INTERNATIONAL JOURNAL OF ENVIRONMENT

Volume-8, Issue-3, 2019 ISSN 2091-2854

Received: 19 June 2019 *Revised: 7 Nov 2019* *Accepted: 8 Nov 2019*

MODELING OF PHOSPHOROUS LOAD AND TRANSPORT PATHWAYS IN DHIDHESSA CATCHMENT, OROMIYA, ETHIOPIA

Adisu Befekadu Kebede*, Fekadu Fufa Feyessa and Wakjira Takala Dibaba

Faculty of Civil and Environmental Engineering, Jimma Institute of Technology, Jimma University

P.O. Box 378, Ethiopia

*Corresponding author: adisu04@gmail.com

Abstract

Pollution of surface water with harmful chemicals and eutrophication with excess nutrients are recent serious environmental concerns. This lends the need of knowing the nutrient loading and transport mechanism that will occur with different spatial and temporal extent. Thus, effective information regarding the nutrients load and transport mechanisms are important to hydrologists, water use planners, watershed managers and decision makers for water resource projects and planet ecosystem. Our study aimed for modeling of phosphorous loading and its transport pathways and to identify the most vulnerable sub basin responsible for a significant phosphorus load in Dhidhessa catchment using Soil and Water Assessment Tool (SWAT) model. The pathways of phosphorus were identified and found that the organic phosphorus was dominant exporting mechanism accounted for 58.89% of the total path in the study area. For all forms of phosphorus, surface run off was the most dominant means of transport agent. The average annual loading of total phosphorus was identified as 20 kg ha^{-1}. The sub basins 17, 23, and 3 were identified as the highest loading area of total phosphorous in the study catchment. Best management plan which is simple, economical and adaptable over the study catchment for managing severe impact of surface run off on water resources should be adopted. It is better to undergo detail re-examination over the physical and chemical properties of P in fertilizers and manures to propose the minimizing, neutralizing, replacing strategies to reduce at the source.

Keywords: Dhidhessa; Nutrient load; Sub basins load; Surface runoff; Transport mechanism

DOI: http://dx.doi.org/10.3126/ije.v8i3.26614

Introduction

Good quality water has become an expensive item, because many water sources have been polluted by waste coming from various point and non-point sources. This leads to declining quantity of water sources so that the sources could not meet the ever growing need. Nutrient enrichment of a stream from agricultural activities is one of the most fundamental causes affecting the management of river basins on a worldwide basis (Neitsch et al., 2005).

Thus, sustainable management of water resources has been a raising demand recently throughout the world (Tilman, 2007). In order to achieve water quality management goals, evaluations of nutrient and pollution loads from various sources are compulsory. Phosphorus (P) compounds are among the nutrient loads annexes. Regardless of its importance for plant and animal growth and maintaining crop and animal production, P can increase the biological productivity of surface waters by accelerating eutrophication. Eutrophication is an accumulation of excessive nutrient mainly phosphorus and nitrogen in slow moving water resulting an excessive algal growth in receiving water bodies (Abudu et al., 2012). This process can be accelerated by human activities that increase nutrient loading rates to water (Sharpley et al., 2003). This can create much water supply problems for communities depending on these fresh water bodies due to threats to public health when the affected water body is used for the communities' water supply, fishing or recreation purposes. In fact, water supply based on these water resources may in a long-run becomes unsustainable due to water quality deterioration.

Ethiopia has embarked on extensive water resources development plan since few years back. Though the development activities encompass all major river basins of the country, the huge agricultural and hydroelectric power potentials in the Abay (Upper Blue Nile) Basin have attracted considerable attention (Adgolign et al., 2016). There are currently a number of water resources development projects under the construction and planning phases in Didhessa sub-basin of the Abbay Basin. Although the Dhidhessa sub-basin study area provides the largest amount of the Blue Nile River flows and the agricultural practices in the catchment dominantly practiced with using inorganic and organic fertilizer. However, Dhidhessa sub-basin is less studied areas (Sima et al., 2011).

