Lake level rise modeling with Artificial Neural Networks (ANN) and Hydrodynamic model

Abebe Tadesse Tadesse Bulti (abebulti@yahoo.com)
Hawassa University Institute of Technology https://orcid.org/0000-0001-9695-0438
Gonse Amelo yutura
Hawassa University Institute of Technology

Research Article

Keywords: Lake Level, ANN, Hydrodynamic models, Water balance, Lake Hawassa

Posted Date: December 6th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2300780/v1

Abstract

The water level in a lake increases as a result of changes in the hydrologic processes in the lake catchment that can cause a flood in the lake's surrounding areas. The lake system needs a comprehensive investigation to alleviate an increase in the water level and consequently flooding. Some different methods and approaches can be applied to predict the lake level increase. A water balance study, hydrodynamic model application, and ANN simulation applications are some of the methods. Each method has merit and complexity in terms of data requirement, the reflection of the physical processes, and ease of modeling application. A simple water balance model application is relatively good in considering all the physical processes. However, model outputs are not good during the model performance evaluation. The hydrodynamic models are simulation models which base on the physical processes of the lake system, with the same modification. Somehow it considers all the real processes with simplification. A good understanding of the application provides a favorable condition to provide all the input/factors contributing/ indirectly to a system modeling. The simulation through a hydrodynamic model is within a good range on performance indicators. Artificial Neural networks (ANN) are recent applications that focus on data science rather than physical processes. The ANN provides an opportunity to include all the contributing factors in the modeling processes. The output from ANN modeling processes is in a very good range. The choice of the method of prediction needs to understand the actual event in a lake system and the model's background for good prediction.

1. Introduction

Lakes are the major sources of water especially if it contains fresh water and is connected to perennial rivers, they can be sources of water for different purposes like irrigation, water supply, and energy production. In some cases, lakes increase the attractiveness of surrounding areas around the city and can be a place to be visited by many tourists which increases income from tourism. On other hand, the water level increase in a lake is a major concern for most nearby cities as its consequence cause flooding in the surrounding areas. Lake catchment hydrologic processes can be used to evaluate the causes of lake water level variation. The change in land use, evaporation, precipitation, runoff, and other metrological issues can be the causes of the lake level change (Vuglinskiy et al., 2009, Guo et.al., 2015, Finney et al., 2019). The temporal variation of a lake level depends on the catchment area to lake surface area ratio (Mason et al., 1994, Zhang et al., 2017). Besides, lake water level rise to a rainfall relation depends on the size of the catchment areas and lake.

The lake level variation needs a detailed understanding of the hydrologic and physiologic characteristics of the catchment. All the factors contributing to the lake levels need to be considered for a better prediction of variations. The simplification and assumptions in models are other challenges that make the inclusion of all the factors. East African seasonal rainfall distribution is bimodal and governed by the Indian oceans surface temperature (Verschuren et al., 2009, Tierney et al., 2013). The variation in the rainfall and rapid land use change in hydrologic basins are among the foremost causes of the lake level rises in lake Hawassa. One of the gaps in most lake level rise studies, all the contributing factors will not be included for instance the effect of sedimentation (Ayenew, T., & Gebreegziabher, Y. (2006), Ayenew, T., & Becht, R. (2008). Most of the studies are based on water balance studies. It is well understood that simplification in a model application is common. However, under current rapid rainfall and land use changes in most catchments, model simplification leads to a wrong result. Data requirement and the gap in data records even if it is available is further a bottleneck problem in considering all the factors contributing to lake-level modeling.

The lake level prediction is a complex process that requires an understanding of catchment hydrologic characteristics and models background for a better prediction. Simple water balance equations are a practically ideal method to estimate the lake level since all the contributing factors can be included easily (Biskop et al., 2016). However, the accuracy and availability of the measurement of individual components in the water balance have a significant effect on the final output. Some of the components are not measured directly but need to be transformed to the water balance equation requirements. All such conditions can affect the accuracy of the prediction processes. There are different approaches besides the water balance models. ANN and Hydrodynamic modeling are some of the options. ANN application is good at predicting the lake water level with a good performance indicator. The main drawback of the ANN the link between the input and output is not strongly related to the physical processes. It focuses on the input and output data, even without considering some of the inputs it can predict the final output with a good performance indicator. On the other hand, hydrodynamic models can be applied for lake-level modeling. These models consider the bathymetric information, which can easily transform the outputs in terms of water level. In the hydrodynamic model, some of the input data are not directly provided, but it needs simple analytic analysis.

This study aimed to evaluate the effects of the hydrological variability in the catchment on a lake level rise on lake Hawassa (Closed Lake). Some optional models were applied to compare and contrast the prediction of a lake level. The consideration of all the contributing factors and model capability were the major issues in the simulation process. Inclusion of sediment deposition effects on lake level rises is an additional effort from similar water balance studies. The accurate prediction through different models will significantly assist the flood management works around lakes and surrounding areas. The models were not developed for a specific case and lake-level modeling needs a systematic approach to consider all the contributing factors in a modeling approach. The compromise between the contributing factors, assumptions, and simplification of the model background are the issues addressed in this research.

2. Study Area

Lake Hawassa is one of the lakes in rift-valley regions in Ethiopia, the study of the lake hydrology including climate change effects is important for sustainable use of the lake in the future. The lake has multi purposes, fishing and small irrigation development works are the direct uses. The lake was on the western side of Hawassa city which make the city very attractive and increase the tourism activity in the town. The Lake Hawassa Sub-basin is located in the central northeast of the Rift Valley Lakes Basin and covers an area of 1,436 km^2. It is a closed lake situated in a caldera depression. River Tikur Wuha is the only tributary connecting Lake Hawassa to the upstream lake Cheleleka. The city of Hawassa is located at the western shore of the lakes.

The lake level increases from time to time and making flood management difficult. The Hawassa city municipality tries to manage the lake level by constructing a dike. The lake is used as a mouth for a drainage network in the city. The connection of the storm drainage network to the lake was a challenge due to the lake level increase that causes backflow and temporary storage in front of the dike constructed to flood protection. The lake level increased from time to time, and the wetland at the upstream area which was named Cheleleka was almost lost due to deforestation and urbanization upstream of the lake. This event was considered a major factor in the rapid increase of the lake level. Figure 2 shows the lake level increase in lake Hawassa in the last 30 years.

