SWAT for Land Vulnerability Assessment in Wonogiri Dam Catchment

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SUMMARY

Wonogiri Dam is one of the most important reservoir in Indonesia that plays a key role in flood prevention, irrigation, hydro energy and tourism. However, this multi-purpose dam face a severe silting because of sedimentation from soil erosion and run-off in its catchment. During 30 years period, the capacity of the dead storage decreases significantly less than 40 % and it is predicted that the age of this dam less than 20 years from now. Therefore, identification of soil erosion-prone locations and estimate quantitatively of soil loss with reliable accuracy are important for planning and applying suitable soil and water conservation practices as well as controlling soil erosion. It is also important to consider the source of erosion by using vegetative conservation treatment, which can have a positive impact on the long-term preservation of nature.

Moreover, the development of a decision support tool in support of catchment management plans is required that is based on scientific research in land use change and the effect of rainfall intensity on sediment-yield. This plan includes hydrological models and soil and water conservation measures, as can for instance be simulated with the Soil and Water Assessment Tool (SWAT). The main aim of this thesis is to locate and identify areas that are prone to soil erosion in the Wonogiri Dam catchment using a SWAT model and also to estimate runoff and soil loss potential as well as map the vulnerable areas. This map is important for integrated soil erosion reduction planning programme.

This study concluded that the severity of the situation in the Wonogiri Dam catchment especially from Keduang watershed is reflected in the model's estimation of soil erosion. An average estimated soil loss of 7.9 t/ha from the land surface of the Keduang watershed was determined for the period from 2007 to 2016, which is below the soil formation rate in the watershed. However, areas of severe erosion are dominated in the north upland sub watersheds where the slopes are steeper than in the southern part of the watershed. Extreme soil erosion rates of more than 60 t/ha/year are estimated for many sub watershed of the Keduang watershed.

In order to determine the impact of topography, land use and soils on the estimated erosion, several HRUs were selected and average monthly soil loss was compared. It was determined that slope is the most dominant factor for erosion, followed by land use, rock fragment and soil type. However, for future studies, it is important to include crop species in the SWAT model because most published studies on erosion modelling in Keduang watershed have so far not been including specific crops. In combination with the use of a detailed land use map, this might improve the accuracy of model predictions significantly.

Well maintained reverse side bench terraces were implemented and simulated in SWAT by setting the USLE_P factor to 0.2 for agricultural land and rice field sloping more than 8 %. This practice is already used in the Keduang watershed and parts of Wonogiri Dam catchment. The model output suggests that this conservation practice could decrease average erosion rates from the land surface (based on HRU) of the basin from 7.9 to 3.2 t/ha. Increasing efforts in soil conservation are in any case essential to improve the livelihood of the Wonogiri Dam catchment farmers by improving food security.

DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Signed...

Date.........11 July 2018...

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1. Problem Statement

Soil erosion, as a form of land degradation, is generally caused by runoff through rainfall. Approximately more than 15 % of the soil in the world is vulnerable to erosion. In general, human activity in the land has a negative impact on the soil around 1,094 million Ha, of which 751 million Ha is highly vulnerable (Lal 2003). Moreover, Walling and Fang (2003) described that 43 % of forest area be affected by deforestation, 29 % suffer from overgrazing and 24% have a negative impact from the agricultural mismanagement as well as 4% facing over-exploitation of natural vegetation. Human intervention on land is an example of the destructive activity in the natural resources, and this issue is recognized as the important role for land conservation in this century (Reich, Eswaran & Beinroth 1999). In the upland area with mountainous landscape, soil erosion often becomes the main cause of low production capacity of agriculture (Lal 2001).

Identification of soil erosion-prone locations and quantitative estimation of soil loss with reliable accuracy are important for planning and applying suitable soil and water conservation practices as well as controlling soil erosion (Shi et al. 2004). Similarly, research in erosion and sedimentation with an appropriate understanding of the physical processes are essential to improve understanding in the development of landform temporally and spatially (Wainwright et al. 2003).

One of the areas with severe soil erosion is the catchment of Wonogiri Dam. This dam plays a key role in hydro-electricity power, irrigation, fisheries and tourism as well as importantly for flood prevention (Rahman, Harisuseno & Sisinggih 2013). Moreover, this dam catchment is in the upper area of the Solo watershed, the largest watershed in Java Island, which is to be one of the most severely degraded watersheds in Indonesia (*Ministry of Environment and Forestry* 2015). This dam was built from 1978 to 1982 with the main purpose to control flood in Bengawan Solo River due to the big flood that occured in 1966 in Surakarta City. This flood inundated more than 50 % of the urban area in the city, which was up to 1 m to 2 m flooded with hundreds of victims and millions of material loss (Ruzziyatno 2015). Furthermore, due to severe deposition (sedimentation), the storage capacity of the lake is significantly decreasing and the risk of flood will automatically increase. In 2008 and 2015 the flood occurred again and the destructive impact was higher than in 1996 (Rahman, Harisuseno & Sisinggih 2013).

Although the catchment of Wonogiri Dam is one of the most affected regions, effective measures that can be used to mitigate the problem and locate the source of soil erosion, have not been taken yet. According to Rahman, Harisuseno and Sisinggih (2013) to tackle the erosion problem Government of Indonesia focus on reducing sedimentation using sediment dredging and technical measures that temporarily control sediment such as check dams. Sediment dredging from the dam is not only an expensive way but also will negative impact the environment. Therefore, it is also important to consider the source of erosion by using vegetative conservation treatment, which can have a positive impact on the long-term preservation of nature. Therefore, the development of a decision support tool in support of catchment management plans is required that is based on scientific research in land use change and the effect of rainfall intensity on sediment-yield. This plan includes hydrological models and soil and water conservation measures, as can for instance be simulated with the Soil and Water Assessment Tool (SWAT).

1.2. Research Questions

The general purpose of the research is to gain a deep understanding about soil erosion issues in Wonogiri Dam catchment. Important research questions are:

1. What is the present status of erosion in the catchment and which locations are most vulnerable?
2. Which physical properties are most influential in the modelling of soil erosion processes?

By answering the research questions, this study will improve the understanding of land degradation in the catchment.

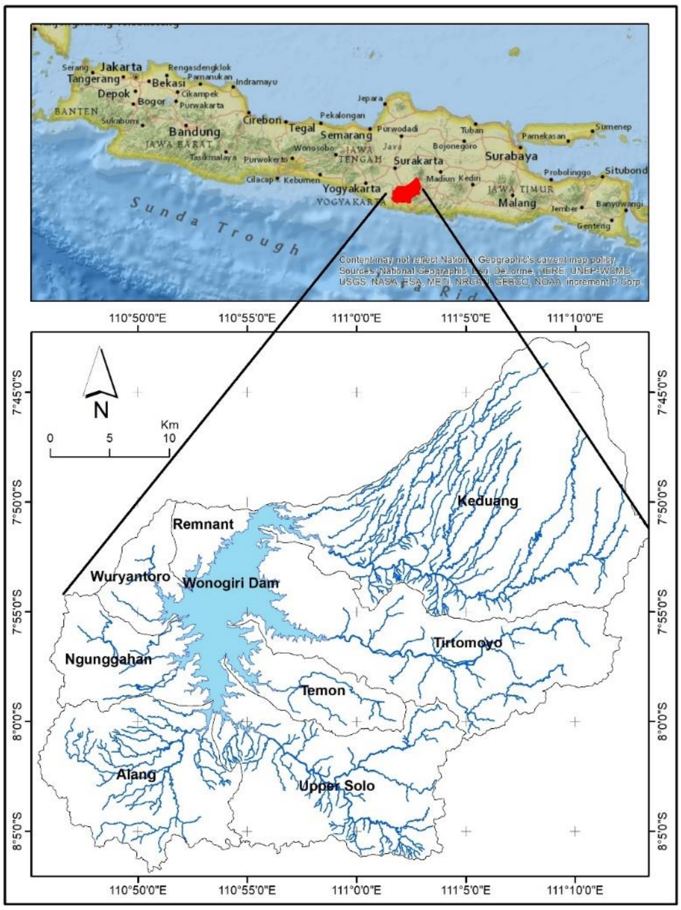

Figure 1. Location of the Wonogiri Dam and its catchment (BIG 2000).

1.3. Research Objectives

The main aim of this thesis is to locate and identify areas that are prone to soil erosion in the Wonogiri Dam catchment using a SWAT model. The source of erosion or erosion hotspots will be analysed regarding soil and land use as well as topographic characteristics, in order to locate the most vulnerable area for erosion in the catchment. The advantages and problems of erosion modelling using SWAT in Wonogiri Dam catchment will be described in the process. The specific objectives that should be gained to achieve the goal are:

a. The collection and processing of all input data which is required for the modelling SWAT.
b. Model setup, calibration and validation.
c. Analysis of erosion sensitive areas that relates soil, topography and land use.
d. Evaluation of the model.

2. BACKGROUND

The background section contains all material, which was compiled from the literature. The research area is explored regarding topography, climate, water, land use resources, soil types and geology. The soil erosion processes, as well as its governing factors for erosion in the Wonogiri Dam catchment area, are discussed. The SWAT model and the formulas that explain the process of erosion are described.

2.1. Study Area

The Wonogiri Dam catchment is located in the southern parts of Central Java (Figure 1). The catchment stretches over an area of 124,333 Ha of which 8,762 Ha are covered by Wonogiri Dam. The elevation of the catchment ranges from 116 m a.s.l. to approximately 2,015 m a.s.l. Seven rivers flow into the lake, of which Wuryantoro, Tirtomoyo, Temon, Upper Solo, Alang, Ngunggahan and Keduang (the largest sub catchment) (Figure 2). The only outflow of the Wonogiri Dam is the Bengawan Solo River.

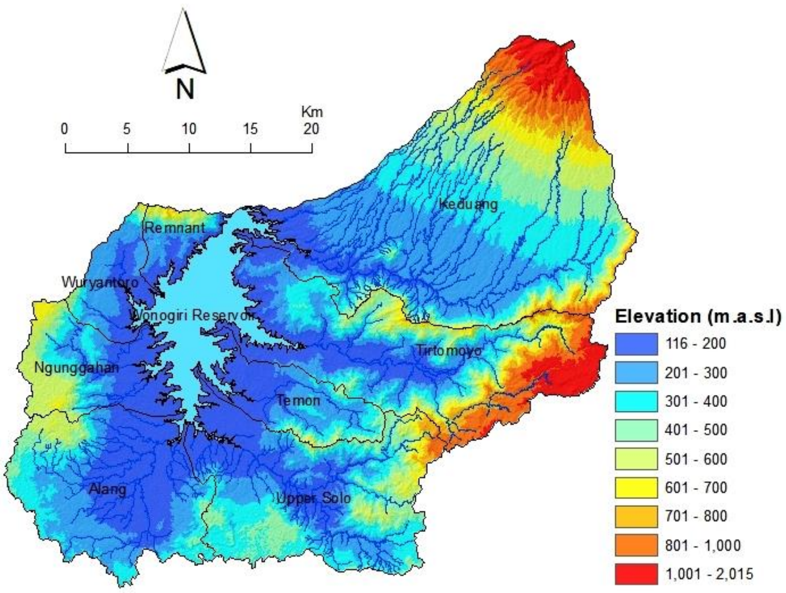

Figure 2. Topography of the Wonogiri Dam catchment.

2.1.1. Climate

The climate of the area is tropical and is subject to the tropical monsoon. The south to South-East winds prevail from July to October and dry up the basin. While in the period from November to April, the south-west to north-west winds prevail and they bring the rainy season to the catchment.

There are at least eight meteorological stations in the study area. The hydro-meteorological data used for this study was obtained from Bengawan Solo Project and Irrigation Services and from Centre of Public Work, Water Resources and Regional Planning of Bengawan Solo River. Most of the stations have data for an observation period from 1987 to 2005, although there are some interruptions. The mean values of meteorological data for each station and the location of the stations are presented in Figures 3 and 4, respectively.

The average annual temperature (1987-2005, Ngancar weather station) at the Wonogiri Dam is around 29.3 ºC. The temperature slightly fluctuates from the lowest monthly average temperature of 28.3 ºC in July to the highest monthly average temperature of 30.4 ºC in October. The temperature in the dry season (from June through August) is relatively low. Average monthly temperature is depicted in Figure 3.

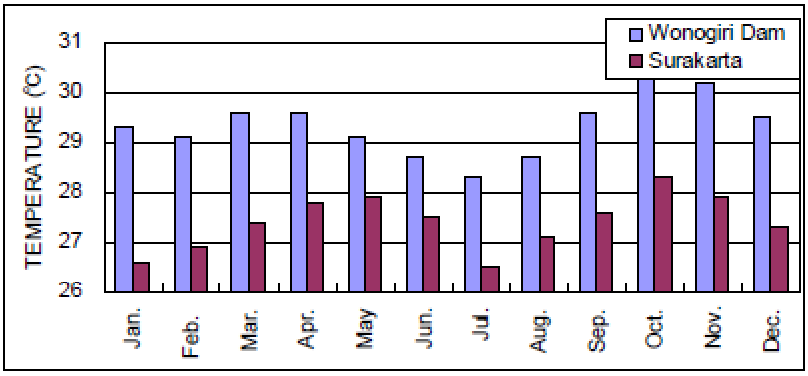

Figure 3. Mean Monthly Temperature in the Study Area (Ouchi 2007).

Average annual relative humidity (1987-2005, Baturetno weather station) is around 77.4% in the dam catchment. The lowest average monthly relative humidity is 75.4%

in October, while the highest is 79.7% in December. Average monthly relative humidity is presented in Figure 4.

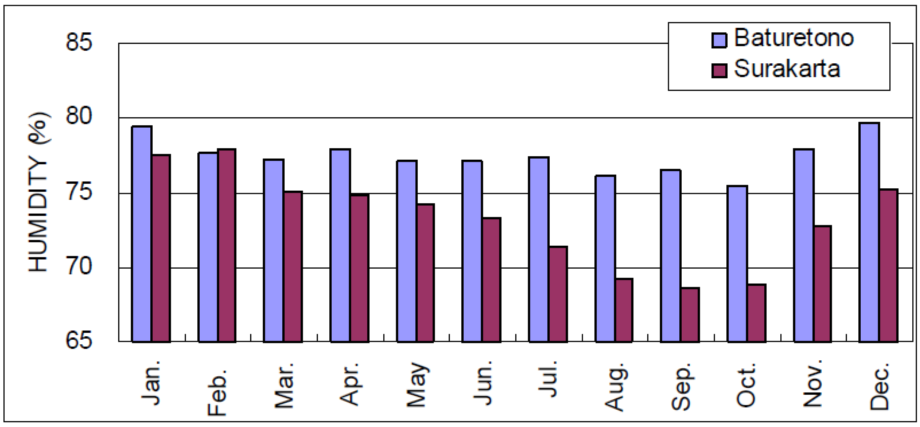

Figure 4. Mean Monthly Humidity in the Study Area (Ouchi 2007).

The pan evaporation at the Ngancar weather station is used for estimation of evaporation in the Wonogiri Dam. Annual average of actual evaporation rate at the Wonogiri Dam (1983-2005, Ngancar weather station) is 5.3 mm/day. Evaporation in the wet season of December to June is relatively lower than that in the dry season of July to November. Monthly mean daily evaporation rate is shown in Figure 5.

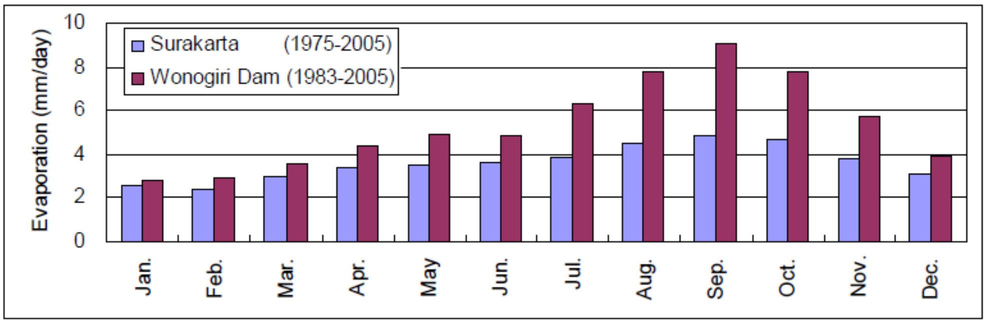

Figure 5. Monthly Mean Daily Evaporation in the Study Area (Ouchi 2007).

2.1.2. Water Resources Development

Wonogiri Dam has a function to supply the irrigation system in Wonogiri, Sukoharjo, Karanganyar, Klaten dan Sragen. It started to supply after completion of the Wonogiri Irrigation Project in 1986. Irrigation water is regulated by Wonogiri Dam weir and the Colo intake weir located about 13 km downstream of the Wonogiri Dam. The Colo intake weir was constructed in the years 1981 to 1983 to regulate the outflow of Wonogiri Dam and to stabilize the water level of the Bengawan Solo River.