A sustainable agriculture requires a delicate balance between crop production, natural resources uses, environmental impacts, and economics. To properly understand environmental risks and manage nutrient pollution in watersheds, it is necessary to have knowledge of the transport mechanism and loading quantity to the discharge points. Commonly, water quality assessment at the watershed scale is accomplished using two techniques: (a) watershed monitoring and (b) watershed modelling (Molina et al., 2017). As continuous water quality monitoring is extremely expensive, time consuming and spatially impractical at catchment level, modelling has become a primary technology for analysing diffuse source pollution. A model would be used to assess pollutant loadings allowed to be discharged in to receiving water bodies when measured data are insufficient to detect the pollution within catchment (Taffese et al., 2014). This is because models provide quick and cost-effective assessment of water quality conditions, as they simulate hydrologic processes, which are affected by several factors including climate change, soils, and agricultural management practices (Soni and Udani, 2017). Thus, the present study focuses on the modelling of phosphorous transportation pathways and loading into Dhidhessa sub-basin of Abay basin.

Materials and Methods

Description of study area

The study area is situated in Abay/Nile River basin to the south direction called as Dhidhessa sub-basin, which is situated in the Oromiya National Regional State, southwest Ethiopia. It is geographically located between 35°48'14" and 37°03'57" E longitudes and between 7°42'06"and 9°12'29" N latitude (Figure 1).