3. Lake Level Modeling Approach

3.1. ANN modeling

Artificial Neural Networks (ANNs) are alike regression models that use some weighting factors, but ANN is more advanced and the intelligence to learn from the processes and make improvements again and again in the prediction process. The approach in ANN is based on the cognitive function of the human brain in simulating any physical processes. It tries to imitate the human brain structures and function for the simulation processes. Currently, ANNs can solve multifaceted, nonlinear, and noisy types of physical events (Allende et al., 2002; Wilamowski, 2007; Khashei and Bijari, 2009). ANNs depend on data readiness from physical processes and the back and forward learning capability of the approach to simulate an observed and simulated event with a higher data fitting accuracy. To reduce the difference between the predicted and target values, the ANN reads the values of the input and output in the training data set and adjusts the value of the weighted links. Over many training cycles, the prediction error is reduced until the network reaches the desired accuracy level. Even if the physical mechanisms controlling the behaviors of the system are poorly understood, the available data is used to describe the behaviors of a system and attempt to establish a relationship between these data. As a result, they are ideal for modeling the intricate behaviors of a heterogeneous and anisotropic hydrologic system.

An ANN is built on the interconnection of neurons, or nodes, which function as a collective system. There are neurons and links in this system. Figure 3 shows that each link has a weight, which is a numerical value that indicates how strong the connections between the neurons are. A transfer function is used to turn the sum of the input weights into outputs (Wilamowski, 2007). By iteratively adjusting the weights, a neural network is trained to map a set of input data. The ANN's ability to recognize objects relies heavily on the use of weighted links. The network forwards information from inputs to optimize the weights between neurons. During the training or learning phase, error propagation backward is used to optimize the weights. To reduce the difference between the predicted and target values, the ANN changes the value of the weighted links and reads the values of the input and output in the training data set. Over many training cycles, the prediction error is minimized until the network reaches a certain level of accuracy.

Complex hydrodynamic processes alike a lake level variation can be simulated using ANN application. The simulation processes fully depend on the data collected from the lake system. The advantage of the use of ANN it provides an evaluation of the system with different options with a full understanding of the lake characteristics. The lake is a closed lake with little abstraction for small irrigation works in nearby areas. All the components of rainfall, runoff, evaporation, direct rainfall, sediment inflow, and groundwater components were provided as input for the model. The lake level was output from a modeling process.

The ANN modeling needs the inputs and output variables data for any simulation task. The variables for the modeling lake level system for lake Hawassa was shown in Fig. 4. Rainfall (direct over the surface of a lake), surface runoff (Tikur Wuha River), and Evaporation was directly collected from the local organization (Rift valley basin and metrological agency in the southern branch of Ethiopia). The runoff from the catchment has two components gauged and Ungauged catchment. Hydrological modeling application was applied and the gauged data was used to calibrate the ungauged catchment surface runoff. The calibrated surface runoff from the whole catchment that was derived from hydrological modeling was used as an input for ANN. Similarly, sediment modeling both from the catchment and Tikur Wuha River was derived from hydrological modeling and sediment rating curve application. (See sediment modeling section) ((Tadesse and Dai (2019), Ferguson, (1986).

3.2. Hydrodynamic modeling

Hydrodynamic models are a computational suite for a multi-disciplinary approach to nearshore wave and morphodynamical modeling. For this reason, this suite is composed of several modules which allow any user to carry out simulations of flow, sediment transport, waves, water quality, and ecology. The hydrodynamic module, Delft3D-FLOW, accounts for two-dimensional (2DH, depth-averaged) or three-dimensional (3D) unsteady flow phenomena. If the fluid properties can be considered vertically homogeneous, solving depth-averaged equations is appropriate and hence the 2DH approach may be used. In contrast, 3D modeling is particularly adequate if the flow field features show a significant variation along the vertical direction. (Deltares 2014 a and b)

3.2.1 Hydrodynamic equations

Hydrodynamic models solve the Navier Stokes equations for an incompressible fluid, under shallow water and the Boussinesq assumptions. In the vertical momentum equation, the vertical accelerations are neglected, which leads to the hydrostatic pressure equation. In 3D models, the vertical velocities are computed from the continuity equation. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on a finite difference grid. The depth-averaged continuity equation is derived by integrating the continuity equation for incompressible fluids (∇ • ~u = 0) over the total depth, taken into account the kinematic boundary conditions at the water surface and bed level, and is given by:

$$\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial((d+\zeta)\,U\sqrt{G_{\eta\eta}}}{\partial \xi} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial((d+\zeta)\,V\sqrt{G_{\xi\xi}}}{\partial \eta} = (d+\zeta)\,Q\,\ldots\ldots(xx)$$

With U and V, the depth average velocities

The momentum equations in ξ- and η-direction are given by:

$$\frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial \eta} + \frac{w}{d+\zeta}\frac{\partial u}{\partial \sigma} - \frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} + \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} - f_v = \frac{1}{\rho_0 \sqrt{G_{\xi\xi}}}P_\xi + F_\xi + \frac{1}{(d+\zeta)^2}\frac{\partial}{\partial \sigma}\Big(vV$$

and

$$\frac{\partial v}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial \eta} + \frac{w}{d+\zeta}\frac{\partial v}{\partial \sigma} - \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} + \frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} - f_u = \frac{1}{\rho_0 \sqrt{G_{\xi\xi}}}P_\eta + F_{\xi\eta} + \frac{1}{(d+\zeta)^2}\frac{\partial}{\partial \sigma}\Big(vV$$

Density variations are neglected, except in the baroclinic pressure terms, P_ξ and P_η represent the pressure gradients. The forces F_ξ and F_η in the momentum equations represent the unbalance of horizontal Reynold's stresses. M_ξ and M_η represent the contributions due to external sources or sinks of momentum (Deltares, 2014 a).

3.3. Simple water balance computation

A simple water balance equation was used to evaluate the monthly water balance. Models have different approaches to simulating a physical process. The water balance application is a simple model that considers all the components significantly contribute to a lake level increase. Estimation of the water level rise from a water balance modeling is challenging, because of the difficulty to collect the data components all the time. Besides, the error during measurement and handlining has a significant effect on the simulation process.

$$Q_I = Q_w + R - E + Q_s \pm Q_G$$

…………………………………… 1

where Q_I= inflow, Q_w= runoff, R= rainfall, Q_s= sediment load, E=evaporation and Q_G=ground water flow.