Storage capacity analysis indicated that the current capacity is more than required for the irrigation of an area of 25,319 ha (Simonovic & Qomariyah 1993). Therefore, the larger size of the dam can be used for additional purposes. By optimizing the water yield, the reservoir can provide for industrial and municipal water supply as well as hydropower.

Figure 6. Colo Weir (Google Maps, 2017)

The flow regulation provided by the Wonogiri Dam weir is also important for the hydropower plant. The hydropower plant is located near the lake outlet and managed by Indonesia Power Company of Mrica Wonogiri. This renewable energy electric power plant produces 2 x 6.2 MW and supplies electricity to the Wonogiri Sub Station System (Nugroho, Widihastuti & Ary 2017). However, the hydropower operation depends on the water level of the reservoir. Unfortunately, the reduction of reservoir capacity because of sedimentation at the bottom of Wonogiri reservoir creates unstable supply for hydropower (Samosir, Soetopo & Yuliani 2015). This instability creates significant energy loss because as Wonogiri Hydropower is connected to the Wonogiri Substation system it will cause soaring of reactive power (kVAR) (Nurullita, Karnoto & Handoko 2012). Because of this problem, there are urgent needs of good planning and management as well as an operation to optimize the Wonogiri hydropower function again.

2.1.3. Land use and Land Use Dynamics

The main land use in the catchment is non-irrigated dry field agriculture (35 %) (Figure 7 and Table 1), with key crops maize (wet and dry season), cassava (wet and dry season) and bean (only dry season). Other crops include sugar cane and rice. Only smallholder farms exist in the catchment with farms sizes of 0.5 to 1 ha (Sofiyuddin 2007). The small farm sizes and low grain yields (< 2 t/ha) make additional livestock an important source of income for the farmers. Grass field comprises about 183.28 Ha, i.e. less than 1 % of the catchment. The capacity of the pasture land is not enough for the considerable livestock population.

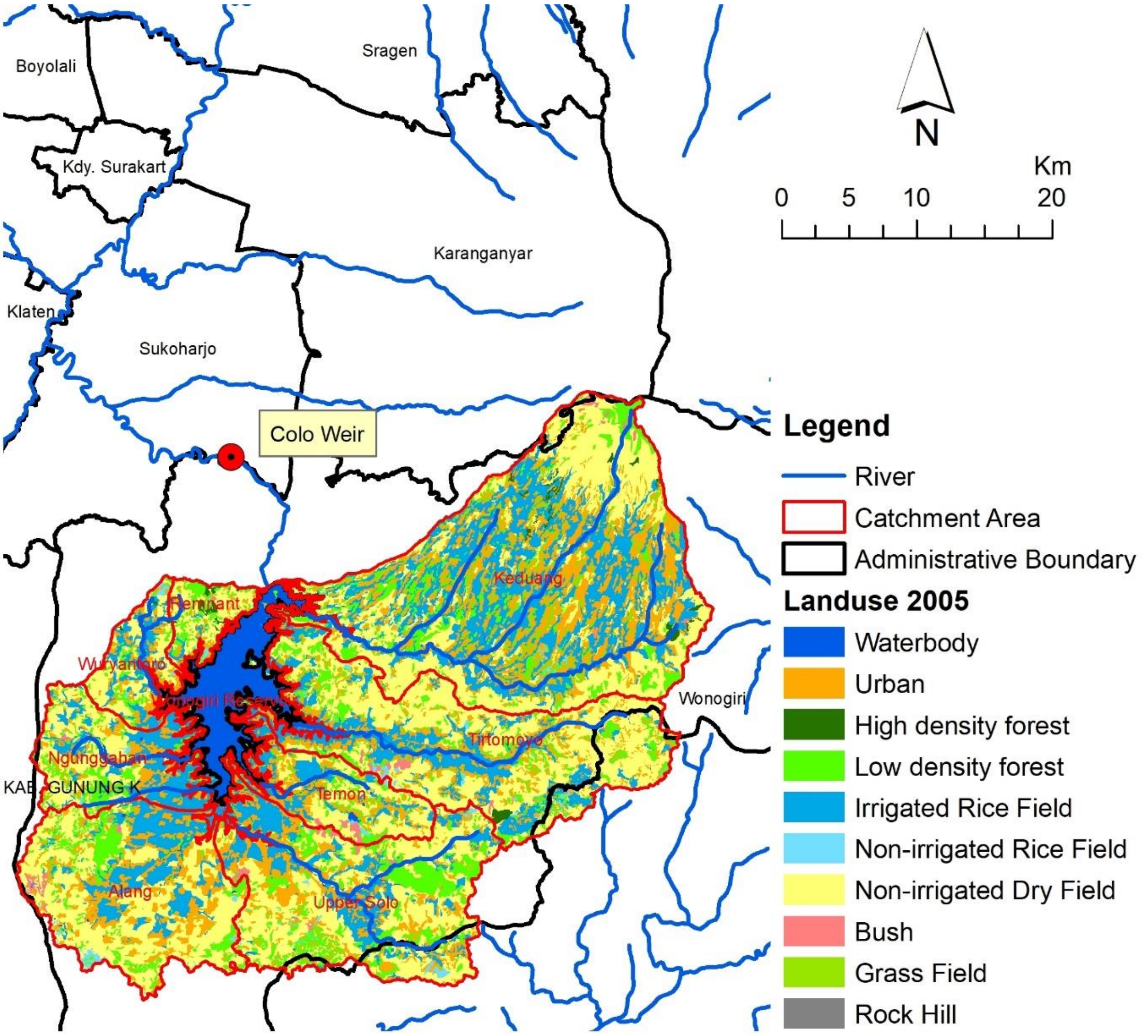

Figure 7. Landuse map of the study area based on aerial photo by BIG (2000) and ground check in 2005.

Table 1. Landuse in Wonogiri Dam catchment Area

No	Landuse	Area (Hectares)	Percentage
1	Water Body	6,832.35	5.13%
2	High-Density Forest	664.52	0.50%
3	Low-Density Forest	7,903.62	13.45%
4	Irrigated Rice Field	31,035.89	23.32%
5	Non-irrigated Rice Field	1,152.26	0.87%
6	Non-irrigated Dry Field	47,296.48	35.54%
7	Bush	1,056.23	0.79%
8	Grass	183.38	0.14%
9	Urban	26,873.23	20.19%
10	Rock Hill	97.31	0.07%
		133,095.27	

The second largest land use is irrigated rice field because rice is a staple food for people in this area, 23.32 %. Dense forest cover has been largely removed and only there is less than 1 % of the catchment area left, however, low-density forest covers 7,903 hectares. Other land use types include water body, bush/shrub and grasslands. And urban constitutes 20.19 % of the catchment.

Based on Sutrisno (2011), there has been a significant land-use change in the Keduang sub-watershed, the largest sub watershed in the Wonogiri Dam catchment area, from 1993 to 2008. The shrinking land uses are forests/shrubs, plantations/gardens, rice fields, rainfed paddy fields and other land uses. Meanwhile, land use for moorings and settlements/buildings has increased. Agricultural land conversion to non-agriculture in Keduang sub-watershed occurred during the period of 1993 - 2008 and covers 297 hectares, with an average rate of 20 hectares/year. Agricultural land converted to non-agricultural land consists of paddy fields (18 hectares), rain-fed rice fields (44 hectares), fields (66 hectares) and plantations/gardens (169 hectares). There are four patterns of conversion of agricultural to non-agricultural land in Keduang sub-watershed, i.e. from irrigated rice fields to settlements, non-irrigated rice fields into settlements, fields/settlements into settlements and gardens/plantations into settlements.

2.1.4. Soils

The main soil types in the basin are Alfisol, Entisol, Inceptisol, and Vertisol (Figure 8 and Table 2). The soil classification is based on the United States Department of Agriculture (USDA). On the first level, the USDA distinguishes between 12 'Soil Classifications' (e.g., Alfisol) based on buried soils, mineral and organic soil material (USDA 2014).

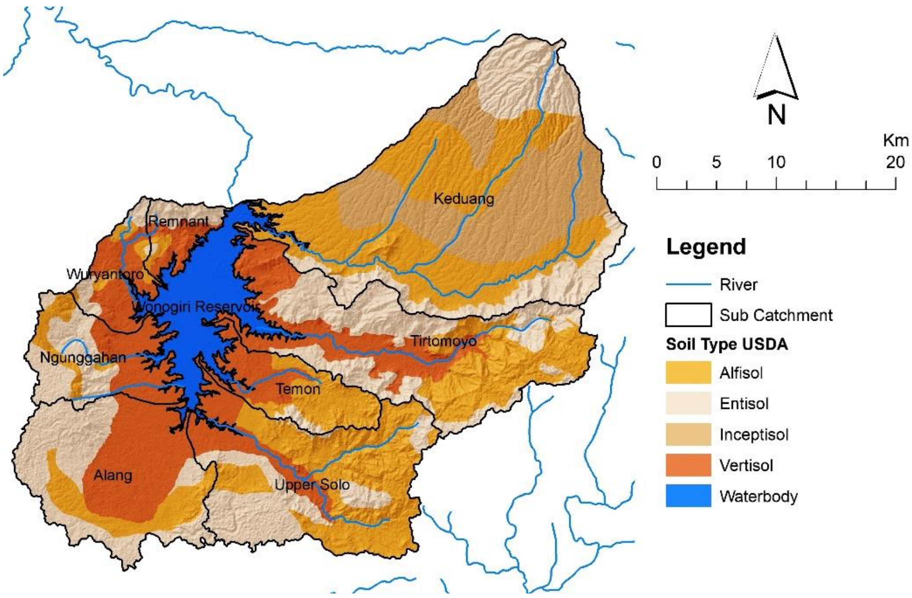

Figure 8. Soil map of the study area (Puslitanak, 1992)

Table 2. Soil types in Wonogiri Dam catchment

No	Soil Type	Area (Hectares)	Percentage
1	Alfisol	45,089.94	33.88%
2	Entisol	37,447.35	28.14%
3	Inceptisol	14,134.11	10.62%
4	Vertisol	27,661.83	20.78%
5	Waterbody	8,762.28	6.58%
	Total	133,095.50	

Alfisol: They are the most dominant soils in the catchment (> 33 %). This type of soil occurs typically under a dense forest cover and has a relatively high native fertility and clay-enriched subsoil. In this area, this type of soil is used in both forestry and agriculture, due to its ability to be more fertile than other humid-climate soils. However, when nitrogenous fertilizers are used, this type of soil has a tendency to acidify when heavily cultivated. Alfisols are moderately leaching and have at least 35% base saturation, meaning potassium, magnesium and calcium are relatively abundant (USDA 2014).

Vertisol: These soils have a high content of expansive clay known as montmorillonite. In drier seasons, this type of soil forms deep cracks because swelling and shrinking or so called self-mulching (Figure 9). It occurs when the soil material consistently mixes itself. This clayey soil is difficult to manage, as it is hard during the dry season and sticky during the rainy season. Low infiltration rates and a low plant available water content are stressors for plant growth (USDA 2014). In Wonogiri Dam catchment, they are present around the lake and in the southern parts of the catchment, around 20 % of the area.

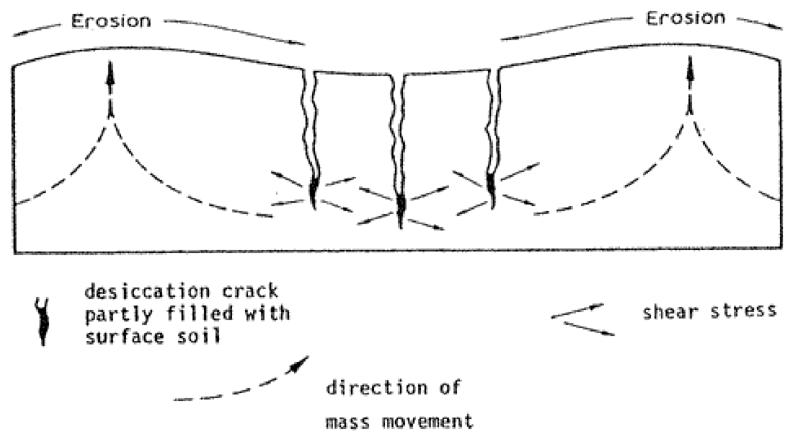

Figure 9. Self-mulching process because of cracks in common in Vertisol soil (Driessen et al. 2000).

Inceptisol: This type of soil form rapidly from alteration of parent material and have no accumulation of aluminum oxide, iron oxide, organic matter or clays (USDA 2014). Inceptisols generally occur on relatively active landscapes such as mountain slopes. In this soil, erosional processes are commonly occurring and actively exposing river valleys and unweathered materials. In the Wonogiri Dam catchment, Inceptisol occurs in the slope of mountainous northern parts of the basin.

Entisol: These soils are signified as soils that do not show any development of profile other than an “A horizon”. An Entisol has no diagnostic horizons, and most are basically unaltered from their parent material, which can be unconsolidated sediment or rock. Under cultivation, the unstable surface soil is prone to erosion (USDA 2014). In Wonogiri Dam catchment they are dominant in the hilly area of the northern and southern part of Keduang sub-watershed. This soil type covers around 28 % of the whole basin.

2.1.5. Geology and Geomorphology

The Java Island geo-tectonic and geomorphic zones form belts of West to East direction and from the South to North (Setijadji et al. 2006). There are five zones, namely the Solo zone, the Southern Mountains, the Kendeng zone, the Rambang zone and the Randublatung zone. The study area is located in the Southwest of a low hill at the base of the Lawu Mountain between Southern Mountains and Solo Zone (Figure 10).

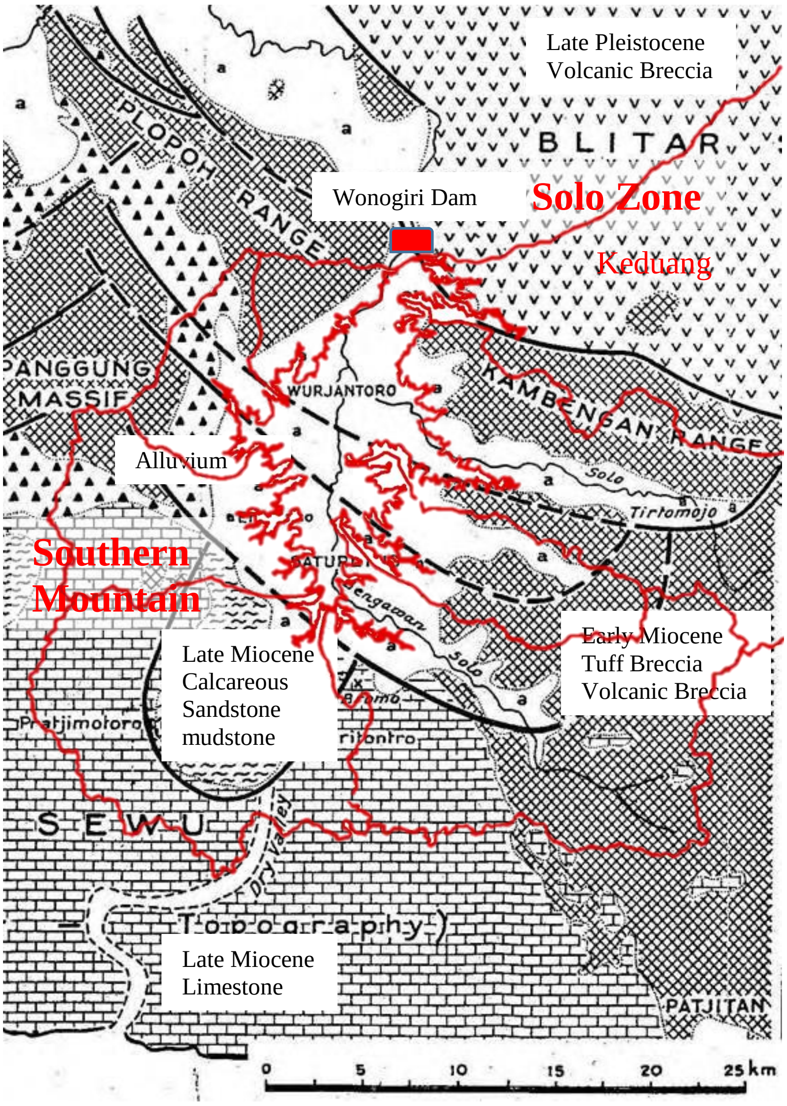

Figure 10. Geology map of the study area (Bemmelen 1970)

The Solo Zone

According to Saibi et al. (2012), the Solo zone formed from a number of Quaternary volcanic products that covers the Tertiary formations. In the Upper Pleistocene, a further warping of this tiled surface has taken place and a basin of Baturetno was formed. Due to this later warping, the drainage took a reversed course (towards the North) and became part of the catchment basins of Solo River. During the uplift the crest of the anticline, step faults sliding northwards are supposed to have been developed (Figure 11). The Southern Mountains has an anticline in the southern flank, which was tilted and elevated southward during the Quaternary. As a result, an old southward river pattern and the dry valley formed on the surface of the Southern Mountains (Figure 10).

