i^{obs} - X^{mean})^2} \right] \quad (5) \qquad PBIAS = \left[\frac{\sum_{i}^{n} (X_i^{obs} - X_i^{sim}) \times 100}{\sum_{i}^{n} (X_i^{obs})} \right] \quad (6)$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \left[\frac{\sqrt{\sum_{i}^{n} (X_i^{obs} - X_i^{sim})^2}}{\sqrt{\sum_{i}^{n} (X_i^{obs} - X^{mean})^2}} \right] \quad (7)$$

Where: X_i^{obs} is observed variable, X_i^{Sim} is simulated variable (*a*, *m*, or storage in Mm^3), and X^{mean} is the mean of *n* values, *n*= number of observations.

5 Analysis and Results

Sediment inflow has been estimated in order to correlate the total load with deposit one, afterwards, two Grey prediction models results, DGM (1, 1) and Verhulst models, have been set up using the extracted a, m parameters from bathymetric survey data analysis as initial values to run the model, the model results and their calibrated values for three reservoirs, namely, Sennar, Roseires, and Girba are shown in *figures (6)* and *(7)*.

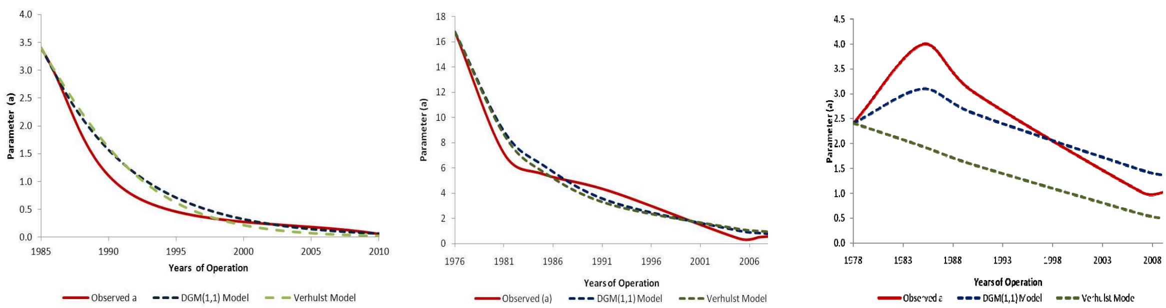

Figure 6: Observed and simulated (a) parameter for (a) Sennar, (b) Roseires, and (c) Girba dams.

Accordingly, the simulated parameters, (*a*) and (*m*), have been used to estimate the reservoirs storage capacity using equation (1), the results are shown in *figure (8)*.

The two grey system prediction models- DGM(1,1) and Verhulst- were calibrated using yearly storage-level (*a, m*) parameters data from 1925-1992, 1966-1992,1964-1990, and validated for the period 1993-2010, 1993-2009, 1991-

2009 for Sennar, Roseires, and Girba reservoirs respectively. The models performances were evaluated using the NSE, RSR, and PBIAS measures as discussed in section (4).

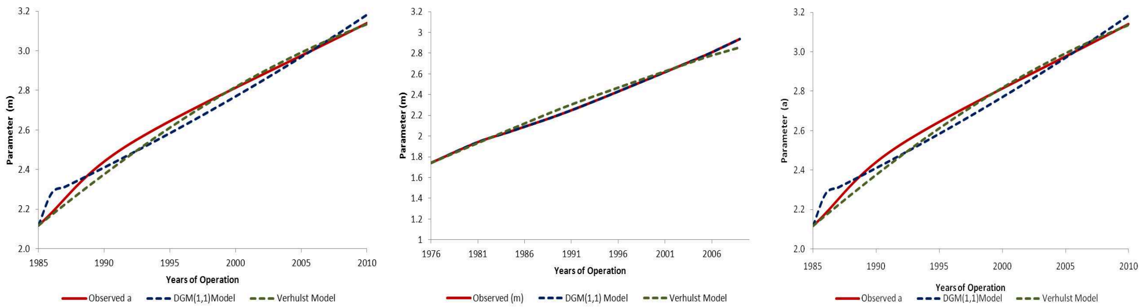

Figure 7: Observed and simulated (m) parameter for (a) Sennar, (b) Roseires, and (c) Girba dams.