The above simple water balance Eq. (1) was used to compute the water levels in the lake. All the values computed from the water balance equation were changed to flow depth values, to compute the lake level rise. Further, the computed values were compared with the observed values, and simulated values from hydrodynamic and ANN models. The water balance equation helps to observe the physical processes in the simulation process.

4. Sediment Inflow To The Lake Hawassa

Perdition of sediment yield from the catchment and later transport to the lake are the important components of the water balance of lake level rise. The water balance studies (Ayenew, T., & Gebreegziabher, Y. (2006), Ayenew, T., & Becht, R. (2008), in the lake basin do not consider the effect of sedimentation on the lake level. In this study, the rapid land use change in agricultural and urban areas which are contributing significant sediment flow to the lakes was considered. The sediment flows to the lake were estimated by using the few sediment concentration data available at the gauging station near the inlet of the lake.

The sediment load was calculated from the rating curve developed based on the statistical parameters estimated from Fig. 5 and the Eq. (2) was used further to compute the sediment load. Bed loads were considered in the sediment-to-flow computation. Eq. 2 calculate the suspended loads and 15% of the additional load was considered for the bed loads consideration. Besides, to consider the underestimation effect of the sediment rating curve from the statistical ((Tadesse and Dai (2019), Ferguson, (1986)) method 50% of additional loads were considered. The sediment from the ungauged part of the catchment was calculated by an area proportion.

$$Qs = 26.3815 * Q_w^{0.7335}$$

………………………………….2

5. Model Output Analysis

5.1 ANN modeling outputs

The ANN model setup requires the knowledge of the lake level rise and overall hydrologic processes. The model setup was shown in Fig. 4 for the lake level modeling, the input, hidden layers and output. The ANN model was run by using the five inputs (runoff, sediment, evaporation, direct rainfall, and groundwater flow). There is no significant water abstraction from the lake. The output was the lake water level.

The output from the model setup was shown in Fig. 6. The outputs of the ANN modeling are good in terms of predicting the overall lake level rise. The performance of the model is very good and can be used for practical management of the lake level. ANN methods consider the data and advanced statical analysis of the data provided. It does not provide any condition to evaluate the real processes in the lake level rise. Besides, the lake level rises complex processes which have many parameters which need to be either measured or estimated to suit as an input for the model setup in ANN model. Figure 7 shows the output for the performance of the ANN model during the training and validation steps. The ANN method was very good in predicting the lake level. As compared to the other method it can predict accurately with including all the contributing factors on the lake level rise. ANN is good advancement for hydrological study in practical flood management and controlling such like lake level rise.

5.2 Hydrodynamic modeling outputs

The lake bathymetric survey data of the lake was shown in Fig. 8a, and b was developed from the DEM 12.5 m by 12.5 (https://www.asf.alaska.edu). The Delft 3D quicken tool was used to interpolate points and generate the bathymetry data that can be used as input to model the lake level. The bathymetric information in the hydrodynamic models is used to predict the water level in the observed format. Besides, it helps to estimate the morphological changes at the bed of the lake. This output helps to understand the effect of the sediment on the lake level and to suggest a management solution for flood prevention. The recent bathymetric data are difficult to find, but the combined use of the past bathymetry and GIS and Remote sensed data can be used to develop the main input for the hydrodynamic model (Jawak et al., 2015). The validation at the sample points was done to check the accuracy of the new lake bathymetry. Figure 8 shows the bathymetric data that was used for the modeling of lake level. The bathymetric data was also evaluated using the old bathymetric data for comparison.

The hydrodynamic model has advantage to simulate both water level rise at the surface and bed level changes at the bottom of the lakes. This helps strategical to understand the effect of sediment on the lake level rise. The output of lake level rise from hydrodynamic model (Delft 3D) was shown in the Fig. 9. The simulation output is in good range on range (R^2 = 0.75 and NSE 0.7). The average lake level rise in lake Hawassa from the historically recorded data for was above 2 m. From the hydrodynamic model output analysis more than 45% of the lake level rise was from sediment deposition on the lake beds. It was also cross checked based on the rating curve developed from statistical analysis. Further research with more data must be carried out in the future.

5.3 Comparisons of different outputs.

The model output comparison was done to evaluate the model's performance and the processes in capturing the actual natural processes in the lake level rise. The water balance equation is a practical simple application and considers somehow all the contributors in the simulation processes. But the simulation output from the water balance equation was poor. This can be related to the accuracy in measurement, the effect of the estimation of the derived variables, etc. Figure 4 shows the output of the simple water balance equation, as it is shown in the figure the simulated lake level was almost below the measured water levels for the whole simulation period. The water balance model needs accuracy in data measurement and the inclusion of all the processes for accurate simulation.

The simulation in ANN methods is very accurate in comparison to the other models. Since this method is based on data analysis rather than processes. The accuracy in data collection and understanding of the relationship between each component is important for accurate prediction. The main drawback of ANN methods is they can provide good simulation output even without considering the important variables. As a general suggestion application of ANN in hydrological studies or for any complicated physical process, the simulation needs a good understanding of physical processes interactions and the ANN application techniques. The performance of the model cannot be the sole indicator of the model performance, it should be supported with additional model process indicators for an applicable simulation application.

The hydrodynamic model is good in simulating the lake-level dynamic processes. The data requirement in temporal and spatial consideration is the major challenge. The variation in the bed level in the lake is a challenge in hydrodynamic processes due to the frequent change and unavailability of such data as per required in the modeling application.

6. Conclusion

The model application to a Lake level rise needs the knowledge of the hydrologic processes and the model's capability and assumptions. Real natural processes are complex and challenging to make a simulation with all the factors that have effects on the processes. Based on the model background and the problems to be solved in the modeling processes, different models can be used such as ANN, Hydrodynamic model, water balance model, etc.

The comparisons of the models for the lake level indicate that ANN models have an advantage in considering all the processes and the accuracy in predicting the outputs. The water balance equations were vulnerable to different errors in process data measurement and handling; hence it has low accuracy. The hydrodynamic modeling is physical processes based and needs some data arrangement in the input, it has limitations in predicting a long-term water level. However, it has an advantage in predicting both lake level and bed level changes in a lake, which can provide good information for practical lake-level management.