The Southern Mountains

The Southern zone is divided into a northern mountainous part, the karst plateau and a southern part of Late Miocene limestone, and of Early Miocene tuff breccia or volcanic breccia (Kusumayudha et al. 2000).

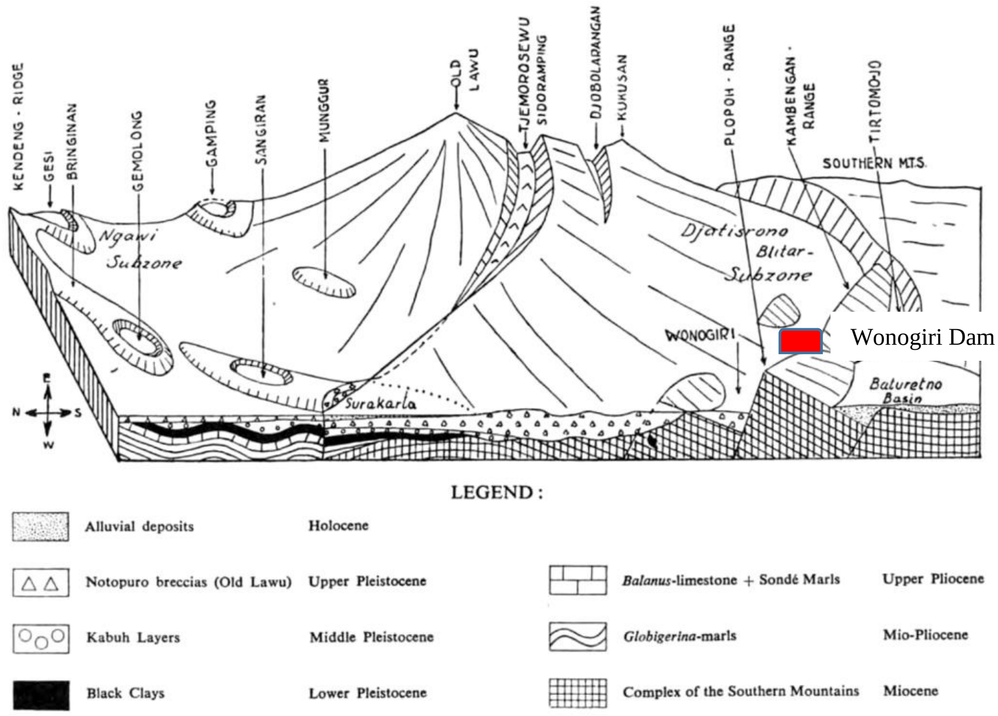

Figure 11. Schematic Profile of the Study Area (Bemmelen 1970)

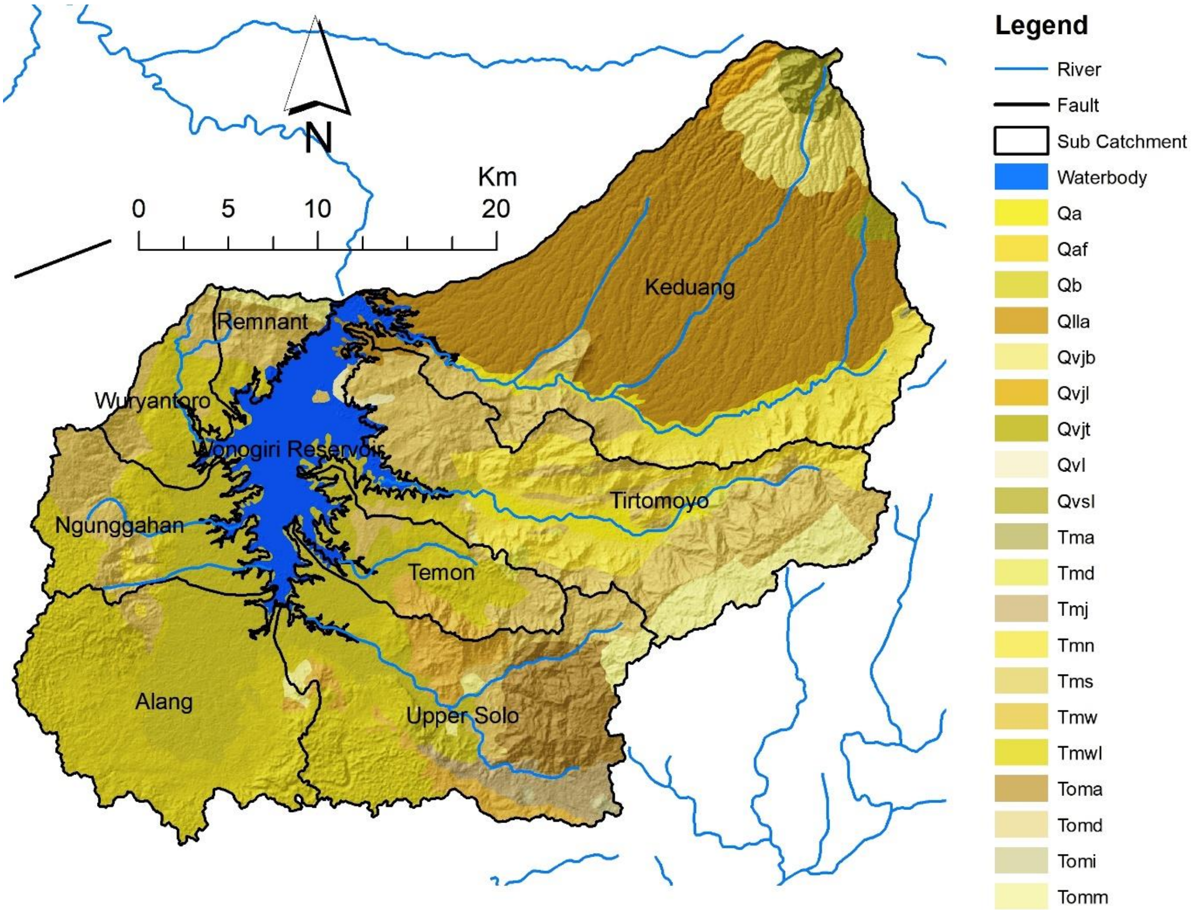

Figure 12. Detailed geology map of the study area (Sampurno & Samodra H 1991), description of the legend codes presented in Appendix 1.

The catchment of Wonogiri Dam is topographically divided into the following three mountain regions from the East to the West, and one plain area surrounding Wonogiri reservoir (Figure 12) (Sampurno & Samodra H 1991). The southern area forms the plain karst area with numerous small hills that have an elevation around 400 masl (Figure 2). Almost all of the rainwater on the plain area infiltrates into the underground, and only small part of the precipitation becomes runoff. There are several springs along the foot of the plain area.

In the Northern area, there is the Semilir mountain, the highest area of the catchment 2,023 masl, which lays on the south slope of Mt Lawu. This area forms a volcanic cone which has deep and radial V-shape valleys. The middle area is ranging in elevation from 500 to 1,200 masl and consists of steep valleys and mountains. This area has dendritic drainage features and spreading from the East to the West.

Relatively wide plains spread out around the Alang River and in the downstream area along Tirtomoyo River.

Based on Bemmelen (1970), there are four geological formations in the Wonogiri Dam catchment area, which are Semilier Formation, Ojo Formation, Wonosari Formation and Nitopuro Formation.

1) The Nglanggrangan / Semilier Formation

Semilier and Nglanggran Formation are mainly composed of lapilli tuff and volcanic breccia. However, it is difficult to distinguish the boundary of both formations in the research area. This formation is distributed from the East to the West at 500-1200 m elevation between the left bank of Keduang River and Bengawan Solo River. It has a lithology, which includes early Miocene volcanic breccia, tuff breccia and lapilli tuff composed of hard andesitic fragments and relatively soft sandy matrix. It has massive structures and partially sedimentary facies. Residual soils and weathered rocks are exposed in the cultivated area spread over the dam catchment, they are assumed to be a major source of reservoir sediment material due to their easily erosive character.

2) The Ojo Formation

Ojo Formation formed a gently inclined plane upstream of Wonogiri reservoir area and is widely developed upstream to the middle-stream area of Alang River. Its lithology includes Late Miocene calcareous mudstone and thin-bedded sandstone of approximately 50 cm thickness. It has a gently dipping southward structure and is grading downward into a tuffaceous stone. In terms of weathering speed, it has moderately hard to moderately soft material that has a low potential of tractional load.

3) The Wonosari Formation

The Wonosari Formation is formed by numerous small mountains that have an elevation of around 300 m-400 masl. This formation is distributed around the

Southern part of the Wonogiri reservoir and is called “Gunung Sewu”, which means one thousand mountains. It consists of a karstic limestone of late Miocene age lithology, which is gently dipping southward and which is partially massive. In terms of weathering speed, this formation is dominated by subsurface runoff, therefore, it has probably a small tractional load.

4) The Nitopuro Formation

The Nitopuro Formation is distributed along the right bank of the downstream and around the upstream area of the Keduang River. It has a lithology, which includes tuff breccia of late Pleistocene age, tuffaceous sand-silt and volcanic breccia that partially consists of lahar facies with andesitic and/or basaltic fragments. In general, this formation gently inclines southward. This formation has a moderately soft to soft weathering speed. Residual soils and completely weathered rocks are exposed in the farm area around the middle stream of the Keduang River. This condition is considered to be a major source of sediment materials that flow to the Wonogiri Dam. Paddy fields are widely distributed in the downstream area, while the upstream area is covered by natural forests, both have probably little potential for erosion.

Figure 13. Semilir Formation (top left, Ojo Formation (top right), Wonosari Formation (bottom left) and Nitopuro Formation (bottom right) (Ouchi 2007).

3. WATER AND SEDIMENT TRANSPORT PROCESSES MODELLING

The degree of land vulnerability and soil erosion depends on several factors including vegetation cover, the physical properties of the soil and its topography. The first two factors are often severely modified because of long-term human activities. When assessing the soil erosion issue, the rate of new soil formation under particular conditions also needs to be considered. This part explains the governing erosion processes, the factors that are important in soil erosion and the specific situation in the Wonogiri Dam catchment.

3.1. Erosion Processes

Rainfall soil erosion is either induced by flowing water, the kinetic energy of raindrops or both. It is defined by Kinnell (2005) as a process involving the detachment of soil material from the surface of the soil matrix and the transport of the material away from the site of detachment. There are several types of rainwater erosion processes that all occur in the study area.

Splash and Sheet Erosion: Falling rainfall drops impacts the soil surface and removes small particles of soil from the aggregates and outspreads them around the splash area. Moreover, Kinnell (2005) explained that this process causes small amount of soil movement. Moreover, soil compaction and aggregates breakdown by raindrops exacerbates sheet erosion. According to Farres (1987), aggregate stability is an important factor in the rule of splash erosion. The aggregates destruction makes pores be clogged due to the sealing of the topsoil. This blocks water infiltration and as a consequence will make more erosive runoff if heavier rain occur. Therefore, sheet erosion is categorised as uniform removal of soil on the soil surface (Morgan 2009).

Rill Erosion: Sheet erosion most likely leads to rill erosion, if gradient and slope length allow the runoff to concentrate, it may create small rills (a few centimeters) in the soil. However, it is possible to remove these rills by ploughing (Morgan 2009).

This process is a dominant form of erosion, especially on agricultural lands, and is responsible for considerable erosion in the Wonogiri area.

Gully Erosion: Gullies are channels of erosion, which are wide and too deep to be crossed in normal cultivation. When the ditch cannot stabilized, they will keep increasing their cross section with every flood occurrence (Morgan 2009).

The development of gullies can be demonstrated as a threshold process:

$$s \geq kA^{-b} \tag{1}$$

s : the local gradient,

k : a coefficient of resistance that depends on soil type and land cover,

A : the part that drains to the gully head and,

b : an exponent.

Another type of erosion that develops in connection to gully erosion is pipe erosion.

Pipe Erosion: This type of erosion occurs below the surface of the soil and makes a macropore network. It makes rill and gully erosion if it causes the soil surface to collapse. According to Deckers, Spaargaren and Nachtergaele (2001), vertisol soils that are rich in smectites (shrink and swelling clays) area sensitive to piping due low soil permeability.

Bank Erosion: This type of erosion occurs by wearing away of the riverbanks. It is different with scouring which is an erosion of the bed of the stream or river (Thorne 1982).

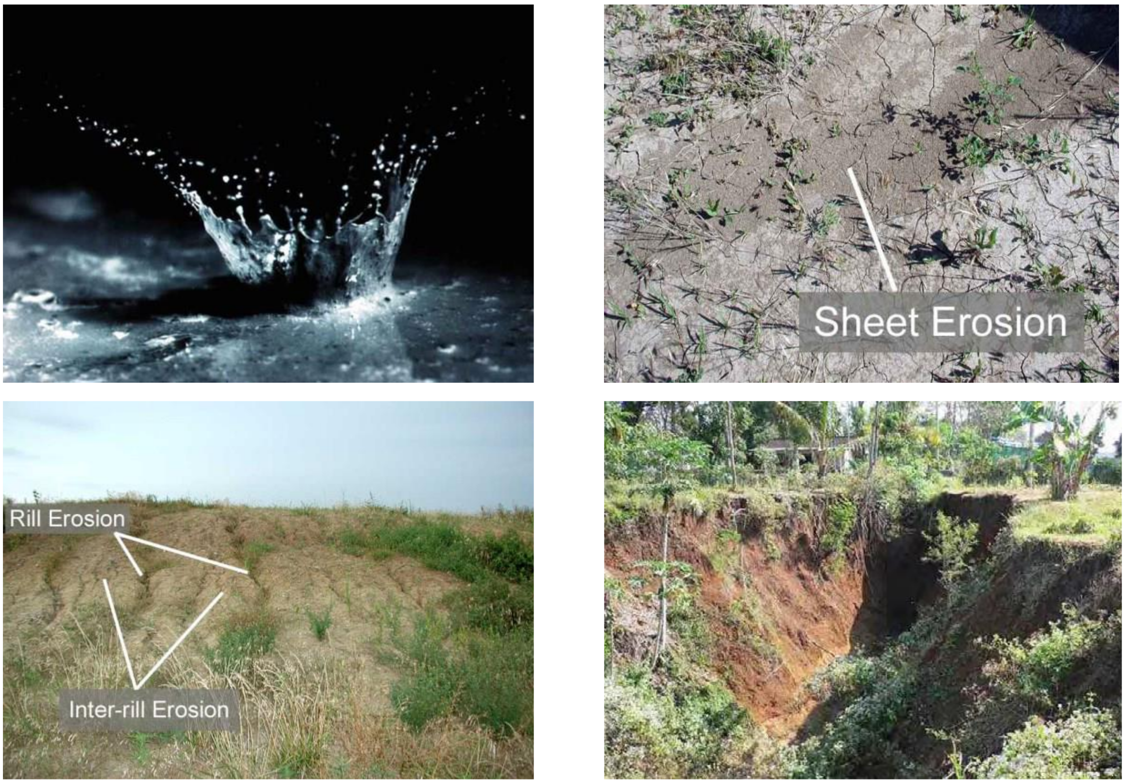

Figure 14. Types of erosion: Splash erosion (top left), sheet erosion (top right), rill erosion (bottom left) (PASSEL 2017) and active gully head in Keduang Sub catchment (below right) (Donie 1996).

3.2. Governing Factors

The main factors contributing to soil erosion by water are shown in Figure 15 (FAO 2015). Based on this figure, the most important factor for soil erosion is land use, followed by land slope, erodibility and erosivity. These factors are defined in some detail in the following section.

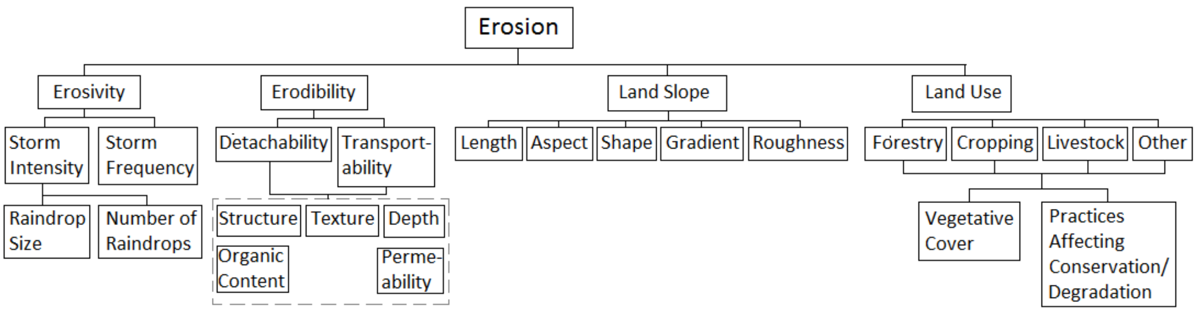

Figure 15. Factors contributing to erosion by water (FAO 2015).

Topography

As indicated in the section on erosion processes, slope and slope length are governing factors for rainfall erosion. The slope affects the runoff velocity and thus the transport capacity of the runoff (Ali et al. 2012). The slope length influences the runoff concentration and thereby formation of rills and gullies.