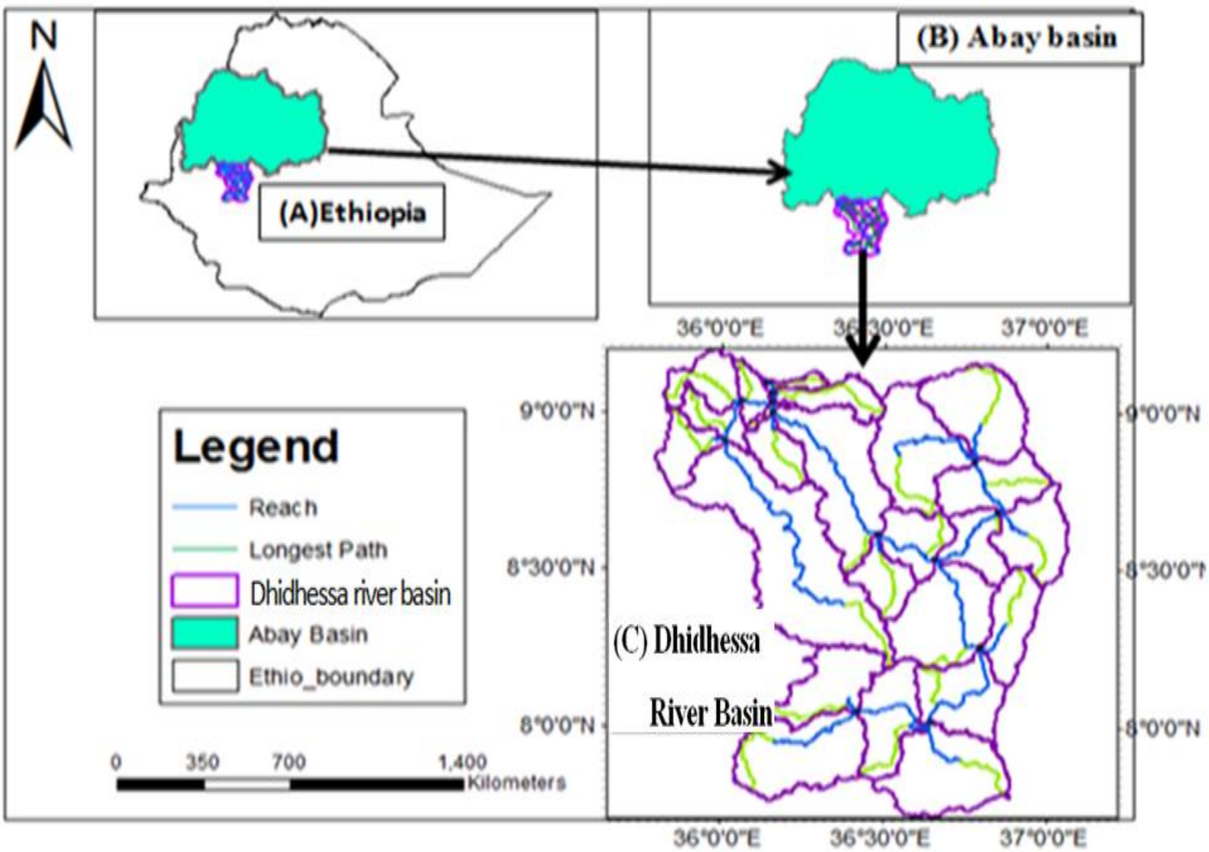

Figure 1: Location of the study area

The highlands of the basin are composed of basic rocks, mainly basalts, while the lowlands are mainly composed of metamorphic rocks and sedimentary rocks of old geological ages. The major soils of the basin are Leptosols, Alisols, Nitisols, Vertisols, Cambisols, and Luvisols. Most of these soils are reddish brown in colour, clay to clay loam in texture, well drained and very deep. The majority of the area is characterized by a humid tropical climate with heavy rainfall and most of the total annual rainfall is received during one rainy season (June, July and August) called kiremt. Dhidhessa watershed sub basin has a number of tributaries that contributes its flow to Blue Nile River which made its flow volume the largest of other sub-basin to Nile River. The maximum and minimum temperature varies between 21.1 – 36.5^{0}c and 7.9 – 16.8^{0}c, respectively. The mean annual rainfall in the study area ranges between 1509 mm in the southern to 2322 mm in the northern catchments.

The study was a kind of a longitudinal research design using secondary data for simulation of annual phosphorus load by ArcSWAT2012 software during 2000 – 2010. Later, the model efficiency was calibrated and validated with stream flow, since the overland flow was the major transport agent for nutrients and there were no recorded nutrients data during study periods.

The major data types used include Digital Elevation Model, meteorological, hydrological, soils, land use/land cover and phosphorus load data. All the temporal data were gathered from Ethiopia National Metrological Agency and from Ministry of Water, Irrigation and Electricity.

The spatial data were obtained from Ministry of Water, Irrigation and Electricity of Ethiopia. All the secondary data were prepared for SWAT input. Missed rainfall and other metrological data were filled before using for simulation. Land use and soil data adjustment was done to fit SWAT database and the prepared land use/ land cover and soil were given as input to the model data of the SWAT to describe the HRU of the watershed.

The main tools used for input data preparation and analysis are: ArcGIS10.1, ArcSWAT2012, SWATCUP 2012. ArcGIS10.1 was used for creating and using maps, managing geographic information in a database and execution of GIS processing tools such as clipping, overlay, and spatial analysis. SWAT2012 model was used for setting up the study project, delineating the study area, analysing HRU, writing all input tables, editing inputs and simulating all inputs. Dhidhessa watershed was delineated to 25 sub-basins and 253 Hydrological Response Units (HRUs), determined by unique intersection of the LULC, slope and soil (Figure 2). SWAT predicts the land phases of the hydrologic cycle separately for each HRU and routes to obtain the total loadings of the catchment. Since there was no measured data of phosphorus at national level in Ethiopia catchment, the calibration and validation of the model for phosphorus were not conducted. Instead the model was calibrated and validated by flow as hydrological process had strong impact on nutrient loading and transport pathways. SUFI-2 was used to carry out calibration and validation of the model.