The comparison of different model on the simulating a physical processes needs good understanding of the model background and the prosses to be simulated. The model performance indicators are not the only conditions that can show the effectiveness of the modelling processes but also the representation of all the important aspects in the simulation process must be addressed.

Declarations

Acknowledgement

The authors acknowledge Hawassa Metrological Agency and Rift valley Basin Authority in southern Ethiopia, and Ministry of Water Resources, Energy and Irrigation of Ethiopia, for a cooperation on a data collection.

Ethical Responsibilities

The manuscript complies with all the ethical requirements, the paper was not summited to any journal at a time. All the sources and contributors were acknowledged properly.

Consent to Participate

We are interested participate in the task for the journal including reviewing similar works.

Consent to Publish

We are fully agreed to publish the manuscript "**Lake level rise modeling with Artificial Neural Networks (ANN) and Hydrodynamic model** " after peer review on the journal of water resources management.

Authors Contributions

Abebe.T : Conceptualization, Methodology, Software, Writing- Reviewing and Editing **Gonse. A**: Validity tests, Data curation, Writing- Original draft preparation.

There are no conflicts of interest on this work

Funding

No direct funding was available, but the data sources were acknowledged for their contribution to the research.

Data Availability

All the data sources were acknowledged and cited in the manuscript.

References

1. Allende, H., Moraga, C., & Salas, R. (2002). Artificial neural networks in time series forecasting: A comparative analysis. *Kybernetika*, *38*(6), 685-707.
2. Ayenew, T., & Becht, R. (2008). Comparative assessment of the water balance and hydrology of selected Ethiopian and Kenyan Rift Lakes. *Lakes & Reservoirs: Research & Management*, *13*(3), 181-196.
3. Ayenew, T., & Gebreegziabher, Y. (2006). Application of a spreadsheet hydrological model for computing the long-term water balance of Lake Awassa, Ethiopia. *Hydrological sciences journal*, *51*(3), 418-431.
4. Biskop, S., Maussion, F., Krause, P., & Fink, M. (2016). Differences in the water-balance components of four lakes in the southern-central Tibetan Plateau. *Hydrology and Earth System Sciences*, *20*(1), 209-225.
5. Deltares (2014a). Delft3D-FLOW. Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments. Delft.
6. Deltares (2014b). Delft3D-QUICKIN. Generation and manipulation of grid-related parameters such as bathymetry, initial conditions, and roughness. Delft.
7. Deltares (2014c). Delft3D-QUICKPLOT. Generation and manipulation of grid-related parameters such as bathymetry, initial conditions, and roughness. Delft.
8. Ferguson, R. I. (1986). River loads underestimated by rating curves. *Water resources research*, *22*(1), 74-76.
9. Finney, B. P., Scholz, C. A., Johnson, T. C., & Trumbore, S. (2019). Late Quaternary lake-level changes of Lake Malawi. In *The limnology, climatology, and paleoclimatology of the East African lakes* (pp. 495-508). Routledge.
10. Guo, M., Wu, W., Zhou, X. *et al.* Investigation of the dramatic changes in lake level of the Bosten Lake in northwestern China. *Theor Appl Climatol* 119**,** 341–351 (2015). https://doi.org/10.1007/s00704-014-1126-y.
11. Jawak, S. D., Kulkarni, K., & Luis, A. J. (2015). A review on the extraction of lakes from remotely sensed optical satellite data with a special focus on cryospheric lakes. *Advances in Remote Sensing*, *4*(03), 196.
12. Khashei, M., & Bijari, M. (2010). An artificial neural network (p, d, q) model for timeseries forecasting. *Expert Systems with applications*, *37*(1), 479-489.
13. Li, E. Y. (1994). Artificial neural networks and their business applications. *Information & Management*, *27*(5), 303-313. doi:10.1016/0378-7206(94)90024-8.
14. Mason, I. M., Guzkowska, M. A. J., Rapley, C. G., & Street-Perrott, F. A. (1994). The response of lake levels and areas to climatic change. *Climatic change*, *27*(2), 161-197.
15. Ngoie, S., Lunda, J. M., Mbuyu, A., & Makenda, G. (2018). Overview of Artificial Neural Networks Applications in Groundwater Studies.
16. Tadesse, A., & Dai, W. (2019). Prediction of sedimentation in reservoirs by combining catchment based model and stream based model with limited data. *International journal of sediment research*, *34*(1), 27-37.
17. Tierney, J. E., Smerdon, J. E., Anchukaitis, K. J., & Seager, R. (2013). Multidecadal variability in East African hydroclimate controlled by the Indian Ocean. *Nature*, *493*(7432), 389-392.
18. Verschuren, D., Sinninghe Damsté, J. S., Moernaut, J., Kristen, I., Blaauw, M., Fagot, M., & Haug, G. H. (2009). Half-precessional dynamics of monsoon rainfall near the East African Equator. *Nature*, *462*(7273), 637-641.
19. Vuglinskiy, V., Monteduro, M., Sessa, R., Gronskaya, T., & Cretaux, J. F. (2009). Water level in lakes and reservoirs, water storage. *Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables*, (59).Wilamowski, B. 2007. Neural networks and fuzzy systems for nonlinear applications. Intelligent Engineering Systems, 11: 13–19.
20. Wilamowski, B. M. (2007, June). Neural networks and fuzzy systems for nonlinear applications. In *2007 11th International Conference on Intelligent Engineering Systems* (pp. 13-19). IEEE.
21. Zhang, G., Yao, T., Piao, S., Bolch, T., Xie, H., Chen, D., ... & Zhang, H. (2017). Extensive and drastically different alpine lake changes on Asia's high plateaus during the past four decades. *Geophysical Research Letters*, *44*(1), 252-260.