Soil Erodibility

Soil aggregates are groups of soil particles that bind to each other. Aggregates and the pore space form the structure of the soil. The distribution and size of pores and the initial pore water content determine the rate at which water can infiltrate the soil during a rain event (permeability) and how much water can be stored by the soil. Aggregate stability and aggregate size are the main soil properties for explaining soil erosion (Abu-Hamdeh, Abo-Qudais & Othman 2006). A high percentage of so-called water-stable aggregates > 0.5 mm (or > 0.2 mm according to Barthès et al. (2000)), which are not easily carried away by water, is significant for an erosion resistant soil. For soil to consist of many large aggregates, the aggregates must possess a certain resistance against dispersion by raindrops. This property is called aggregate stability and depends on a complex of chemical, biological and physical factors. An important factor for aggregate stability is the organic matter content of a soil. A high organic matter content promotes the formation of stable aggregates (Luk 1979).

Soil texture also influences erosion. Soil particles that have a size 0.1 mm (fine sand) are the easiest target for erosion. For fine particles, cohesion forces can decrease erodibility and for larger particles gravitational forces can only be overcome at high flow velocities (FAO 1976). A high clay content can have adverse effects on erodibility: On one hand, electrostatic charges of clay particles generally promote aggregation and thus reduce erodibility. On the other hand, aggregation by clay depends on organic matter and in soils with low organic matter content, unaggregated clay particles are highly susceptible to erosion (Luk 1979). High silt and sand contents are generally positively correlated with soil loss.

Rock fragments (mineral particles > 2 mm) in the soil matrix or on the surface also influence erosion. They protect the soil from splash erosion, prevent sealing and increase infiltration. Furthermore, they increase interception and evaporation and thereby reduce overland flow (Cerdà 2001). Poesen, Torri and Bunte (1994) analyzed the effect of rock fragment cover on soil loss due to rill and interrill erosion (Figure 16).

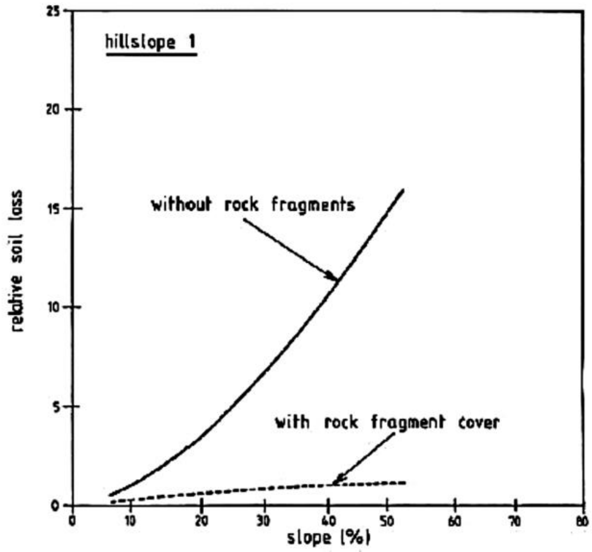

Figure 16. Protective effect of rock fragment on relative soil loss due to rill and interrill erosion (Poesen, Torri & Bunte 1994).

Rainfall Erosivity

Precipitation is one the key drivers of erosion. The erosive power of rainwater is described as rainfall erosivity. It considers the intensity and amount of rainfall, and is generally expressed in Universal Soil Loss Equation (USLE) or Modified Universal Soil Loss Equation (MUSLE) as the R_{factor}. Understanding the effect of the erosive power of water is important because it has a direct impact on the breakdown of aggregates, the detachment of soil particles, and the transport of eroded particles through runoff. According to Wischmeier and Smith (1978) rainfall erosivity is the kinetic power of rainfall and the degree of associated surface flow. The R_{factor} is an index of multi-year average that calculates rainfall's intensity and kinetic energy to explain the rainfall effect on rill and sheet erosion (Renard et al. 1997). Therefore, the R_{factor} or rainfall erosivity depends on rain intensity, kinetic energy, drop size and further physical characteristics of the rain (Janeček et al. 2013). Based on Nyssen et al. (2005) research on rain erosivity in the northern Ethiopian Highlands, it is found that drop diameters are larger than commonly recorded and rain intensities are smaller than expected for a tropical climate.

Land use

In normal conditions, vegetation cover usually protects soil from erosion. Plants shield the soil from the drying effects of wind and sun as well as from the destructive effect of rainfall. The roots hold the soil together and create pores in the soil, which could increase the drainage capacity of the soil. The transpiration and water uptake by plants also reduces the soil water content as well as increases soil capacity to absorb rain.

Roots also strengthen the engineering structures for slope stability, utilization of vegetation and soil washing reduction. Reinforcement provided by plant roots may increase the stability of slope by strengthening shear strength of soils (Shahriar et al. 2016). Plant roots have the ability to maintain tension, thus enhancing shear strength of soils at soil surface by mechanical enhancement (Shewbridge & Sitar 1990).

Plant litter from vegetation is important because it not only protects and covers the soil but is also the source material for the development of organic material. It is also important, that vegetation delays the erosive energy from overland flow by hampering the water flow through numerous obstacles (Nepf 2012).

Forest: Forests can act as an excellent land-cover on the steep area, but in the early plantation period, young seedlings do not have the ability to cover the soil from erosion. Similar to other plants, trees need to be planted on the terraces or contour if the gradient is steep. Some trees in the forest can be harvested with minimum negative impact on the land, however, in other areas, where the soil under the forest is shallow, trees are the best shield for the soil and need to be cut in a selective way. The high density of forest cover is the best land cover to protect soil erosion. However, the Wonogiri Dam catchment is barely covered by forest, except in the upper area (only less than 10 %), and thereby not protected from soil erosion.

Rice field: Crop cover in the Wonogiri Dam watershed is characterized by food crop in paddy field (wetland farming). The wetland farming is practiced in paddy fields and is extended in low-lying areas and rice terraces constructed on sloping land. Paddy production is by far the most important farming activity in the wetland farming.

However, palawija production in rotation with paddy is also intensively practiced in the off-season(s) or season(s) restricted from water availability. Wetland farming is carried out in irrigated and rainfed paddy fields. According to the Statistic Bureau of Wonogiri (2006), the 2005 area extents of paddy fields in the research area are estimated as: irrigated paddy field 31,035 ha (23.32%); rain fed paddy field 1,152 ha (0.87%); and 32,187 ha in total.

Cultivated Land: Various aspects of land cultivation are important to be considered in order to measure the threat of soil erosion on lands. The soil is more vulnerable to erosion during the time when it is ploughed as well as at the early period of the growth when it is not fully covered by vegetation yet. According to Kelley (1990), erosion hastens when the soil in the slope area is ploughed and when plant litter and grass is removed at the start of the agricultural operations in dryland farming. It also accelerates when goats, sheep and cattle are allowed to overgraze as well as forests in slope area are cut or felled indiscriminately. Supported by FAO (2015) particular soil types in the tropical region can lose 50 % or more of their nutrient content during five years because of conversion to agricultural land use and deforestation. And also approximately 80 % of soil loss in the highlands occurs during ploughing period. Small-seeded plants, such as rice, maize, and bean require a finer seedbed. Hence, the fields have to be tilled more often. Tillage for these crops is performed not only along the contour (hillside tillage) but also towards downhill, which promotes soil erosion. This extensive preparation process often delays sowing, as the number of available oxen or machine, which are needed for ploughing, is usually limited. Therefore, the soil is often still bare in the beginning of the rainy season. Another factor is the soil protection by close-grown crops, for example rice, normally protects soil better than row crops such as maize. The intercropping practice, the planting of side crop in between of the main crop, can minimize this effect and also increase yields. For instance, a common practice in the tropical region is the multi-cropping such as cassava-upland rice, cassava-maize, upland rice-peanuts, upland rice-mungbean and other combinations (Islami, Guritno & Utomo 2011).

Protective Measures: Another aspect of soil cultivation that minimises soil erosion is the implementation of protective measures. The construction of so-called bench terrace, ridge terrace and traditional terraces are prominent measures that are used to fight erosion in the upland. Bench terraces are a virtually level strips or series of level vertically across the slope, supported by risers or steep banks (Balci, Sheng & Dembner 1989). These terraces constructed along the contour lines, which over time will lead to the formation of terraces as sediment accumulates behind the wall (see Figure 17).

a) Well maintained bench terrace with grass riser

b) Maintained terrace

c) Traditional terrace

d) Ridge Terrace

e) Unmaintained terrace

f) Poorly maintained terrace

Figure 17. Several types of terraces in the Keduang sub-watershed (Ouchi 2007).

Based on the above graphs it can be simply concluded that the main sources of soil erosion is from the cultivated lands. The majority of soil erosion comes from upland fields with no terraces which extend over steep (over 10% in gradient) mountainous areas in the upper streams of the Keduang sub-watershed. Hence, deterioration of bench terraces into unmaintained or poorly maintained terraces is the most important factor that accelerate soil erosion.

According to Ouchi (2007) around 50 % of the total upland area especially in Keduang sub-watershed, is covered by bench terraces. However, most of the terraces are unmaintained or poorly maintained. The other lands are covered with non-terraces, traditional terraces, ridge terraces, and a combination of ridge terrace/non-terrace. Especially, most of the upland fields extending over the steep mountainous areas in the upper reaches of the main rivers in the Wonogiri Dam catchment and the most critical upland field areas are considered as the most serious potential areas for producing sediment yield. Most of these upland fields are covered by non-terraces, ridge terraces, traditional terraces or a combination of ridge terrace/non-terrace. These terraces, which are not properly managed have a negative impact on the acceleration of soil erosion in the vulnerable areas.

In order to gain more insight on the latest condition of terraces in the basin, Google Earth images were studied. During this uncomprehensive scan of images, bench terrace, ridge terrace and traditional terrace structures were identified on many of the steep sloping fields (> 15 %). Average slopes were measured roughly with the help of the Google Earth ruler tool which allows the measurements of air-line distances. The difference in elevation was calculated from the digital elevation model (DEM) that is included in Google Earth. The resolution of the Google Earth DEM is unknown because Google Earth does not disclose the sources of their elevation data. The accuracy of the data is however comparable to other global digital elevation models such as SRTM and Aster. Figure 18 shows examples of sloping fields, with the various condition of terraces, identified in different sub watershed.

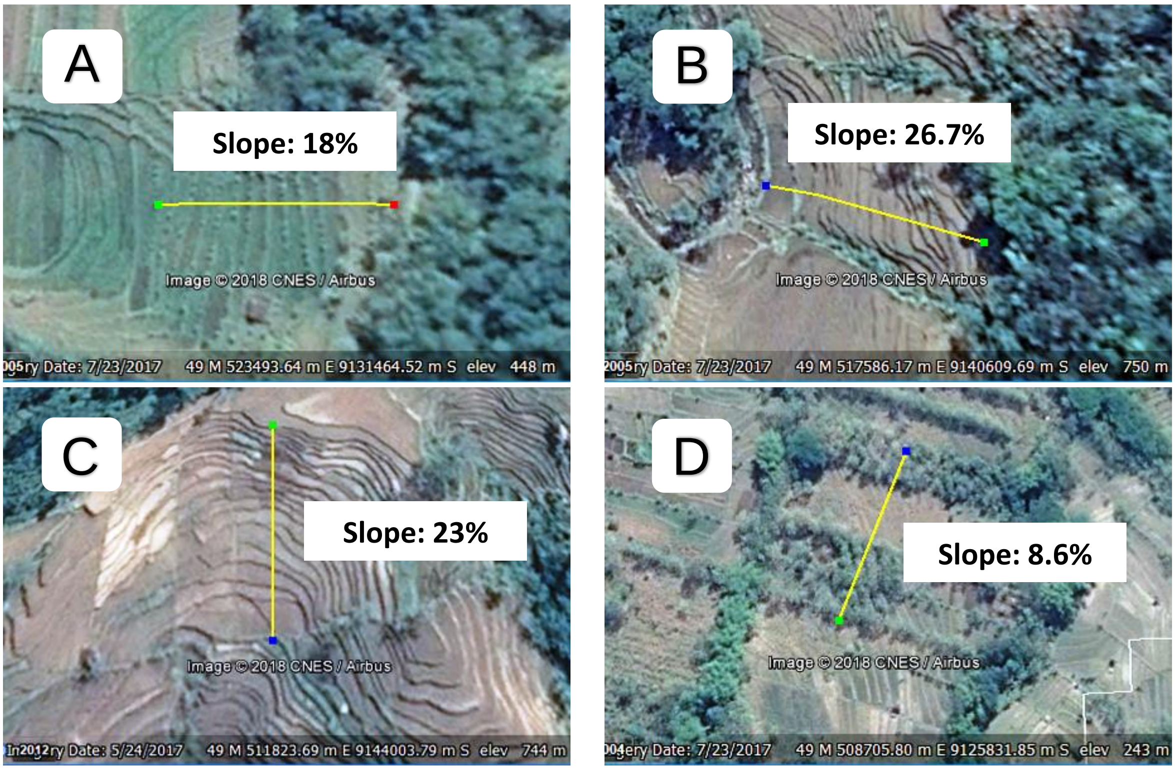

Figure 18. Captured images from Google Earth in Keduang sub-watershed. A) Well-maintained bench terrace. B) Poorly maintained terrace. C) Unmaintained terrace. D) Traditional terrace.

3.3. Tolerable Soil Erosion Rates

The agricultural process of production needs the natural resource as an input; an unwanted side product is produced such as soil erosion away from the tolerable amount. According to Francisco and Angeles (1998), the tolerable rate of soil loss is the amount of soil eroded due to the natural process in an ecosystem which is without any human intervention directly or indirectly. Under this uninterrupted condition, soils have the ability to restore the soil that is naturally lost. This natural restoration system can be called as the tolerable rate. However, when the tolerable soil loss is exceeded, if soil loss is faster than it is restored.

The deterioration of soil resources is a product of two aspects which are the human activities in the process of production and the natural characteristics of the soils' environment such as vegetation, rainfall and slope. Given that, any kind of land use practices on a soil resource unit and physical environment of soils limits the extent, any level of soil loss over the tolerable rate may be considered as human-induced.

Soil erosion as a part of the geological cycle often takes place at low rates and which exceed the soil formation rates. On pastures and cultivated lands, where erosion is often faster, it is important to consider the rate of soil erosion to ensure the soil loss which is not resulting in land degradation. According to Hurni (1988) the estimated rate of soil formation in the highlands depend on land use, climate, slope, soils and geology. For instance, soil formation rates in grass areas are around 0.3 – 0.7 mm/year which is equal to about 3.9 – 9.1 t/ha/year with the assumption that the average bulk density is 1.3 ton/m³. Soil formation can be hastened by various cultivation methods for example tillage (Hurni 1983). In a cultivated area that depends on elevation, soil formation rates are predicted approximately to range from 0.5 – 1.1 mm/year, which is equal to 6.5 – 14.3 t/ha/year. According to (Hurni 1988) regarding the rates of soil formation, soil loss is predicted to average 5 t/ha/year on pastures and 42 t/ha/year on croplands and it will exceed soil formation rate by factors of up to 10 t/ha/year.

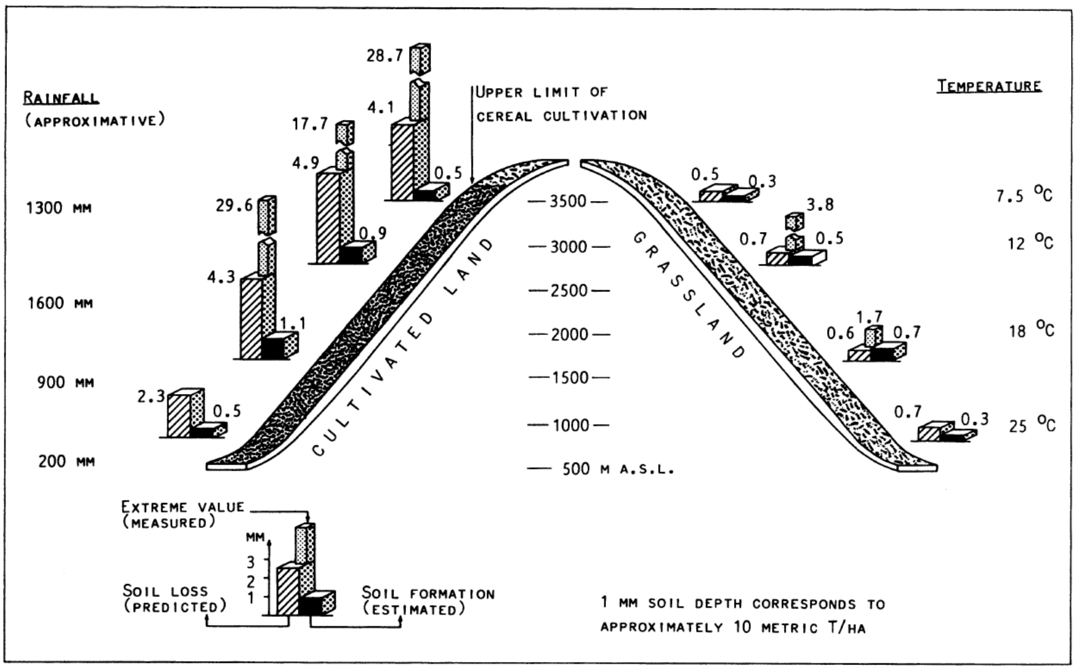

Figure 19. Soil formation and erosion rates in the Ethiopia highlands based on elevation and land use (Hurni 1988).