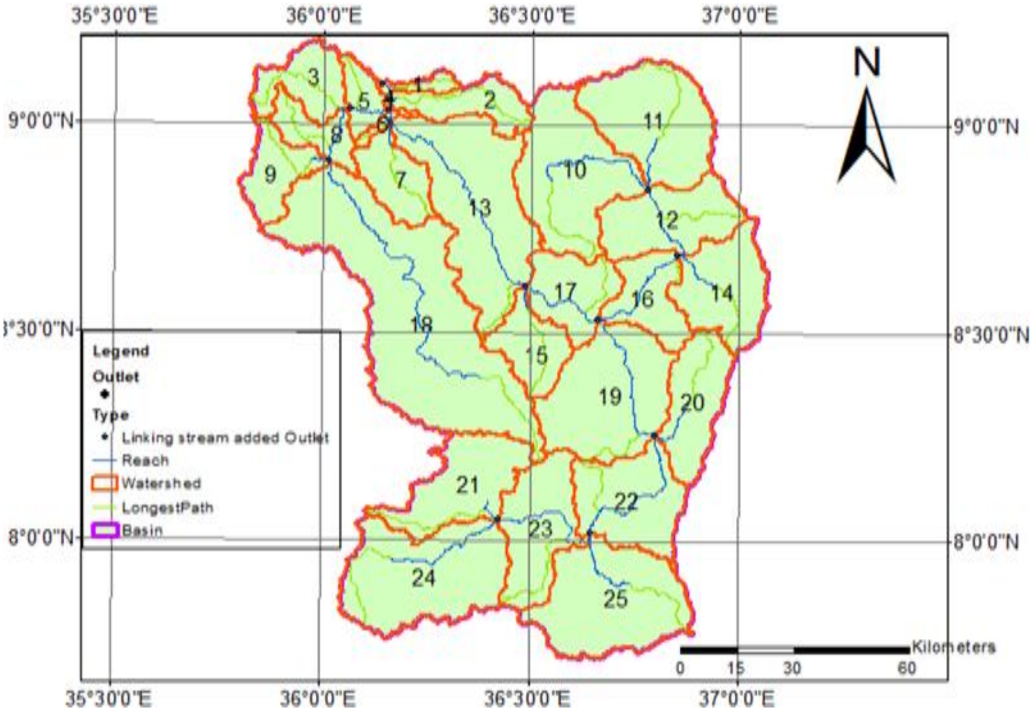

Figure 2: Delineated Dhidhessa watershed and sub-basins

Soil and Water Assessment Tool Model description

Soil and Water Assessment Tool (SWAT) has been already validated in many countries of the world for a variety of applications in hydrologic and developed for simulation and to predict the impact of land management practices on water, sediment and agrochemical yields in large, complex watersheds with varying soils, land use and agricultural conditions over extended time periods (Neitsch et al., 2005). SWAT was selected for its better suited for the accurate simulation of spatial and temporal patterns in surface runoff, sediment, chemicals, and nutrients and their associated transport pathways (Borah and Bera, 2004).

Phosphorus Simulation Processes in SWAT Model

The major phosphorus transformation processes include mineralization of fresh organic P and soil organic matter, and decomposition and immobilization. A surface runoff element is a key component of a hydrological transport model, for assessment of sediment, fertilizer, pesticide and other chemical contaminants (Soni, 2018). SWAT requires estimates for the initial mineral phosphorus and organic phosphorus concentrations in the upper soil layers for phosphorus simulation (Neitsch et al., 2005). Phosphorus transport processes simulated in SWAT include surface runoff in solution, losses of phosphorus attached to sediment and leaching of soluble phosphorus. The amount of soluble phosphorus removed in runoff is predicted using solution phosphorus concentration at the top 10 mm of soil, the runoff volume and a partitioning factor. Sediment transport of phosphorus is simulated with a loading function as described in the SWAT theoretical documentation (Neitsch et al., 2005) . Plant use of phosphorus is estimated using the supply and demand approach. Losses of phosphorus in base flow and subsurface losses are considered in calculating total loads.

Two methods for goodness-of-fit measures of model predictions were used during the calibration and validation periods, these numerical model performance measures are coefficient of regression (R^2) and the Nash-Sutcliffe simulation efficiency (NS).

Results and Discussion

Stream Flow Calibration and Validation

Calibrating and validating stream flow were used as model performance evaluation, and then simulated phosphorus was analyzed. The stream flow calibration results showed good agreement between measured and predicted flow at the station near Arjo Dhidhessa of sub-watershed with an R^2 and NSE = 0.84 and 0.65, respectively. The stream flow validation results showed that the model performance during validation was satisfactory with R^2 = 0.8 and NSE = 0.54. Based on the flow calibrated and validated results, the phosphorus load and transport pathways, and hydrologic impact and their correlation with each other were widely and briefly discussed starting from next title of phosphorus transport pathways.

Phosphorus Transport Pathways

Phosphorus loss from agricultural lands is commonly controlled by the hydrologic events, such as surface runoff. The runoff can transport phosphorus as sediment bound (particulate) or dissolved form. SWAT monitors six different pools of phosphorus in soils, three pools in organic forms of phosphorus while the other three pools are; fresh organic phosphorus associated with crop residue and microbial biomass, and active and stable organic phosphorus pools linked with soil humus. Soil in organic phosphorus is divided into solution, active and stable pools.

Phosphorus solubility is limited in most environments and combines with other ions to form a number of insoluble compounds that precipitate out of solution. These characteristics enhance to build up of phosphorus particulate near the soil surface that is readily transport by a surface run off. Surface runoff is the major mechanism by which phosphorus is exported from the most catchments. Also the positive correlation was found between runoff and total phosphorus loss (r^2 = 0.89, *P*-value = 0.001) on Gilgel Gibe watershed (Adela et al., 2015). Folle (2010) also demonstrates that total phosphorus loss is strongly correlated with total sediment yield with an R^2 value of 0.69 on Le Sueur river watershed of Minnesota River Basin. The fertilized areas would also have great contribution to surface runoff phosphorus concentration (Sharpley and Syers, 1983).