Figures

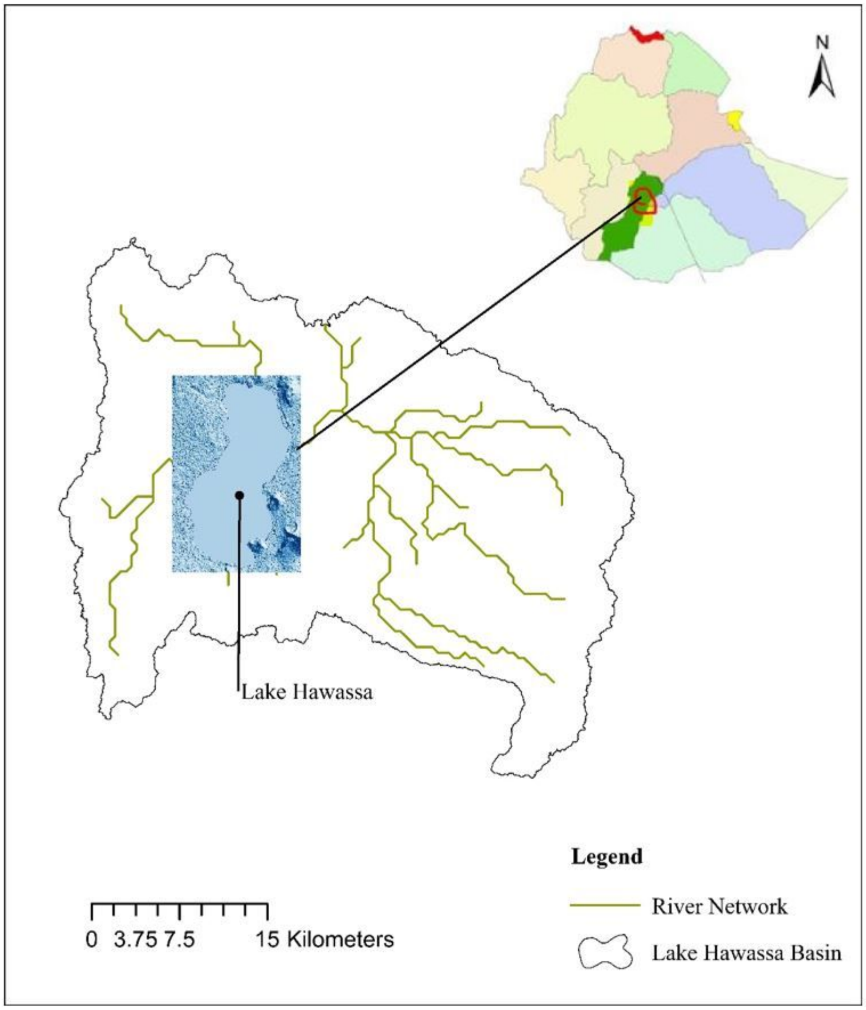

Figure 1

Lake Hawassa Catchment

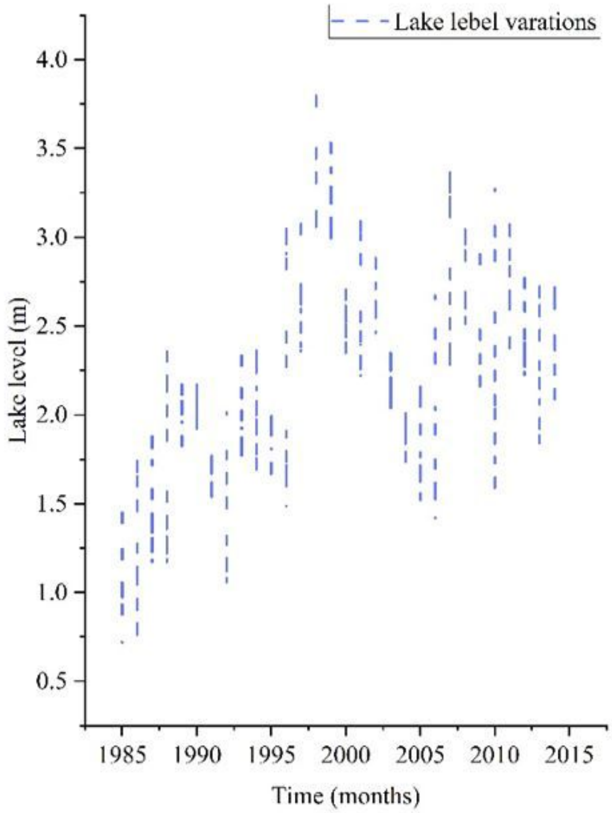

Figure 2

Monthly Lake level variation (Lake Hawassa)