3.4. Erodibilty of the Soils in the Wonogiri Dam catchment

The soil erodibility (USLE_K factors, see section 3.5.3) of the Wonogiri Dam catchment was estimated by the FAO (Food and Agriculture Organization of the United Nations) (Arnold et al. 2012). Entisol (today Mollic Andosol) where estimated to have a higher erodibilty (0.2512) than Inceptisol or Ochric Andosol (0.2202) and Alfisol or Vertic Luvisol (0.1948). These estimations, however, do not reflect the specifics of the Wonogiri DAM catchment but were made for the whole Highland area.

Bonilla and Johnson (2012) also supported the values USLE_K factor for Entisol, Inceptisol and Alfisol based on texture analysis of each soil types. Entisol has the highest sand content (68 %) than Inceptisol and Alfisol, 44 and 40 % respectively. Bonilla and Johnson (2012) also concluded that there is no correlation between organic matter contents and K-factor values. However, erodibility factor is highly correlated with soil texture especially with silt content. When silt content increases, the soil erodibility will increases. Unlike silt content, the sand content is inversely correlated with the erodibility factor.

3.5. Erosion Modelling with SWAT

In this chapter, the SWAT model will be used with an emphasis on its application for modelling of soil erosion. The SWAT model has been developed and advanced by the United States Department of Agriculture (USDA) Agricultural Research Service for over more than 30 years. According to Gassman et al. (2007), throughout this period, this model has become a globally accepted in the various applications as a tool for modelling watershed processes. The SWAT model emphasizes assessment of land management activities on sediment, water, and chemical outputs in agricultural practices. Various topography, land uses, soil types, and land management conditions in complex and large watersheds can be processed and multi-year periods can be simulated using SWAT in daily, monthly and yearly time series (Neitsch et al. 2011). This makes the SWAT model adaptable, therefore, it is possible to be applied for many research purposes for instance research on exploring interfaces with other models or climate change impact. SWAT is a physically based model, hence requires data input from topography, soil characteristics, weather, vegetation and agricultural practices. In order to run the model, it is not necessary to have daily river discharge data from stream gages. Other model output that can be produced are nutrients, plant growth, pathogens, pesticides and bacteria. SWAT's setup is such that input data can easily be generated (Gassman et al. 2007).

The SWAT model is integrated with ArcGIS that offers an easy to use graphical interface and other important tools to prepare the input data and to visualise the model output. The model output can be manually calibrated using SWAT or by utilising another supported program such as SWAT-CUP. This tool is also free software and offers various algorithms in order to perform automatic calibration. It also offers a sensitivity analysis and a basic uncertainty analysis.

The main concern about the applicability of the SWAT model for a watershed in Indonesia is the availability of soil and land use data that are compatible with the SWAT database. This is because SWAT was created and developed for use in the United States, the SWAT soil and weather database is only relevant to the US land management and soil. Since there is no other model that has ability and compatibility with a better fitting database, SWAT was selected for this research because it is easy to use and has many other advantages. The structure of the model will be described in more detail in this chapter with emphasize on the component of the model that directly affects erosion yield.

3.5.1. Spatial Representation

The SWAT model is a semi-distributed model and the basin is categorised into sub watershed on a first level. Those sub-watersheds are again categorised into hydrological response units (HRUs). Sub-watersheds are spatially delineated and then interconnected by the stream reaches they drain. Climate data is also defined by sub watersheds. The HRU's, smaller spatial units, are not distributed spatially, which means that no flows is transferred from one HRU to other HRU. HRU's are defined as an area inside the sub watershed which has a specific combination of slope class, soil type and land use. Then, HRUs are simply aggregated to compute sub watershed outputs (Neitsch et al. 2011)

3.5.2. Hydrological cycle

The hydrological sequence is defined by two stages: 1) The land phase that consists of HRUs, and 2) The water phase that consist of the stream channels and reservoirs. For the model structure including all equations one is referred to the SWAT theory handbook by Neitsch et al. (2011).

Land Phase

The most important equation that governs the hydrological cycle in SWAT is the water balance equation:

$$SW_t = SW_o + \sum_{t=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad (2)$$

It describes the soil water content at the end of a day SW_t as the amount of the previous soil water content SW_o and the daily gains and losses. Then t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is a surface runoff on a day i, E_a is the amount of evapotranspiration on day i (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount groundwater return flow on day i (mm). Figure 20 illustrates the different parts of the land phase and the possibility of water flow in between.

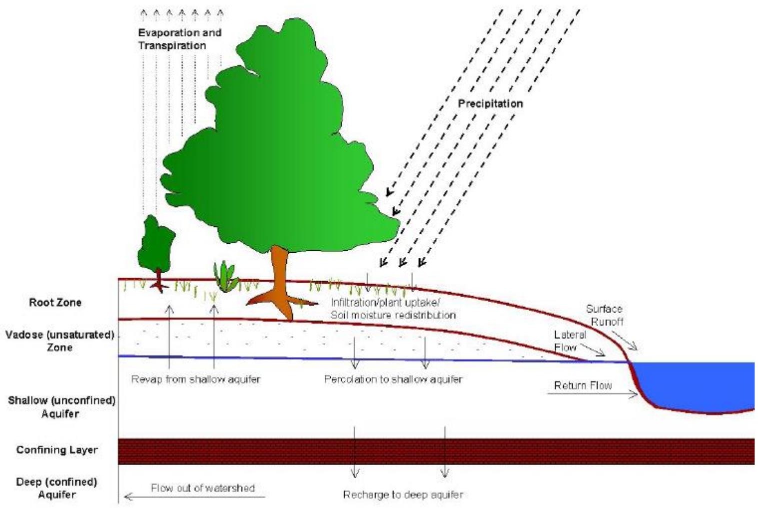

Figure 20. The schematic representation of hydrological cycle in SWAT (Neitsch et al. 2011).

Evapotranspiration

Three approaches are provided by SWAT to calculate potential evapotranspiration. The Hargreaves approach is used in this research. Therefore evapotranspiration is computed as follows:

$$\lambda E_o = 0.0023 \cdot H_o (T_{mx} - T_{mm})^{0.5} \cdot (\overline{T}_{av} + 17.8) \quad (3)$$

where λ is the latent heat of vaporization (MJ/kg), E_o is potential evapotranspiration (mm/kg), H_o is the extra-terrestrial radiation (MJ/(m^2/day)), T_{mx} is the daily maximum air temperature (°C), T_{mn} is the daily minimum air temperature (°C), and $\overline{T}_{av}$ is the daily mean air temperature (°C).

Actual evapotranspiration is subsequently computed by removing water from different parts of the model. Intercepted precipitation is evaporated before soil evaporation and plant transpiration. The actual amount of evaporation and sublimation from the soil is subsequently computed.

Surface Runoff

For the erosion calculation, surface runoff is the most important output of the water balance in the model of SWAT. Lateral flow can also supply to soil yields through a minor extent. There are two approaches provided to estimate surface runoff: the Green & Ampt infiltration method and the SCS curve number method. The SCS curve number was adopted in this study because the Green & Ampt method requires sub-daily rainfall data.

The SCS runoff equation is explained as follows:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \quad (4)$$

Where Q_{surf} is the accumulated rainfall excess or runoff (mm), R_{day} is precipitation of the day (mm), S is the retention parameter, that depends on land use and soil permeability (mm) and I_a is the initial abstraction parameter, that accounts for surface storage, an interception and prior infiltration. The parameter is commonly set to $I_a = 0.2 * S$ (mm).

The retention parameter S is defined as:

$$S = 25.4 \cdot \left(\frac{1.000}{CN} - 10\right) \tag{5}$$

CN, the curve number for the day, has been empirically determined for many different land uses depending on the permeability of the soil and the antecedent soil water conditions. Soils can be classified into four so-called ‘hydrological soil groups’, which represent their permeability.

The vegetation available water, so called as the available water capacity (AWC), is a key aspect for surface runoff. This AWC value is computed by subtracting the fraction of water present at the permanent wilting point from that present at field capacity. The curve number is adapted at a daily time step to the moisture conditions of the soil. It is explained as:

$$AWC = FC - PWP \tag{6}$$

Where FC is the maximum water capacity that the soil can hold over a longer period, PWP is the water content that is not available for plants due to the high matrix potential.

The SWAT model computes FC and PWP, from the soil AWC, clay content m_{clay}, and bulk density ρ_b of a soil. For clays, loams and clay-loams, which are the three texture classes of the soils in the watershed, AWC ranges normally from 17-19% (Hudson 1994).

The daily curve number (CN) falls within the spectrum of the three CNs which are CN_1 (dry conditions – wilting point PWP), CN_2 (average conditions) and CN_3 (wet conditions – field capacity FC). CN_1 and CN_3 are calculated from CN_2.

In the SWAT model, the CN_2 can also be adjusted on a daily basis on agricultural fields and other land use classes by implementing management procedures such as harvest or tillage, for which a specific curve number CNOP can be changed by the user.

In-stream Phase

Once the input of water and sediment to the main channel from a sub-watershed is defined, then it is routed via the river network. The most important aspects and formulas that govern water routing in SWAT include:

- The main river channel has a trapezoidal profile with uniform dimension throughout the reach. The river channel dimensions can either be set to be updated or to remain constant at each time step during a simulation.
- Manning's method for uniform flow is utilised to compute velocity and flow rate.
- Flood routing can be calculated in volumes and by default can also be calculated by using a variable storage method (Neitsch et al. 2011). The Muskingum method can also be used to calculate routing method.
- Losses and gains from the main river channel in the routing process can be due to evaporation, precipitation, diversion, bank storage returns and losses and transmission losses.

3.5.3. Soil Erosion in SWAT

Soil erosion takes place on the land phase and in the rivers if channel degradation occurs.

Land Phase

In the SWAT model, erosion yield from individual HRU is calculated by using the Modified Universal Soil Loss Equation (MUSLE) at a daily time interval. This calculation can be described as follows:

$$sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{HRU})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad (7)$$

where sed is the amount of sediment yield on given day (t), Q_{surf} is the amount of surface runoff, as estimated with the SCS curve number method (mm/ha), q_{peak} is the amount of peak runoff rate (m^3/s), and $area_{HRU}$ is the HRU area (ha).

The runoff coefficient is the ratio of the inflow rate, *i.Area*, to the peak discharge rate, *qpeak*. The coefficient will differ from incident to incident and is estimated with the following formula:

$$\mathrm{C} = \frac{\mathrm{Q_{surf}}}{\mathrm{R_{day}}} \tag{8}$$

Where Q_{surf} is the surface runoff (mm H_2O) and R_{day} is the rainfall for the day (mm H_2O).

The peak runoff rate is calculated by using a modified rational approach that is based on the runoff coefficient C, the HRU Area and the rainfall intensity i [mm/hr] as follows:

$$q_{peak} = \frac{C \cdot i \cdot area}{3.6} \tag{9}$$

In this calculation, it is expected that the runoff rate increases until the entire sub watershed area contributes flow to the discharge at the outlet. The time of concentration is calculated from the overland flow velocity and the HRU area which is estimated with Manning's equation.

The MUSLE also needs other factors for which empirical formulas or tables have been developed:

K_{USLE} : soil erodibility factor. According to Neitsch et al. (2011) K_{USLE} can be defined as "the soil loss rate per erosion index unit for a specified soil as measured on a unit plot". This factor can also be measured by utilising various empirical equations for more easily or direct field measurements. These equations define soil erodibility based on structure, organic matter content and soil texture which can be derived from soil samples. The USLE_K factor (parameter name in SWAT) is determined for each soil layer and type in the SWAT model.

C_{USLE} : land cover and management factor. This value represents how the canopy and plant litter protects a particular vegetation type or crop. It is describes the ratio of soil loss from a particular cropped area to the soil loss from a plot with no tillage. Since this factor always changes during the plant growing period, USLE_C is also updated daily by the SWAT model. The value for USLE_C performs as the maximum protection of a full-grown plant of the crop/vegetation type.

P_{USLE} : represent practice factor. Conservation practices for instance terracing and contour tillage can be reflected by this factor. It is defined as the ratio of soil loss with a particular practice to the related soil loss with up and down slope culture. The practices including terrace systems, strip cropping on the contour, and contour tillage. Stabilized channels for the disposal of excess rainwater are an important part of each of these practices.
LS_{USLE} : topography factor is defined as

$$LS_{USLE} = \left(\frac{L_{hill}}{22.1}\right)^{m} \cdot (65.41 \cdot sin^2\alpha_{hill} + 4.56 \ \cdot sin\alpha_{hill} + 0.065) \quad (10)$$

Where L_{hill} is the slope length (m). In SWAT this is the average slope length SLSUBBSN defined for each HRU. α_{hill} is the slope angle which relates to the average HRU slope HRU_SLP.

$$\alpha_{hill}=\mathrm{arctan(HRU\_SLP)} \quad (11)$$

m is the exponent that is calculated from the average HRU slope as follows:

$$m = 0.6 \cdot 1(1 - \exp(-35.835 \cdot HRU\_SLP)) \quad (12)$$

$CFRG$ is the coarse fragment factor. It is computed from the rock content of the top soil layer. $CFRG$ is determined from the rock content $rock$ as follows

$$CFRG = \exp(-0.053 \cdot rock) \quad (13)$$

The MUSLE does not include soil losses from gully erosion, only from sheet and rill erosion.

Sediment Routing

Sediment transport in the stream network is a result of two mechanisms, degradation and deposition, which operate on the reach simultaneously. SWAT will calculate degradation and deposition by utilising similar river dimensions for the whole simulation. Otherwise, SWAT can also simulate widening and down cutting of the river channel and renew the river dimensions during the simulation. Sediment transport involves two parts such as landscape and channel component. In the landscape part, SWAT maintains two tracks of the distribution of the sediment particle from the soil erosion and routes them via surface water bodies, channels and ponds. In the river channel, deposition or degradation of the sediment can happen depending on the river force, the exposure of channel bottom and sides to the erosive power of the stream as well as the composition of the river bed and bank sediment.

The default approach for sediment routing is calculated from the Bagnold's equation for river force. It does not include scouring of the river bed. The approach defines the maximum quantity of sediment which is transported from a reach part as a function of the peak river velocity.

$$conc_{sed,ch,max} = c_{sp} \cdot v_{ch,peak}{}^{spexp} \tag{14}$$

Where $conc_{sed,ch,max}$ [kg/m³ or ton/m³] is the maximum sediment concentration that can be transported by the water and the coefficient c_{sp} and the exponent $spexp$ is defined by the user. Excess sediment is deposited. In this calculation different particle sizes of the sediment are not tracked. Therefore, in the SWAT output table, all sediment occurs as silt.

In the SWAT model, at least four approaches are available to calculate sediment routing. However, only the Kodatie can be applied in basins that are dominated by fine sediment. In this method degradation of the channel is included, it is defined as:

$$conc_{sed,ch,max} = \left(\frac{a \cdot v_{ch}{}^{b} \cdot y^{c} \cdot S^{d}}{Q_{in}}\right) \cdot \left(\frac{W + W_{btm}}{2}\right) \tag{15}$$

Where

V_{ch} : mean flow velocity (m/s)

a, b, c, d : regression coefficients for different channel bed materials (silt, fine sand, coarse sand or gravel).

y : mean flow depth (m)

S : channel slope (m/m)

W : width at the top of the channel (m)

3.6. State of Research

The main purpose of this chapter is to underline some results and facts from various previous studies that utilise SWAT (Soil and Water Assessment Tool) and other models to predict soil erosion and sediment yield. This section is only a short summary from previous studies that relate to this study especially for supporting the main objectives.

Modelling is an important instrument to develop management practices and understand hydrological processes as well as assess the positive and negative aspects of land use / cover over a particular period (Spruill, Workman & Taraba 2000). Various models have been developed in order to predict the runoff discharge and the transport of sediments from the basin as well as to assess land use changes on sediment transport and to estimate the impact of watershed management measures. Knisel (1980) explained the CREAMS (Chemical, Runoff, and Erosion from Management Systems) model developed by the USDA - Agricultural Research Service (ARS). This model has the ability to evaluate non-point source pollution from field-sized areas by a developed mathematical model. CREAMS consists of three components: chemistry, hydrology and erosion / sedimentation. Based on CREAMS, various other models originated for specific purposes. These derived models which were built for specific reasons sometimes have many limitations especially when generated to model catchment areas with hundreds or more of sub-basins (Spruill, Workman & Taraba 2000). In the early 1990’s, the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) developed the SWAT (Soil and Water Assessment Tool) model which had capability to run thousands of sub-basins, therefore, overcoming polygon size and a number of limitations of CREAMS (Arnold et al. 1998). More details of the SWAT model and its capabilities, including features, strengths, limitations, framework, scientific details and previous model applications will be explained in a further chapter.