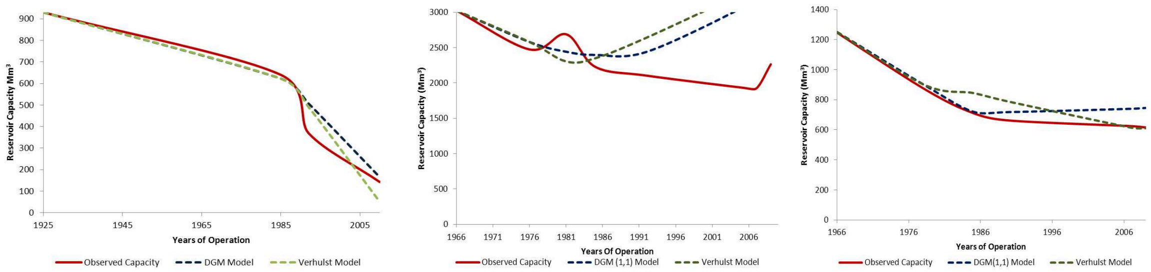

Figure 8: Observed and simulated reservoirs storage capacity for (a) Sennar, (b) Roseires, and (c) Girba dams.

For Sennar reservoir, both grey models show good performance the predicted storage capacity in 2010 was 165 Mm^3 which is close to the observed one 144 Mm^3 with NSE= 0.942, 0.938, RSR=0.241, 0.249, PBIAS=-8.337%,-1.973% for DGM (1,1) and Verhulst Model respectively. However, even with good conformity between observed and simulated data, both models tend to slightly overestimate the storage capacity during the validation period (1992-2010), which might be represents the normal storage decreasing trend if the reservoir was kept operating normally or there is underestimation of reservoir capacity during the last bathymetric survey. On other possible reason for the relatively observed sharp decreasing of reservoir storage capacity is operation policy fluctuation that had been practiced during that period to meet the new extension in irrigation plan, nevertheless, both models showing good convergence and improving by time.

In contrast to Sennar, Roseires reservoir models shows good performance during calibration period till 1981, where reservoir maximum water level has been increased by 1m to be 481 instead of 480m, then the models tend to overestimate the storage capacity extremely afterwards to be over 2600 Mm^3 comparing to observed capacity of 2264 Mm^3 even with a good estimation of *a, m* parameters. The models evaluation measures are NSE= -3.614,-4.233, RSR=2.148, 2.288, PBIAS=-21.613%,-22.462% for DGM (1,1) and Verhulst Model respectively. However, there are some indicators shows the underestimation of 2007 bathymetric survey data which affect the models performance.

Girba reservoir models show good agreement between observed and simulated data by estimated storage capacity of 745 Mm^3 for DGM (1,1) and 610 Mm^3 for Verhulst model comparing to observed capacity of 616 Mm^3 with NSE= 0.905, 0.908, RSR=0.309, 0310, PBIAS=-7.016%,-5.614% for DGM (1,1) and Verhulst Model respectively. however, DGM(1,1) model shows a better conformity than Verhulst model during calibration period, nevertheless, Verhulst model converge at the end of validation period better than DGM(1,1) model.

Interestingly that Girba reservoir has been 1m increased as Roseires reservoir and has sediment flushing operation process since 1978; nonetheless, the both models are able to perform reservoir capacity simulation adequately better than Roseires case.

Generally, both models show good performance and could be applied in such cases where system information are scarce and uncertain, however, the fluctuation of operation policy represents a real hindrance for both model as it disturb the sediment accumulation process and therefore, some of grey system information as well, accordingly, the models tend to fail capturing the phenomena as Roseires simulation case shows above.

6 Conclusion

The DGM (1,1) and Verhulst grey system models were applied to predict the reservoir’s storage parameters in Sudanese Eastern Nile reservoirs-Sennar, Roseires on Blue Nile and Girba reservoir in Atbara River- the model used the available bathymetric survey data to extract the observed parameters in addition to apply an empirical formula to estimate the annual sediment load in both rivers to fill the data gabs between each bathymetric survey process.

The models show as well a rapid decreasing of Sennar storage capacity while Roseires reservoir shows slow storage deterioration mainly in last five years.

Girba reservoir flushing process keeps the storage capacity deterioration at the acceptable rate.