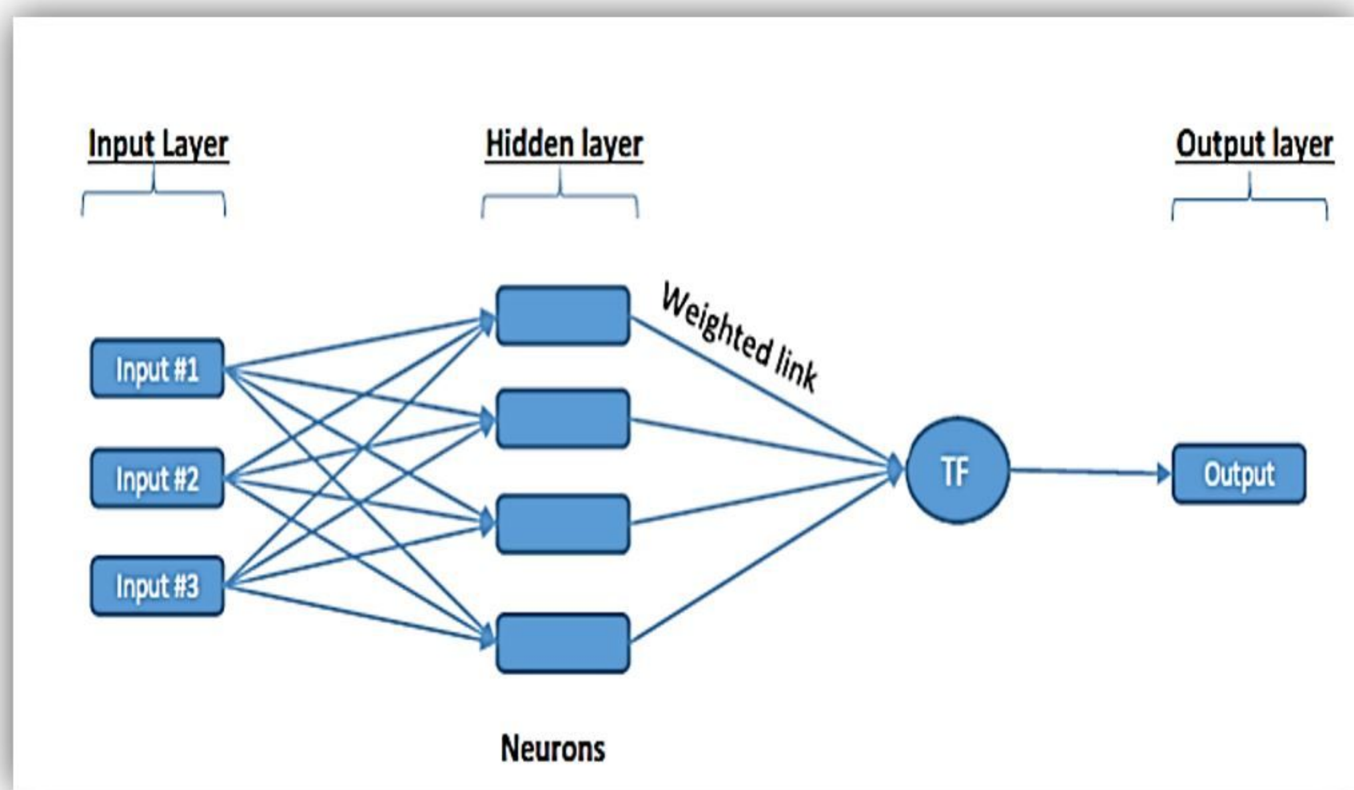

Figure 3

Example of an ANN with hidden layers (Li E., 1994)

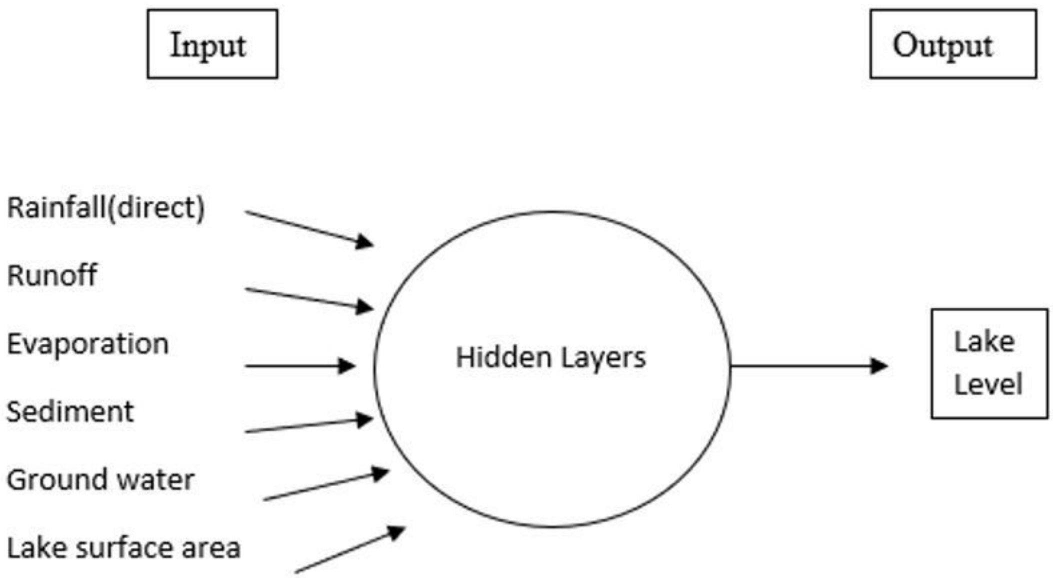

Figure 4

ANN for lake level modeling in lake Hawassa (inputs and outputs)

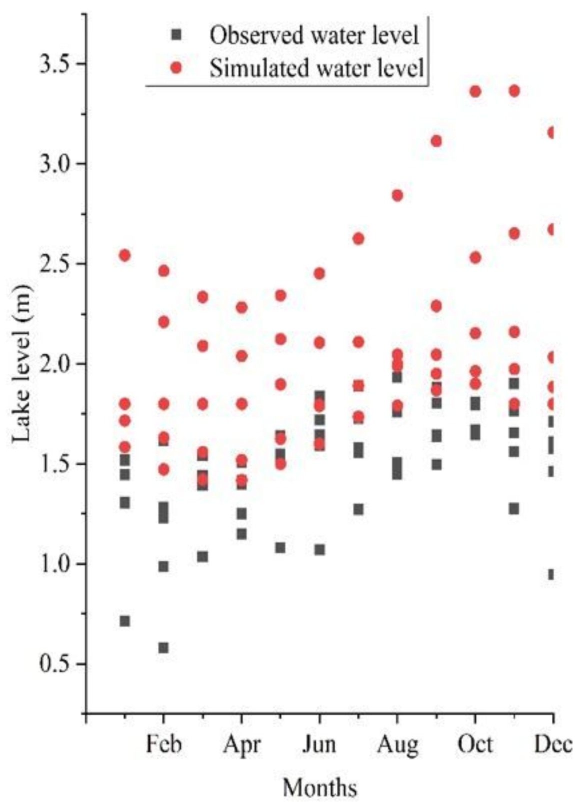

Figure 5

Figure 4 Lake level modeling with simple water balance model

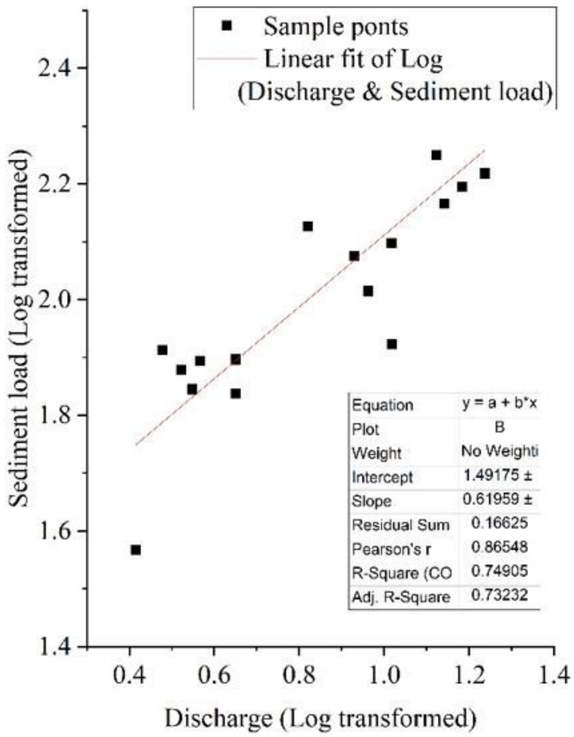

Figure 6

Figure 5 Flow discharge and sediment loads for parameter estimation (Log transformed)