Phosphorus Loading

Organic P

The study analysis shows that, the annual average loss of organic P in the Dihdhessa catchment was 8.48 kg ha^{-1} $year^{-1}$ with 41.46% coverage of the other form of P loss. The maximum organic form of P loaded from the catchment was quantified around 9.26 kg ha^{-1} $year^{-1}$ with 10.02% which was loaded in year 2005. Minimum organic P load observed on the year 2003 was about 4.44 kg ha^{-1} $year^{-1}$ which had coverage of 4.81% of total P loaded during the year 2000 – 2010. The major facts behind the rise of organic P load in the year 2005 was the generation of high amount of surface runoff and sediment load resulted from high altitude area around the edge of the catchment boundary. P loss from fertilized areas can be separated into two components, P contributed directly by fertilizer, and indirectly by the higher P concentration in the soil due to past fertilizer application (Sharpley et al., 2001; Ule'n and Mattsson, 2003).

Soluble P

Soluble P was the smallest form of P load in the area when compared to other form of nutrient p load. The average annual soluble P loss in Dhidhessa catchment was identified as 0.02 kg ha-1 year-1 during study year of 2000 – 2010 and had the coverage of 0.09% of the other form of P loss. A maximum amount of soluble P was loaded in the year 2009 which was around 0.025 kg ha-1 year-1 with a minimum amount in 2003 which was about 0.01 kg ha-1 year-1. The main reasons behind the increment of soluble P in the year 2009, largely was due to high surface runoff and the rate of applications of the fertilizers and the usage of additional manures/residues and corresponding mismanagement might be facilitating the rise of soluble P.

Sediment P

Sediment P is a mineral form of phosphorus that attached to sediment and transported by a surface runoff towards the reach. The annual average sediment P loss in the Dhidhessa catchment was identified as 11.85 kg ha^{-1} $year^{-1}$ with coverage of 58.54% of the other form of P loss. The high amount of sediment form of P was loaded in the year 2002, which holds around 12.96 kg $ha^{-1}year^{-1}$ and the minimum amount of sediment P exported was in 2003 year, which was quantified as 6.32 kg ha^{-1} $year^{-1}$. This was happened in the 2002 year with a high amount of surface runoff and large magnitude of sediment. In general, the surface runoff was prevalent mechanism of sediment load and P load. The areas that have steep slopes, high surface runoff and high sediment losses contributed for high loss of sediment P (Folle, 2010).

Total P

The study results indicate that the three main pathways through which mobilized phosphorous can reach surface waters are surface runoff, subsurface flow and vertical flow to the ground water. The study also confirms total phosphorous transport in Dhidhessa river basin arises when a significant source of phosphorous has good hydrological connectivity to surface water. Based on the literature review and hydrologic correlation of phosphorous, sediment yield and physical condition of Dhidhessa basin, the findings of this study gave directive implication that, the maximum load of total P was in year 2005 which was about 22.22 kg ha^{-1} $year^{-1}$ and the minimum load was obtained in 2003 year with the amount of 10.77 kg ha^{-1} $year^{-1}$ (Table 1). The responsible causes for the rise of total P load in the year 2005 and decrease in the year 2003 was directly associated with increment and decrement of surface runoff and sediment load.

Table 1: Annual loads of phosphorus loss in the Dhidhessa catchment (2000 – 2010)

Year	Org. P (kg ha^{-1})	Sol. P (kg ha^{-1})	Sed. P (kg ha^{-1})	Total P (kg ha^{-1})
2000	8.43	0.02	11.68	20.13
2001	8.35	0.02	11.89	20.25
2002	9.2	0.02	12.96	22.18
2003	4.44	0.01	6.32	10.77
2004	9.2	0.02	12.91	22.12
2005	9.26	0.025	12.94	22.22
2006	9.03	0.02	12.72	21.77
2007	8.9	0.02	12.58	21.5
2008	8.7	0.02	12.35	21.07
2009	8.92	0.02	12.58	21.53
2010	8	0.02	11.37	19.38
Avg.	8.48	0.02	11.85	20.27
Sum	92.44	0.19	130.31	222.93
Median	8.90	0.02	12.58	21.50
SD	1.37	0.00	1.91	3.29
%	41.46	0.09	58.54	

Based on scientific facts and consideration, the study investigation indicated that phosphorus was exported from the catchment in the form of organic phosphorus attached to sediment and transported in the form of particulate. The particulate organic P forms of transport mechanism was accounting to an average of 8.48 kg ha^{-1} $year^{-1}$ that holds 41.46%. Sediment attached P (adsorbed) accommodates around 11.85 kg ha^{-1} $year^{-1}$ of transport path holds 58.45%. The soluble P which was 0.02 kg ha^{-1} $year^{-1}$ the least transport mechanism accounts only 0.09%. For the all forms of P, surface runoff was the dominant means of transport agent. The reason behind the high annual loss of total P (organic P and sediment P = 99.91%) was due to the mineralization of organic P from soil humus, crop residue and microbial biomass as the study area was characterized with highly cultivated location and tillage has taken through the year. Folle (2010), also justified soil humus, crop residue, microbial biomass and agricultural practice highly increase total P load.