Jain, MK, Kothyari and Raju (2005) conducted a research in 14 different catchment areas (10 catchments in India, 3 in the United States, and 1 in The Netherlands) and in various periods. They focused on the temporal and spatial variability in terms of topography, land use/land cover, forest cover, soil and precipitation as well as young geologic materials. They concluded that a high gradient of slope in combination with highly intensive agricultural practices had been a major factor in sedimentation and soil erosion in river reaches.

Another study by Tyagi et al. (2014) assessed the applicability of SWAT model in predicting daily discharge and sediment delivery from a forested catchment area. They also assessed the impact of forest cover types on the characteristic of river discharge pattern and sediment yield in two small sub basins (Bansigad 209.8 ha and Arnigad 304.4 ha). The output of daily discharge and sediment concentration from the SWAT model was calibrated and validated by comparing with the observed data. The result of model calibration for the Bansigad sub basin presented a high performance of the SWAT model with a coefficient of determination (R^2) of 0.91 and Nash-Sutcliff (NS) value of 0.90 for the discharge simulation; and an R^2 value of 0.86 and NS value of 0.82 for the sediment simulation. The output from another sub-basin, Arnigad watershed also showed very good results between measured and simulated daily values with an R^2 value of 0.91 and an NS value of 0.84 in discharge simulation; and an R^2 value of 0.89 and NS value of 0.83 for sediment simulation. Based on this result, it is clear that the SWAT model is capable of estimating the river discharge and sediment yield especially in Himalayan forested sub basins and also can be used to evaluate the sediment yield and hydrological response of the basins in the Himalayan area.

To some extent, the performance of the SWAT model can be affected by the interval of the time series data when calibrating and validating the model. Generally, the output of SWAT model is better in monthly interval than in daily interval. This was shown by Jain, SK, Tyagi and Singh (2010) when applying SWAT model to estimate the sediment yield and runoff in two sub watershed (Kasol and Suni) in the western Himalaya mountains. The model calibration period for the observed runoff and sediment yield was from 1993 to 1994 and the validation period was from 1995 to 1997. The coefficient of determination of sediment yield during calibration was 0.33 for daily and 0.38 for monthly and the R^2 value during validation period was 0.26 for daily and 0.47 for monthly which were lower than in calibration period. The same statistical test was also performed for discharge and the result was similar, the monthly discharge estimations performed better than daily predictions. The simulation output illustrated that the R^2 value for monthly simulation is higher than the daily values. From these results it can be concluded that the monthly results likely smooth the data and as a result it will increase the R^2 value.

The application of a SWAT model was also implemented for a long simulation period in Ethiopia, in Fincha Basin (325,100 ha), situated in the West part of Regional State of Oromiya (Ayana, Edossa and Kositsakulchai (2012). The SWAT model was generated by simulating 22 years of time series data between 1985 and 2006. In the calibration period, this study predicted monthly sediment yield with an NS value of 0.80 and an R^2 value of 0.82. In the validation period, a lower NS value of 0.78 and the same value for R^2 of 0.80 was obtained. The conclusion was that the SWAT model showed high performance in estimating the sediment yield, therefore, the approach can be implemented for other catchment areas with similar characteristics.

Primarily, the SWAT model is developed for simulating periods of two years or more. However, Saleh et al. (2009) applied the SWAT model for a short period of less than a year (few days) for the Mustang Creek Watershed, California. This basin is an ephemeral channel, which flows only during high intensity of rainfall. In this study, the calibration period was in February 2004 (29 days) and the validation period in January and February 2005 (58 days). The result of the research showed that the SWAT performance was good in simulating the monthly discharge with an NS value of 0.72 for the calibration period. However, for the validation period, the SWAT model performed less because of the NS value was only 0.33. The researchers explained that this result occurs because only few observed discharge vales were used, the nature of ephemeral flows in the watershed and the short simulation period. Therefore, the researchers concluded that a longer period of daily discharge data for the calibration and validation would highly likely result in a better fit between observed and simulated discharge. A better comparison would be obtained as a longer period of simulation would not be affected by few unusual peak flow values as in a short record (Saleh et al. 2009).

The applicability of SWAT for sediment yield modelling is also shown for East Africa by Ndomba, PM and van Griensven (2011). Three study locations were selected in this research. The first location was Koka Reservoir Basin (1,100,000 ha) in Ethiopia, the second location was in the Nyumba Ya Mungu (NYM) Dam Sub Basin (14,000 ha) in the upper area of Pangani River Basin in Tanzania, and the third location was the Simiyu River Basin (1,065,900 ha) in the North area of Tanzania. One of the results of this study is the conclusion that the performance of the SWAT model in these three areas is promising, therefore, it can be used for sediment yield modelling in tropical regions (Ndomba, PM & van Griensven 2011).

SWAT was also implemented by Spruill, Workman and Taraba (2000) to simulate daily discharge and to perform sensitivity analysis in Central Kentucky Basin for a period more than two years between 1995 and 1996. In this study, the calibration was performed for 1995 and the validation for 1996. The model estimation was not acceptable because the NSE values were very low only -0.04 (calibration period) and 0.19 (validation period). The SWAT model poorly estimated the timing of peak discharges and recession rates for the last six months of 1995.

Betrie et al. (2011) set up a SWAT model for the Upper Blue Nile watershed to estimate sediment reductions by implementing Best Management Practice (BMP) scenarios. The scenarios simulate four conditions such as maintaining default conditions (control), reforestation, applying stone bunds (parallel terraces) and introducing filter strips. The results indicated that the measured and simulated daily sediment concentrations give good agreement as indicated by the high NSE (0.83). The application of conservation measures included reforestation, stone bund terraces and filter strips significantly decrease the sediment yield at both sub watershed and watershed level. For example, the application of parallel terraces or stone bunds decrease sediment transport and soil erosion by reducing the length of slope. The amount of erosion and sediment transport decreased because the slope length (SL) factor is directly related to the sediment yield estimation from the basin by MUSLE formula. Therefore, the slope length closely related to the terrace interval.

Xu et al. (2009) also estimated sediment yield and runoff by using SWAT model in the Miyun River watershed, China. The physical characteristic of the catchment is showed by deep valleys, steep slope and mountain ranges. The model can predict the daily and monthly sediment yield and runoff accurately, with an NSE value of more than 0.6. In this research, a sensitivity analysis was also performed to find which parameters affect sediment yield and runoff. As a result, the sediment yield was sensitive to the channel re-entrainment linear parameter (SPCON) and curve number (CN) and the runoff was most sensitive to the base-flow alpha factor (ALPHA_BF) and curve number (CN). The sensitive parameter is only specific for this catchment and it is not appropriate to apply directly to other watersheds with different physical characteristics before performing the sensitivity analysis.

In Tanzania, the SWAT model was also implemented by Ndomba, Mtalo and Killingtveit (2008) for a particular complex tropical basin. The result indicated that the SWAT model could be used for ungauged basins in order to identify hydrological controlling parameters. The research result also indicated that the length of the time interval of simulation affects the output, for instance, the longer the generated period the more reliable the results are. The SWAT model performance showed the best result for daily runoff simulation with an NSE value of 0.55 for calibration and 0.68 for the validation period. Thus, the study recommends that it is important to use pre-processed, reliable and adequate spatial precipitation data as well as a long period of discharge data for a SWAT model. Another important suggestion was that calibration could increase the performance of a fully distributed SWAT model.

In Lake Tana Basin, the Blue Nile, Ethiopia, Setegn, Srinivasan and Dargahi (2008) implemented a SWAT model to model the hydrological water balance. The purpose of this research was to assess the applicability of the SWAT model for estimation of discharge in the catchment. The SWAT model successfully simulated daily and monthly discharge for the watershed. The study concluded that there was a high sensitivity between discharge and HRU definition threshold and a lower sensitivity to the effect of sub-watershed discretization.

Mulungu and Munishi (2007) successfully applied the SWAT model to evaluate watershed parameterization. The output of this study explained that the model parameters of surface water were highly sensitive and have a physical meaning such as SOL_K (saturated hydraulic conductivity of soil layers) and CN2 (curve number). However, the coefficient of determination of the model (R2) was low only 0.14. This study concluded that the most important data is not only the spatial land data but also other factors in order to improve the discharge prediction by SWAT in the catchment area.

Tripathi, Raghuwanshi and Rao (2005) studied the effect of basin/ sub basin division on the water balance components in Nagwan basin, India. This study found that the size and number of sub-basins do not significantly affect surface runoff, however, it presented obvious effects on other components of the water balance: soil water content, percolation and evapotranspiration. Hence, it can be concluded that generally the basin subdivision has an effect on the water balance. The size and number of sub-basins for a particular catchment is based on the resolution of terrain data generated in the SWAT model. A higher resolution DEM allows for generating a larger number of sub-basins to increase the result of the water balance estimation.

Regarding gully erosion, Easton et al. (2010) implemented a SWAT model for the Blue Nile watershed in Ethiopia. This study found that the SWAT model is incapable to model gully erosion. The study also indicated that sediment prediction is much lower wherever gully erosion is high. Therefore, it is important to adjust USLE_K (soil erodibility) factor in MUSLE (Modified Universal Soil Loss Equation).

Regarding the study area, land degradation in the Wonogiri Dam catchment has been receiving increasing attention in the past few years while the situation in the area has been exacerbating continuously. Early studies in the Wonogiri Dam catchment in the 1980's and 1990's explored the causes for erosion losses and the decrease in soil fertility and provided first estimations on soil losses using the Universal Soil Loss Equation (USLE) (Loebis & Taryana 1988; Sutadi 1982). During that period, the soil erosion issue was also addressed by several non-governmental organizations and governmental agencies, for instance, the Indonesian government, the World Food Program and the Food and Agriculture Organization of the United Nations. Improper agricultural practices and poverty related issues were recognised as causal problems (Precylia & Sudrajat 1995). Various practices were performed to ameliorate the problems including the construction of bench terraces, the stabilization of gullies and afforestation projects (Donie 1995, 1996).

In the past few years, research conducted in this area has mainly been addressing issue from the following angles: Firstly, field studies are conducted to study the effects of land use and soil properties as well as the impact of conservation practices on soil erosion courses at smaller scales. Secondly, the analysis of remote sensing imagery and aerial photographs is performed to analyse land use-land cover dynamics and gully development. Thirdly, various hydrological modelling exercises are performed in the Wonogiri Dam catchment. A comprehensive review of research on soil erosion and the effects of soil and water conservation methods in Indonesia was put together by Paimin (2010).

Ground surveys at smaller spatial scales have identified several factors influencing the formation of rill and gully erosion in the Keduang sub-watershed. Donie (1996) observed the development of two gullies, in Kerjolor and Kerjokidul village, 1990 to 1993. Based on this observation, the two gullies developed 1.1 m in width and 0.35 m in depth. He also found gully erosion to be approximately 20 times higher than the measured interrill and rill soil erosion. The effect of drainage ditches and stone bunds on gully head development was evaluated by Basuki, T M ., Wijaya and Wahyuningrum (2016). They concluded that, while stone bunds reduce the risk of gully enlargement, fields with drainage ditches are highly vulnerable to the development of gully heads. This conclusion was also supported by Monsieurs et al. (2015), when conducting research on gully head development under different management practices in other areas (Figure 21).

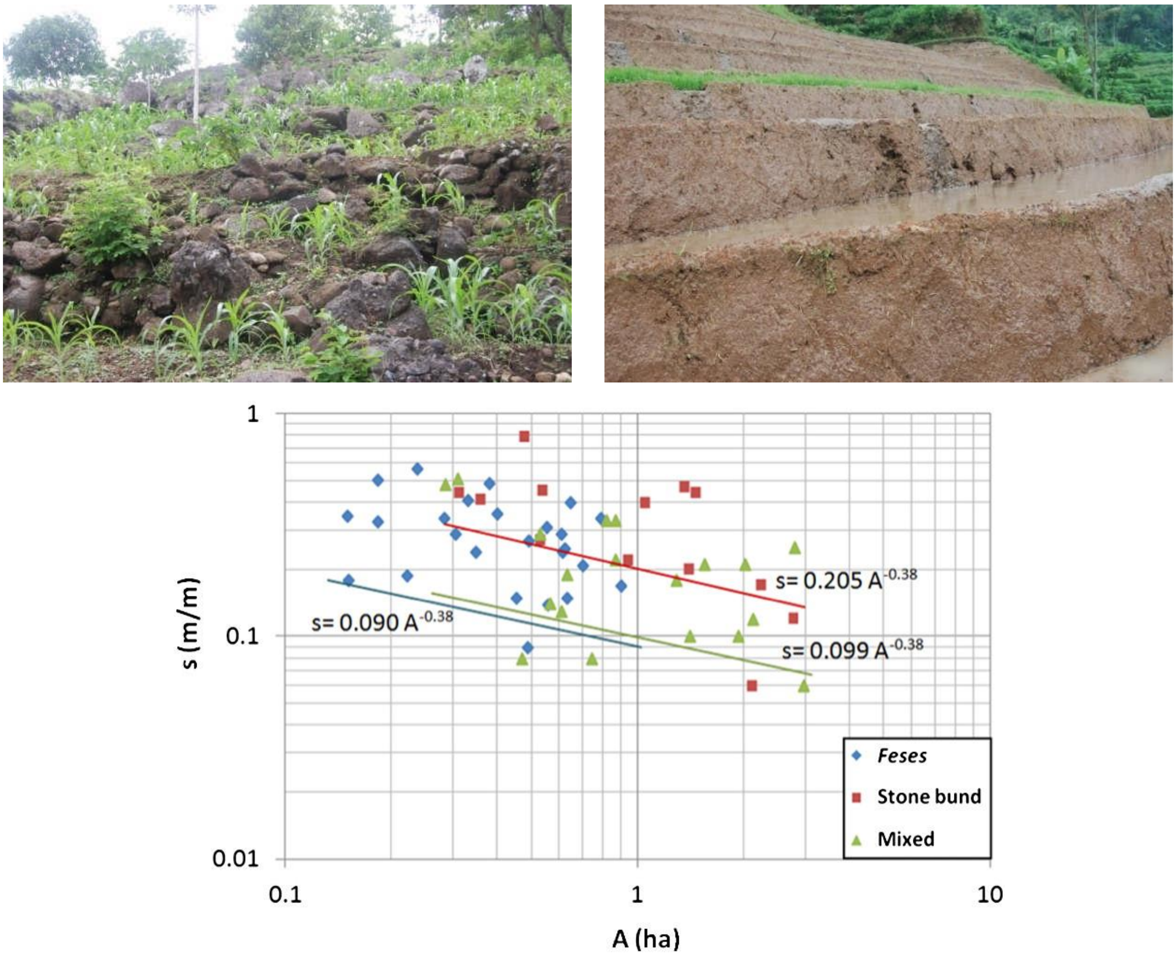

Figure 21. Top Left: Dryland cultivation in steep slope area with stone bunds terraces. Top Right: Bench terraces at paddy field (Basuki, T M ., Wijaya & Wahyuningrum 2016). Bottom: Gully head development under different management practices (Monsieurs et al. 2015).

Therefore, some of these recommendations should be considered for this study:

1. Local calibration points should be considered in the watershed.
2. Landcover and soil characteristics should be checked in land use/land cover studies.
3. Calibrated parameters should maintain their physical meaning.
4. Obtained mass balances should be in equilibrium.
5. The hydrological water balance should be checked with special attention to hydrological losses. Model flaws should not be adjusted by allowing high losses, e.g. as deep aquifer recharge, transmission losses or groundwater re-evaporation.

4. MATERIALS AND METHODS

In this research, data analysis was only performed in the Keduang sub-watershed. Because this watershed is not only the largest sub-watershed in the Wonogiri Dam catchment but also it has the highest sediment rate. Moreover, this catchment also has the closest outflow to the dam.

In the method section, the inputs of the model will be demonstrated and the model setup including how to delineate the watershed and to set the model will be presented. The sensitivity of the parameter will be discussed and followed by model calibration and validation for flow and sediment.

4.1. Input Data and Model Setup

The SWAT model requires several model inputs, which are a digital elevation model (DEM), climate data (precipitation, temperature maximum-minimum, solar radiation, wind speed), a land use map and a soil map. The land use and soil maps must contain detailed information including land use and land management practices as well as soil properties.

4.1.1. Topography

A set of four SRTM DEM (Shuttle Radar Topographic Mission Digital Elevation Model) with a resolution of one arc-second (30 m) was obtained from the United States Geological Survey by accessing http://earthexplorer.usgs.gov. The SRTM image used in this study is the fourth-edition and all the holes or void data have been filled. According to Wang et al. (2011), the SRTM DEM has not only the highest vertical accuracy but is also very fluent compared with ASTER data, which have serious noise.