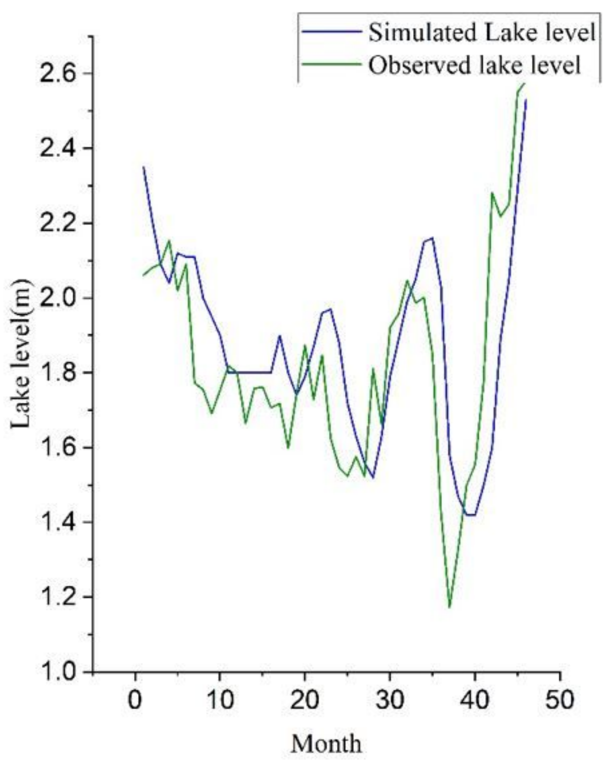

Figure 7

Figure 6 Lake level comparisons with ANN modeling

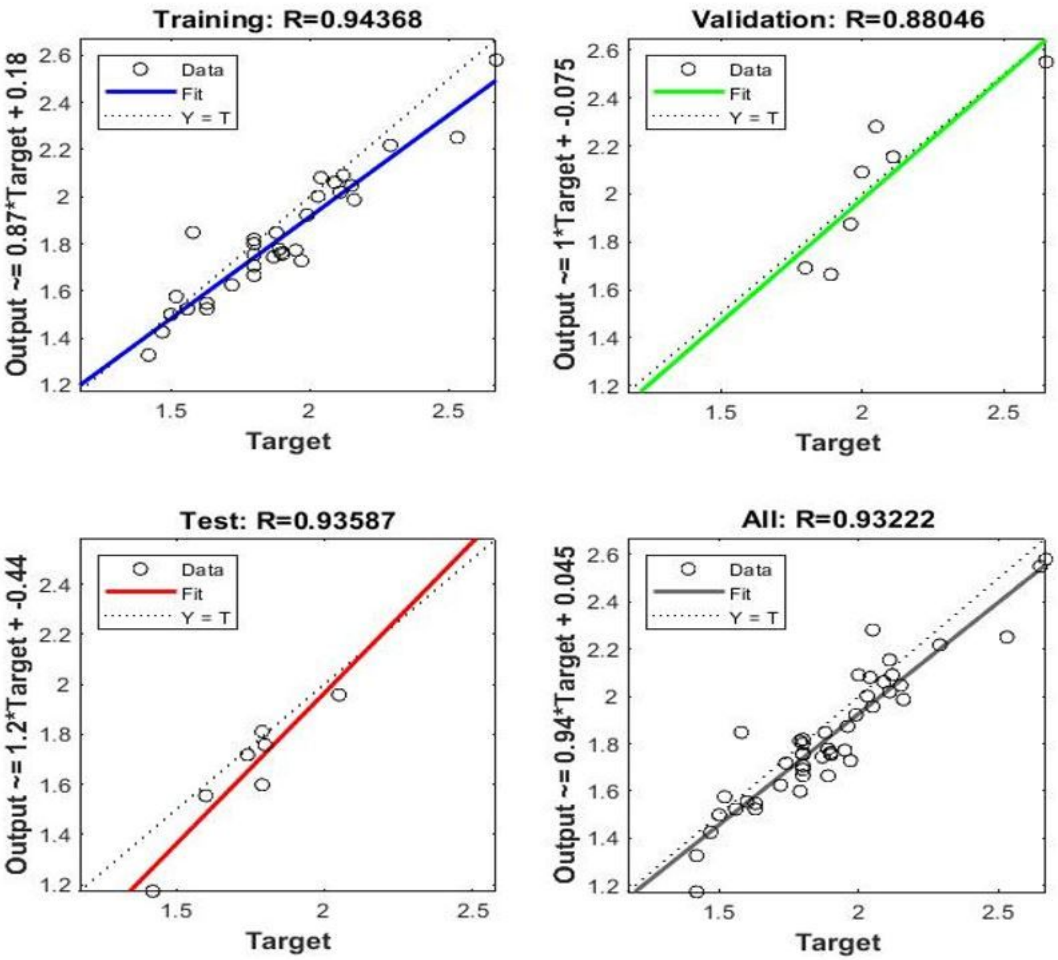

Figure 8

Figure 7 Performance indicator on ANN model

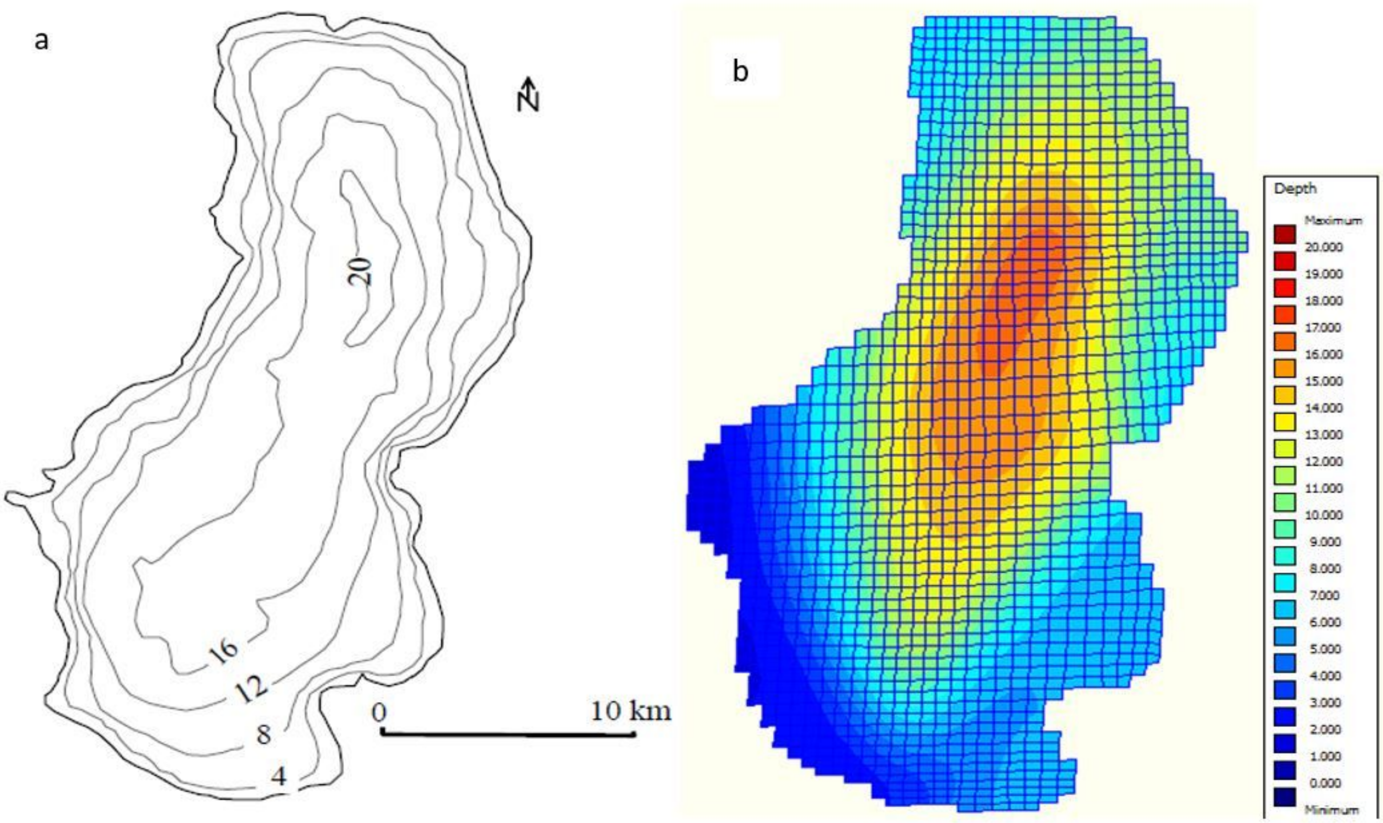

Figure 9

Figure 8 Lake bathymetric survey (a) from previous studies, (b) from