Spatial Distribution of Phosphorus on Dhidhessa Sub-basin

Organic P

At sub-basin level, the three highest amount of organic P was initiated from sub-basin numbers 17, 23 and 24. The values were grouped into three ranges and the spatial distribution was shown in (Figure 3). The possible main cause for high loading of org P in sub basin was rise of slope (> 12%) which exposed the area to high runoff down to the slope. Steep slopes were the main causes of high nutrient load in the agricultural catchment as the soil, fertilizers and animal manure are highly transported with overland flow (Sharpley et al., 2003). The study demonstrated that- the area with high slope and highly cultivated with application of fertilizer were identified a possible area of high organic P loading. Central and lower tips of the study areas were characterized with highly cultivated, steep slope from where the organic P was highly loaded (Figure 3).

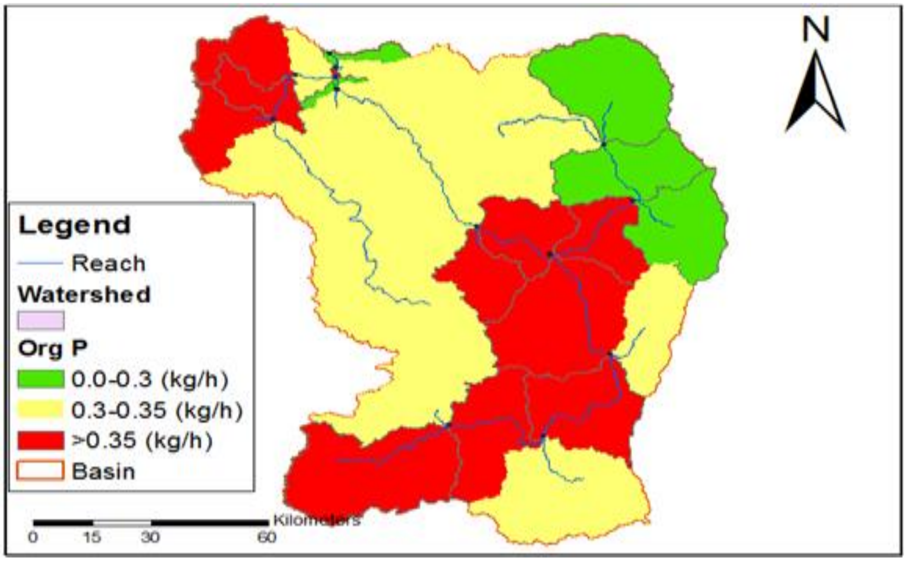

Figure 3: Sub-basins based spatial distribution of organic P

Sediment P

Sub-basin number 17, 23 and 3 were the top three main sources of sediment P load as compared with the rest of sub-basins respectively. Sediment P losses occurred in the particulate or sediment bound form (Folle, 2010). The middle parts across the Dhidhessa River from upstream to downstream were loaded with high sediment (P) as the area has high load of sediment and land use land cover management were poorly handled (Figure 4).