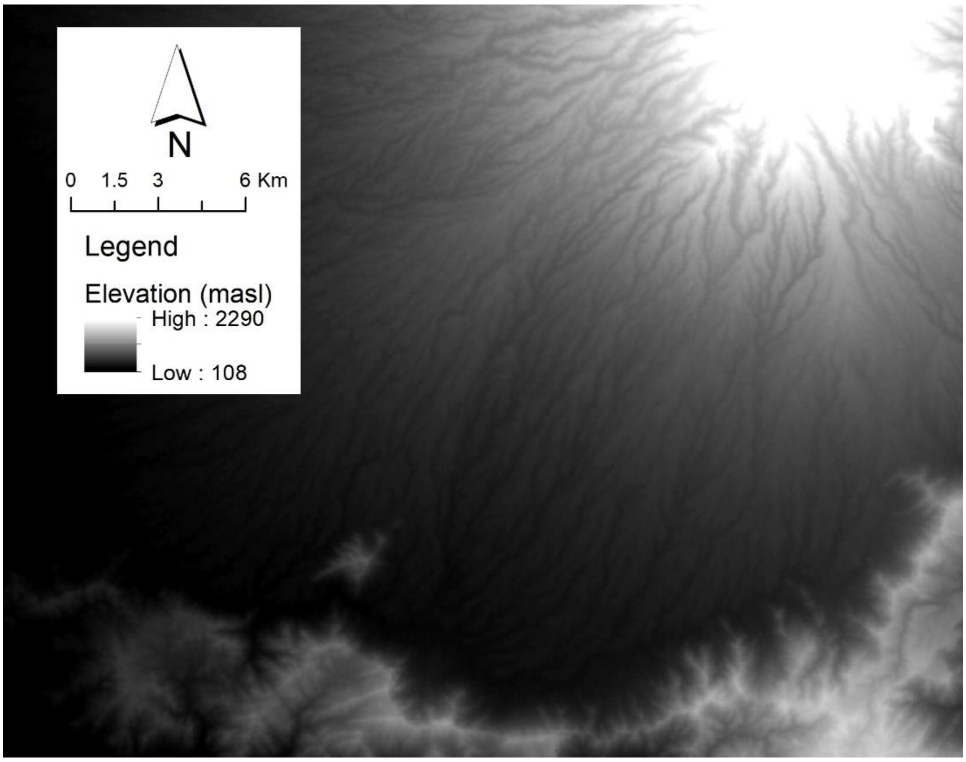

Figure 22. DEM SRTM of the Keduang watershed

4.1.2. Watershed Delineation

In order to generate the sub-basins and the stream network, automatic watershed delineation was performed in SWAT. Keduang watershed outlet was pointed manually at the coordinates of discharge gauge (Longitude 110°59’ 31.2” and Latitude -7°52’36.23”). The watershed was thus split into 193 sub-basins. Figure 23 illustrates the river channel, the 193 sub watersheds and their outlets, and the discharge data stations. The Wonogiri Dam area is also added for a better understanding but is not a part of the SWAT project.

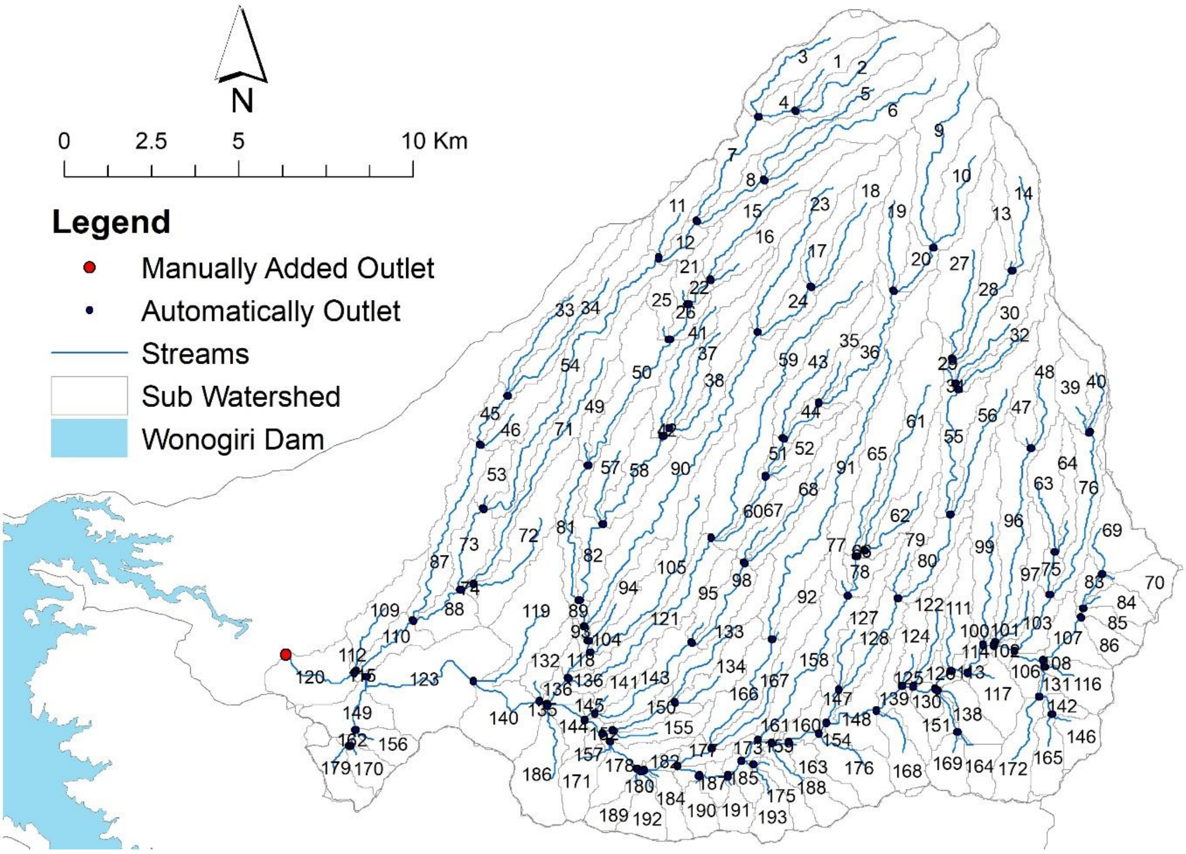

Figure 23. Stream network and sub-basins based on SWAT model and location of discharge measurement stations.

4.1.3. Climate

The requirements of climate input in SWAT depend on what method to calculate evapotranspiration (ET). Many methods have been developed to estimate Potential Evapotranspiration (PET). Three of these methods have been incorporated into SWAT: the Hargreaves method (Hargreaves & Samani 1985), the Priestley-Taylor method (Priestley & Taylor 1972) and the Penman-Monteith method (Allen, Richard G. et al. 1989; Monteith 1965). The Penman-Monteith method and Hargreaves method were both evaluated and evaporation results were overestimated (Trajkovic 2007) with Penman-Monteith (it predicted a ratio of Flow/ET < 0.2). The Hargreaves-Method, which only requires temperature input and precipitation, was therefore chosen. It is also important to calculate plant growth because this calculation is also important for erosion loss simulation. Another important data input is daily solar radiation data that is derived from the daily duration of sunshine.

Climate data from the one weather station within the basin, in Ngancar Weather Station, available from the Centre of Public Work, Water Resource and Spatial Planning of Bengawan Solo, was evaluated in several steps. Firstly, the modelling period was selected to be from 2007 to 2016, as for those years, sufficient climate input data was available for most of the weather stations and precipitation data, as well as discharge and sediment data for calibration and validation.

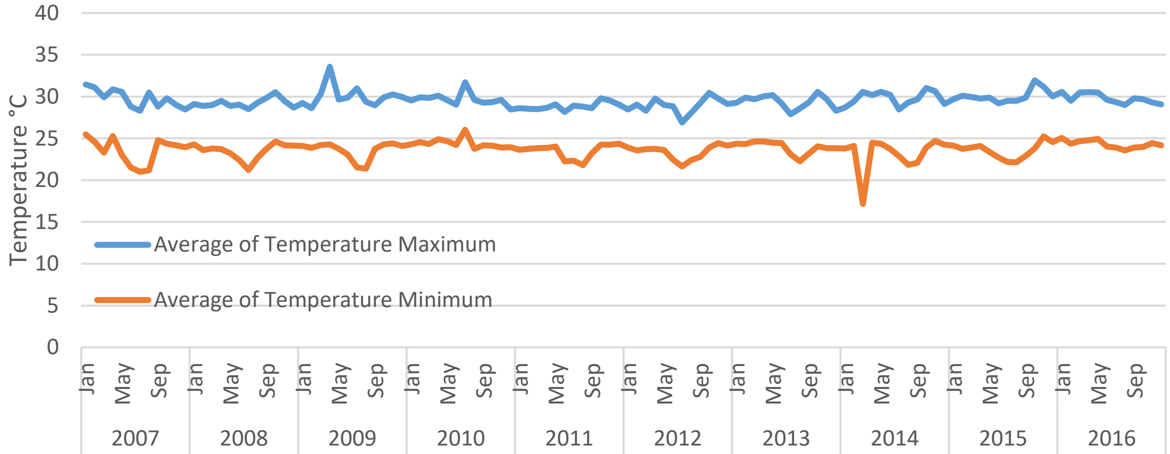

Figure 24. Monthly average maximum and minimum temperature of Ngancar Climate Station.

In the SWAT model, weather data is delineated by sub-basin boundary. If no weather station is located within a sub-basin, the SWAT will select the closest one from another sub-basin. If there is no data or missing, SWAT will not use data from another sub-basin but will give the climate and discharge parameters from weather generator which is not a “real” climate data. This is a real problem if there are many gaps in the climate data records.

Secondly, the input data consistency was evaluated. The daily weather data is to some extent fragmentary: In some years, no records exist from some stations. In the year 2007-2008, precipitation records are missing from three stations (Girimarto PP, Watugede and Puter) as well as temperature records for 2005. Therefore, these three rainfall stations were excluded when generating the SWAT model.

The next procedure was to assess which climate stations best represented the actual climate in the basin or sub-basin. This was done by generating the SWAT model with different climate data as inputs. The model performance was evaluated regarding actual discharge data as an indicator for the climate data. If the discharge is far too low or too high in a sub-basin, the climate data for that basin cannot represent the actual data. Another method was comparing the results of average annual precipitation from SWAT with the precipitation map (Figure 25). The total monthly precipitation from seven rain gauges are illustrated in the Figure 26 to Figure 32.

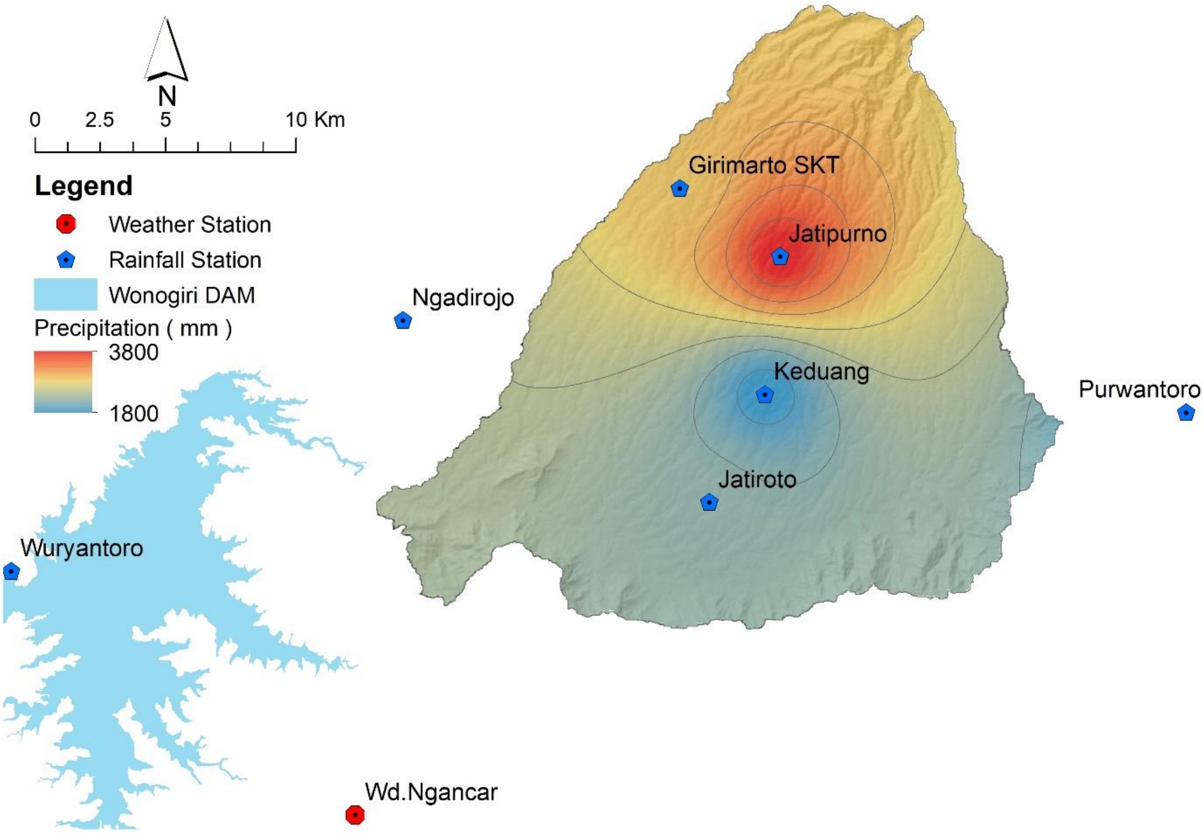

Figure 25. Average annual precipitation in the sub-basins depending on selected weather stations. Weather stations are depicted at their actual locations.

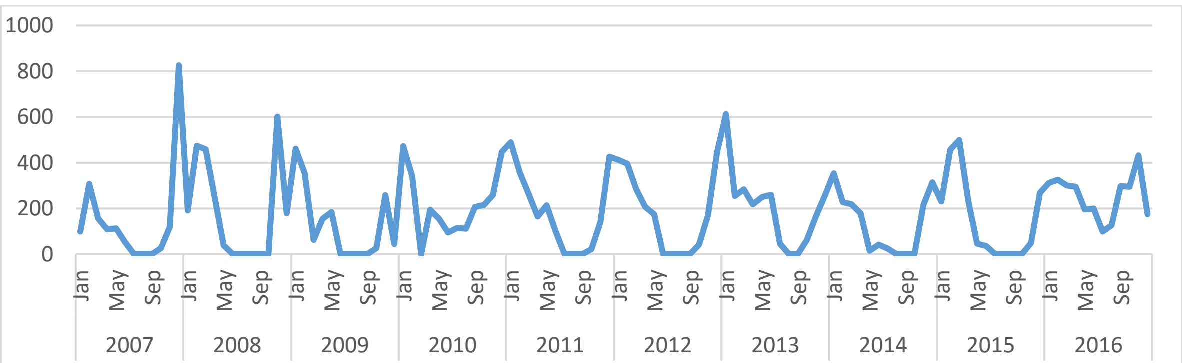

Figure 26. Total monthly rainfall (mm) of Wuryantoro rain gauge.

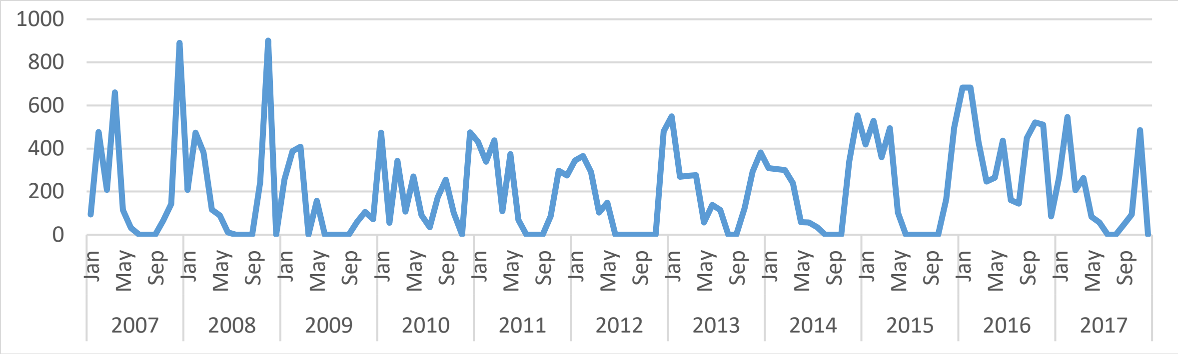

Figure 27. Total monthly rainfall (mm) of Ngadirojo rain gauge.