DEM, and data interpolation in Delft Grid generation (Deltares 2014 b &c).

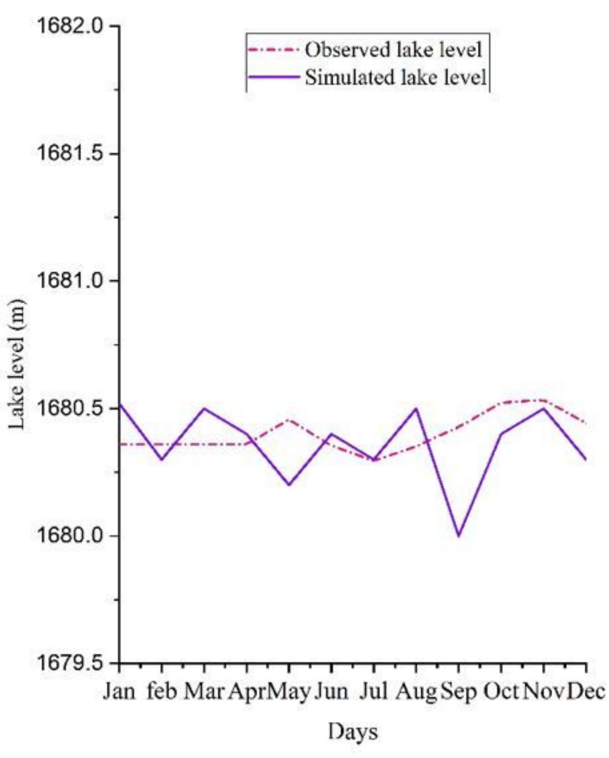

Figure 10

Figure 9 Lake level modeling with a hydrodynamic model (Delft 3D)

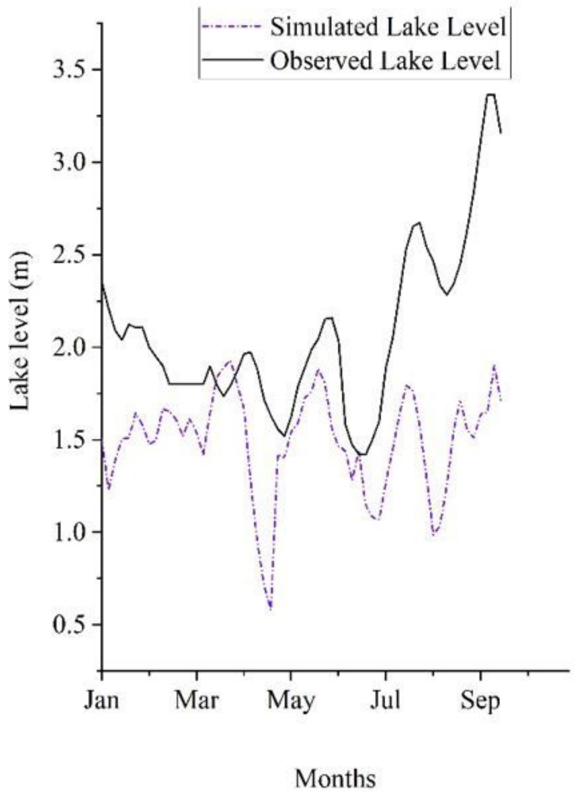

Figure 11

Figure 10 Lake water level simulated vs observed with water balance model