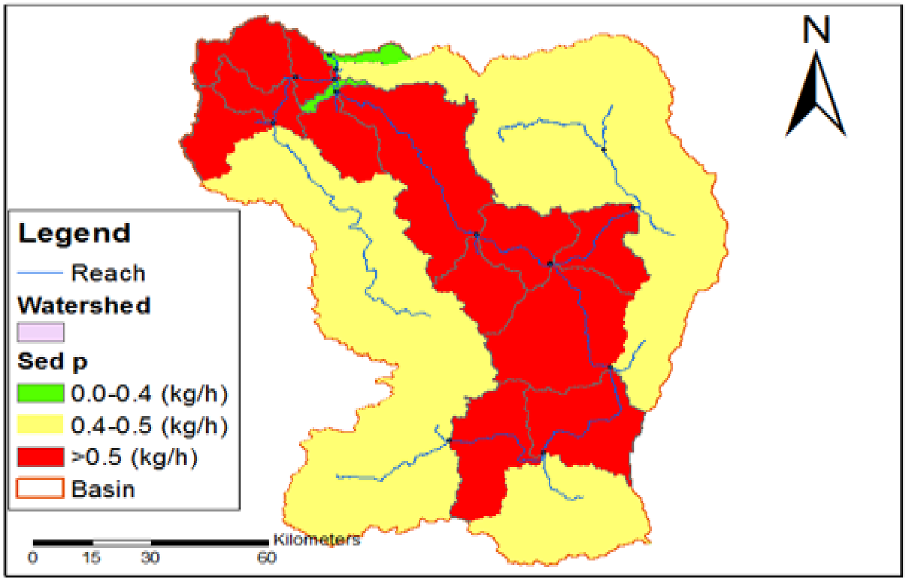

Figure 4: Sub-basins based spatial distribution of sediment P

Total P

According to the study results, the top three sub-basins responsible for high total P load were sub-basins number 17, 23 and 8, respectively relative to the rest sub-basins. Dhidhessa sub-basin has high amount and intensive rainfall and runoff with P application amount and land management practice such as tillage which leads to high amount of total P loss in the catchment. Folle (2010) concluded similar findings as phosphorus is affected by several factors, including the occurrence, amount and intensity of rainfall and runoff, P application amount and timing, and land management practices such as tillage. Map of spatial distribution was shown in (Figure 5).

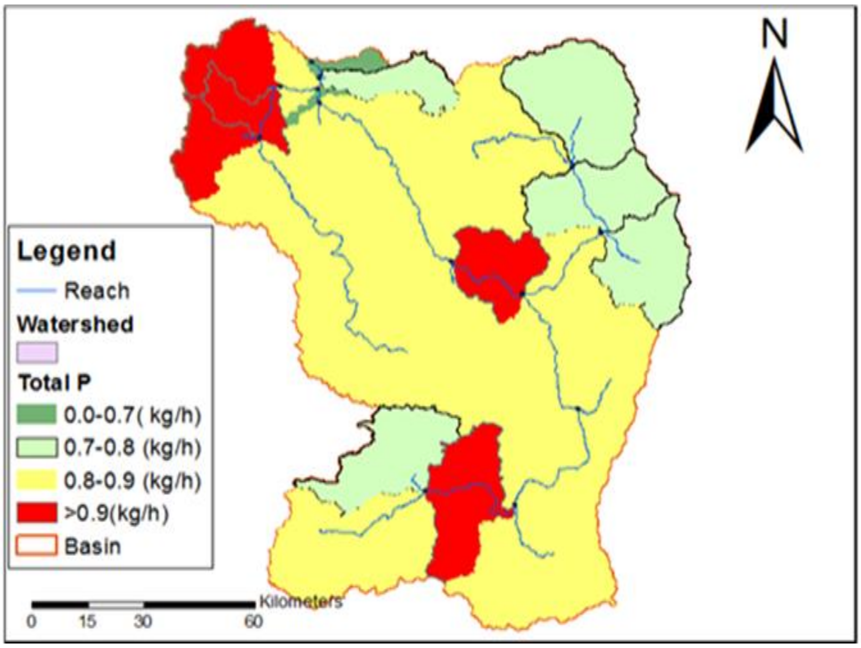

Figure 5: Sub-basins based spatial distribution of total P

Conclusion

The SWAT model was used to simulate P dynamics in the Dhidhessa sub-basins and P loads and transport pathways were identified. The model was calibrated and validated by stream flow for model performance evaluation. The stream flow calibration results show good agreement between measured and predicted flow with an R^2 and NSE = 0.84 and 0.65, respectively. The stream flow validation results show the model performance during validation was satisfactory with R^2 = 0.8 and NSE = 0.54. The three main pathways through which mobilized phosphorous reach the water resources were surface run off, subsurface flow and percolation to the ground water.

Phosphorous was dominantly transported via surface runoff. It is also found that, nutrient dynamics and hydrological process are systematically linked. The annual average total P loss in the Dhidhessa catchment was identified as 20.0 kg ha^{-1} $year^{-1}$ during (2000 – 2010). The sub-basins 17, 23 and 3 were identified as the three highest loading area of total phosphorous respectively in the study catchment. The main factors for loss of phosphorus were the occurrence, amount and intensity of rainfall and runoff, P application amount and timing, and land management practices. Nutrients, sediments and agricultural chemicals are mainly loaded to the water resource via surface runoff.

Acknowledgments

The authors are grateful to Ethiopian Road Authority, ERA, for financially sponsoring the MSc program hosted by Jimma Institute of Technology. We also extend our thanks to Jimma Institute of Technology for giving the opportunity to the corresponding author to attend his MSc study at the institute.