This study shows clearly the potentiality of using grey system in reservoirs storage capacity prediction particularly where system information are scarce and uncertain, yet, instability of system operation policy from 1990th on, had severely increased the Sudanese Eastern Nile reservoirs sedimentation more than the normal rate and has an obvious impact on model performance as a consequence" Sennar for instance", therefore, developing and applying firm operating policy is crucial besides improving sediment load estimation method to avoid this limitation in future, nevertheless, the grey system theory approach can be used and developed as an efficient tool and can be integrated with further studies such as simulation and optimization procedures to improve the water resources system operation and management in eastern Nile.

7 References

Arora, P.K., and Goel, M.P. (1994): Estimating life of a reservoir. Proceedings of Workshop on Reservoir Sedimentation held in Mysore, Karnataka, on May 17- May 19 1994, pp. 4-11, India.

Churchill M.A. (1948): Discussion of "Analysis and Use of Reservoir Sedimentation Data", Proceedings of Federal Interagency sedimentation Conference, edited by L. C. Gottschalk, Denver, pp. 139-140, USA.

Hamad, O.E. (1993): Optimal Operation of a Reservoir System during a Dry Season. PhD Thesis, University of Newcastle Upon Tyne, UK.

MOI Report (1968): Regulation rules for the working of reservoirs at Roseires and Sennar. Ministry of irrigation and Water Resources (MOI), Sudan.

Moriasi, D. N.,et al., (2007): Model evaluation guidelines for systematic quantification of accuracy in watershed simulations,T. ASABE, 50, 885–900.

Morris, G.L., and Fan, J. (1998): Reservoir Sedimentation Handbook. New York: McGraw Hill.

Moussa, O.M, et al., A Hydrologic Regression Sediment-Yield Model for Two Ungauged Watershed Outlet Stations in Africa.

Nash, J. E. and Sutcliffe, J. V, (1970): River flow forecasting through conceptual models part I – A discussion of principles, J. Hydrol., 10, 282–290.

S. Elshek.S, et al., (1991): Intensive sediment transport from the upper Nile basin and water resources management in Sudan, Hydrology for the Water Management of Large River Basins/Proceedings of the Vienna symposium, August 1991). IAHS Publ. no. 201, 1991.

Seleshi Bekele Awulachew.S.B, et al.,(2008): A Review of Hydrology, Sediment and Water Resource Use in the Blue Nile Basin, international management institute.

Sifeng Liu and Yi Lin (2010), Grey Systems,Theory and Applications, Springer-Verlag Berlin Heidelberg

Siyam, A.M.,et al., (2005): Assessment of the Current State of the Nile Basin Reservoir Sedimentation Problems,NBCN-RE (Nile Basin Capacity Building Network for River Engineering), River Morphology, Research Cluster,Group – I Report.

Yang, X. (2003): Manual on Sediment Management and Measurement. World Meteorological Organization, Operational Hydrology Report No. 47, WMO-No. 948, Secretariat of the World Meteorological Organization – Geneva: Switzerland.

Yevdjevich V.M. (1965): stochastic problems in design of reservoirs. Paper presented at the seminar in Water resources research at Colorado State University, USA.

Yoon, Y.N. (1992): The State and the Perspective of the Direct Sediment Removal Methods from Reservoirs, International Journal of Sediment Research 7(20), 99–115.

Yousif, D.A. (1999): Application of Non-Linear Optimization to Multipurpose Reservoir Systems. PhD Thesis, Loughbrough University, UK.

Authors:

MSc-Eng.Mohammed Abdallah

Institut für Wasserbau und Technische Hydromechanik
Technische Universität Dresden
George-Bähr-Straße 1
D-01062 Dresden

Tel.: +49 (0)351 463 35844
Fax: +49 (0)351 463 37120
E-Mail: Mohammed.Abdallah@mailbox.tu-dresden.de

Prof.Dr-Ing.Jürgen Stamm

Institut für Wasserbau und Technische Hydromechanik
Technische Universität Dresden
George-Bähr-Straße 1
D-01062 Dresden

Tel.: +49 (0)351 463 34397
Fax: +49 (0)351 463 37120
E-Mail: Juergen.Stamm@tu-dresden.de