References

Abudu, S., Cui, C. L., Saydi, M. and King, J. P., 2012. Application of snowmelt runoff model (SRM) in mountainous watersheds: A review. Water Science and Engineering, 5(2), 123–136. https://doi.org/10.3882/j.issn.1674-2370.2012.02.001

Adela, Y., Alemayehu, E. and Adugna, T., 2015. Seasonal Variability of Flow and Nitrate Flux in Gilgel Gibe River, South West, Ethiopia. Hydrology Current Research, 7(1), 1–5. https://doi.org/10.4172/2157-7587.1000221

Adgolign, Bekele, T., Srinivasa, R. G. V. R., and Yerramsetty, A., 2016. WEAP modeling of surface water resources allocation in Didessa Sub-Basin, West Ethiopia. Sustainable Water Resources Management, 2(1), 55–70. https://doi.org/10.1007/s40899-015-0041-4

Borah, D. K., and Bera, M., 2004. Watershed‒scale hydrologic and nonpoint‒source pollution models: review of applications. Trans. ASAE, 47(3), 789-803.https://webcache.googleusercontent.com/search?q=cache:gg_pwR5gG88J:https://www.isws.illinois.edu/iswsdocs/journals/BorahTransASAE47-3-789803.pdf+&cd=1&hl=en&ct=clnk&gl=et&client=firefox-b-d

Folle, S. M., 2010. SWAT Modeling of Sediment, Nutrients and Pesticides in the Le-Sueur River Watershed, South Central Minnesota Ph.D. Dissertation, University of Minnesota, Minneapolis, Minnesota.

Molina,N. E., Andersen, H. E., Nielsen, A., Thodsen, H., and Trolle, D., 2017. The impact of the objective function in multi-site and multi-variable calibration of the SWAT model. Environmental Modelling and Software, 93, 255–267. https://doi.org/10.1016/j.envsoft.2017.03.018

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., and Williams, J. R., 2005. Soil and W Ater a Ssessment Tool

Theoretical Documentation. Blackland Research Center, Texas Agricultural Experiment Station and Grassland, Soil and Water Research Laboratory, Temple, TX.

Sharpley, A. N., Daniel, T., Sims, T., Lemunyon, J., Stevens, R., and Parry, R., 2003. Agricultural Phosphorus and Eutrophication second edi. Retrieved from http://ddr.nal.usda.gov/dspace/bitstream/10113/26693/1/CAT30907360.pdf

Sharpley, A. N., Mcdowell, R. W., Weld, J. L., and Kleinman, P. J. A., 2001. Assessing Site Vulnerability to Phosphorus Loss in an Agricultural Watershed. Journal of Environmental Quality, 30(6), 2026 -2036. https://dl.sciencesocieties.org/publications/jeq/abstracts/30/6/2026

Sharpley, A. N., and Syers, J. K., 1983. Transport of phosphorus in surface runoff as Influenced by liquid and solid fertilizer Phosphate addition*. Water, Air, and Soil Pollution, 19, 321–326. https://doi.org/0049-6979/83/0194-0321500.90.

Sima, Admassu, B., and Bishop, P. K., 2011. Flow Regime and Land Cover Changes in the Didessa Sub-Basin of the Blue Nile River, South – Western Ethiopia, M.Sc. thesis, Department of Aquatic Science and Assessment, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Soni, H.B., 2018. Hydrological Transport Modeling: A Software Paradigm. Inspire. (ISTAR E-Newsletter). 1 (1): 16-22.

Soni, H.B., and P.M. Udani., 2017. Environmental Modeling: A Software Approach. International Journal of Information and Computing Technology. 6 (1): 10-17. ISSN: 0976-5999

Taffese, T., Tilahun, S. A. and Steenhuis, T. S., 2014. Phosphorus Modeling, in Lake Tana Basin, Ethiopia. Journal of Environment and Human, 2, 47-55. https://doi.org/10.15764/eh.2014.02007

Tilman, D., 2007. Resource competition and plant traits: A response to Craine et al. 2005: Forum. Journal of Ecology, 95 231–234.https://doi.org/10.1111/j.1365-2745.2007.01201.x

Ule´n, B., and Mattsson, L., 2003. Transport of phosphorus forms and of nitrate through a clay soil under grass and cereal production. Nutrient Cycling in Agroecosystems, 65, 129–130. https://doi.org/https://dx.doi.org/10.1023/A:1022133031584