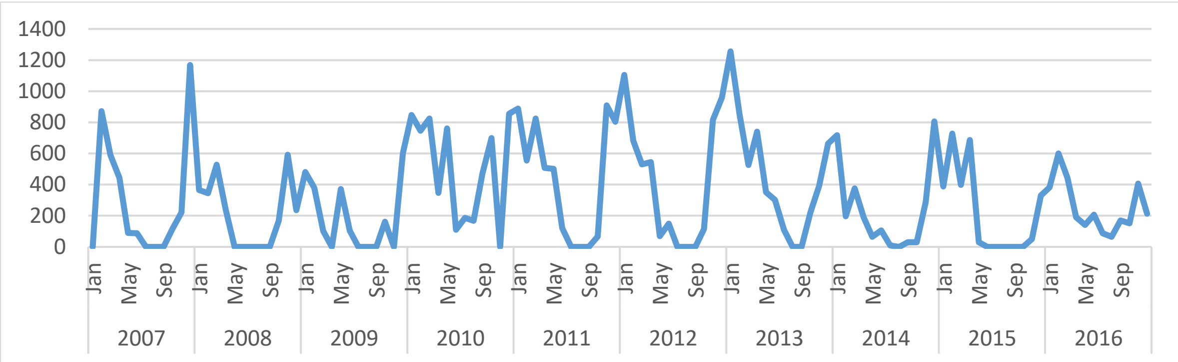

Figure 28. Total monthly rainfall (mm) of Jatipurno rain gauge.

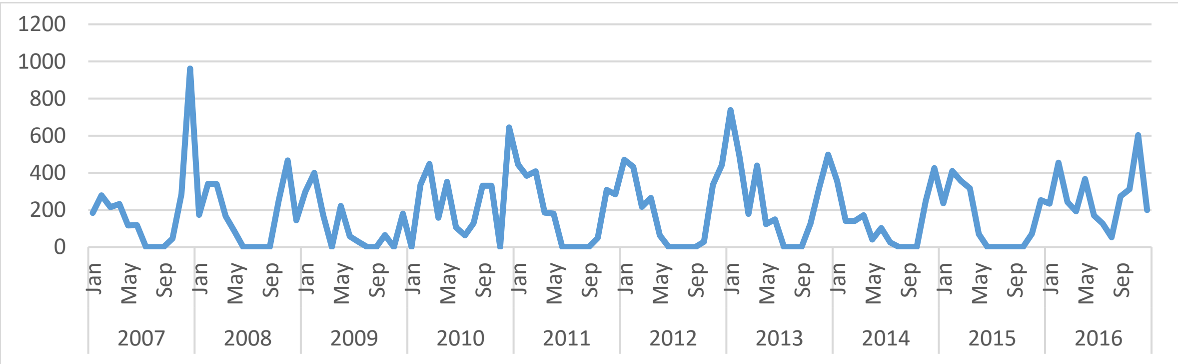

Figure 29. Total monthly rainfall (mm) of Jatiroto rain gauge.

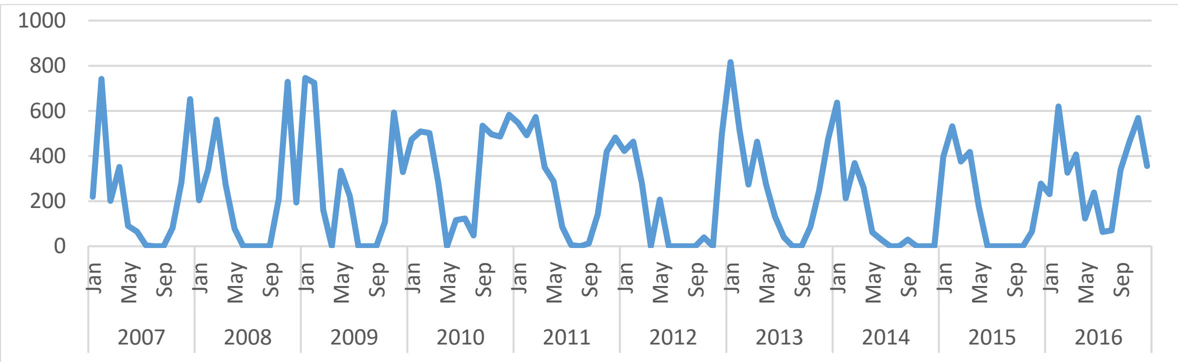

Figure 30. Total monthly rainfall (mm) of Girimarto SKT rain gauge.

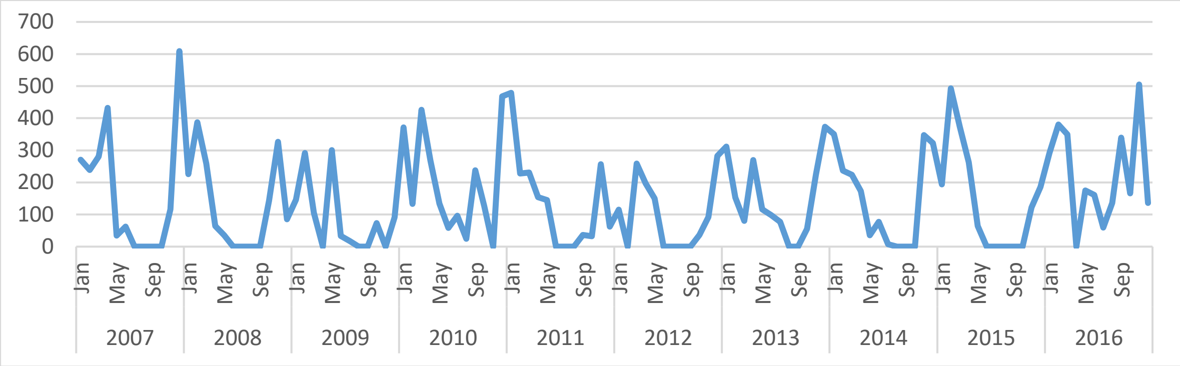

Figure 31. Total monthly rainfall (mm) of Purwantoro rain gauge.

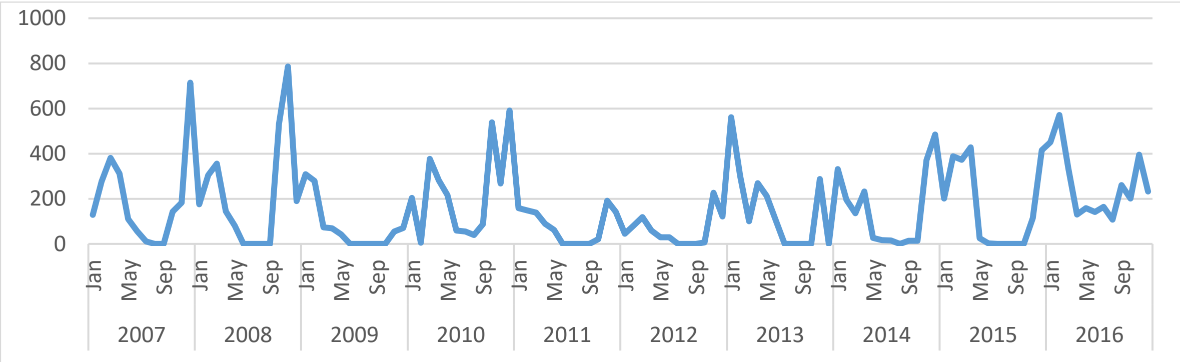

Figure 32. Total monthly rainfall (mm) of Keduang rain gauge.

Finally, the average annual rainfall for the entire basin which is simulated by SWAT is evaluated. With this final configuration, average annual precipitation is predicted at 2,815.8 mm from 2007 to 2016. The findings from literature research range between 2,000 mm – 3,000 per year and are thereby well represented by the model. Average annual potential evapotranspiration is predicted at 721.6 mm by SWAT.

Records of solar radiation which is derived from sunshine hours is obtained only from Ngancar Weather Station. In this station sunshine hours are recorded daily since 2007. This data is important in order to simulate plant growth in SWAT when there is minimum solar radiation. If the solar radiation, R_s, is not measured, it can be calculated with the Angstrom formula which relates solar radiation to extraterrestrial radiation and relative sunshine duration (Allen, Richard G et al. 1998), as follows:

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \tag{16}$$

R_s is shortwave or solar radiation [MJ m^{-2} day^{-1}]. a_s is a regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0). $a_s + b_s$ are a fraction of extraterrestrial radiation reaching the earth on clear days (n = N). n is the actual duration of sunshine [hour]. N is the maximum possible duration of sunshine or daylight hours [hour]. n/N is relative sunshine duration [-]. R_a is extraterrestrial radiation [[MJ m^{-2} day^{-1}].

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s sin(\varphi) sin(\delta) + cos(\varphi) sin(\omega_s)] \qquad (17)$$

G_{sc} is solar constant = 0.0820 MJ m^{-2} min^{-1}. d_r is inverse relative distance Earth-Sun. ω_s is sunset hour angle in radians.

The daylight hours, N, are given by:

$$N = \frac{24}{\pi} \omega_s \qquad (18)$$

Mean values for N (15th day of each month) for different latitudes are given in Table 3.

R_s is expressed in the above equation in MJ m^{-2} day^{-1}. The corresponding equivalent evaporation in mm day^{-1} is obtained by multiplying R_s by 0.408. Depending on solar declination (latitude and month) and atmospheric conditions (humidity, dust), the Angstrom values a_s and b_s will vary. According to Allen, Richard G et al. (1998) if no actual solar radiation data are available and no calibration has been carried out for improving a_s and b_s parameters, the values a_s = 0.25 and b_s= 0.50 are recommended.

Table 3. Daily extraterrestrial radiation (R_a) and mean daylight hours (N) of the study area (latitude 7S) for the 15th day of the month.

Lat 7S	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ra	38.3	38.7	38.0	35.6	32.7	30.9	31.5	34.0	36.8	38.2	38.2	38.0
N	12.3	12.2	12.0	11.9	11.7	11.7	11.7	11.8	12.0	12.1	12.3	12.3

Solar radiation data is only available as sunshine hours per day which most likely is not very accurately measured. This simplification should therefore not decrease the quality of the model. SWAT requires solar radiation as MJ/m² as input, not sunshine hours. The average daily sunshine hours in the records from Ngancar Weather Station are 5.88 hours and 17.72 MJ m^{-2} day^{-1}. Considering the high uncertainty of the available measurements and for simplification, the daily sunshine hours were used as radiation input in SWAT. Figure 33 illustrates the monthly average of solar radiation from 2007 to 2016. Figure 34 shows the discharge curve of the uncalibrated model.

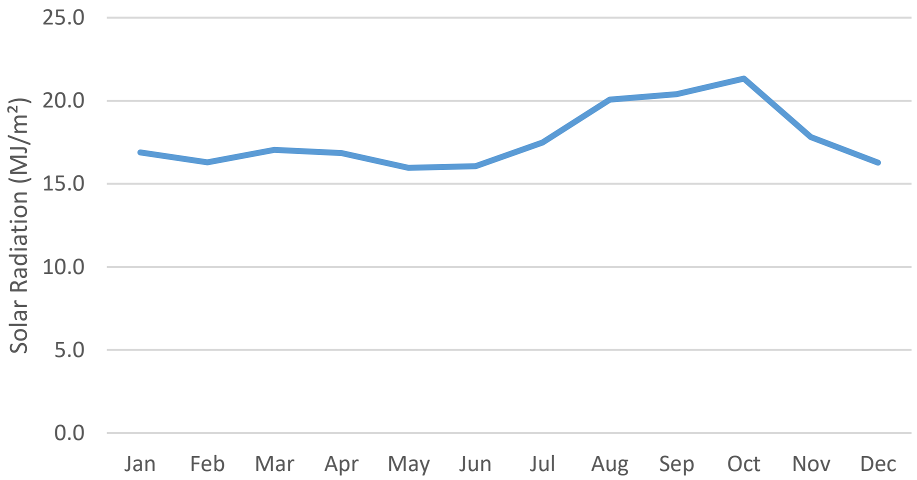

Figure 33. Monthly average (2007-2016) solar radiation.

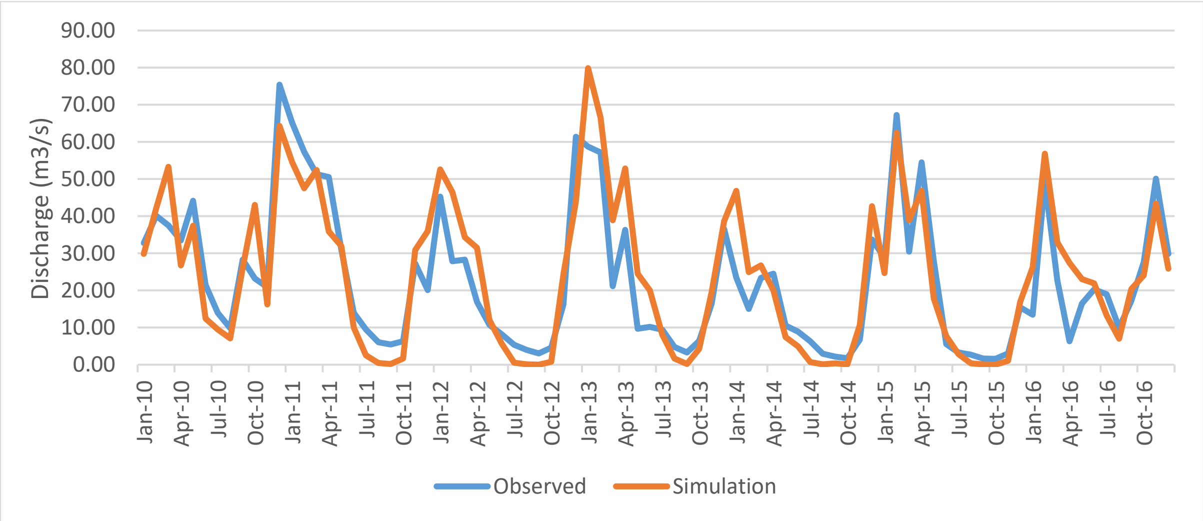

Figure 34. Observed and uncalibrated discharge of Keduang watershed.

4.1.4. Soils

The soil map of the catchment that was used is presented in Figure 8. The combination of soil properties from Puslitanak (1992) and the FAO world soil map were generated into the SWAT2012 database. The boundary of the world soil map from the FAO is much less detailed, but the description is more detailed than the soil map from Puslitanak. The FAO soil classification is assigned by a specific code, for instance, Lv5-3b. This code can be explained in the following way:

- Lv is the dominant soil, a Vertic Luvisol.
- 5 is the code for the associated soil, Vertic Luvisol.
- 3 defines the textural class (1 coarse, 2 medium, 3 fine),
- b defines the slope class (a 0 – 8 % slope, b 8 – 30 % slope, c > 30 % slope)

Each soil from the soil map of the Wonogiri Dam catchment had to be assigned to a soil-code from the database. This might not always be reliable, as properties of a soil can vary even in the same qualifiers and soil group.

Table 5 illustrates the classified soils from the Wonogiri Dam catchment and the FAO soils they were assigned to. Apart from soil reference group and qualifiers, the FAO soils were selected based on the parent material, texture class, slope, region and the best fitting associated soils (cover > 20 % of area).

The soil characteristics in the SWAT database were examined in order to understand whether the effect of soil properties on erosion can be modelled with this database. As described in section 3.5, the parameters that are directly related for the incidence of erosion in SWAT are those used in the MUSLE and those used in the SCS curve number approach. Table 6 describes all soil parameters that are directly relevant for the soils from the database. The soils are sorted based on erodibility factor (USLE_K1, from high to low). It can be observed that the database does not include rock fragment of the soils. This is problematic due to the influence of rock fragments on erosion and its importance in the MUSLE model. Rock fragment cover was assumed to be significantly higher than the rock content of the soil because the fine material is more easily washed from the soil surface. Rock content was adapted depending on slope and parent material (see Table 4). Rock fragment cover proved to be a very sensitive parameter for erosion.

Table 4. Rock fragment cover.

	Tertiary Soils	Quaternary Soils
Slope %	Rock Content (%)	Rock Content (%)
0-4	0	0
4-12	10	5
12-20	20	10
>20	20	10

Table 5. Soil assigned from the FAO database.

Soil Map USDA System	Assigned FAO–Soil	FAO Associated Soils	FAO Occurrence	FAO Lithology
Alfisol	Lv5-3b	Vertic Luvisol	Java	Consolidated clastic sediments (Sandstone, siltstone, shale, conglomerate)
Entisol	Tm23-2c	Mollic Andosol	Java	
Inceptisol	To25-2b	Ochric Andosol	Java	

Table 6. Extract of parameters from the soil database.

Soil Name	**SNAM**	**HYD-GRP**	**TEX-TURE**	**SOL_BD1**	**SOL_AWC1**	**USLE_K1**
Mollic Andosol	Tm23-2c	C	Loam	1.1	0.172	0.2512
Ochric Andosol	To25-2b	C	Clay Loam	1.1	0.192	0.2202
Vertic Luvisol	Lv5-3b	D	Clay	1.4	0.178	0.1948

4.1.5. Land use

The land use data that was selected is based on the land use map from BIG (2000) which was created by classifying satellite and aerial images as well as validation through ground surveys. This map does not include specific crops except rice. The most dominant land use classes in the catchment are rice (35 %), residential (26 %), agricultural land close grown (17%), forest deciduous (16 %) and forest mixed (6 %). Of some relevance are also waterbody (0.42 %) and grasslands (pastures and range-grasses 0.15 %).

The SWAT database contains various crop types and other types of land cover. Thus, it was easily possible to connect or relate the land use data to the SWAT database. It is, however, unknown if the parameters are accurate for the crop species used in the Wonogiri Dam catchment. A similar uncertainty exists for other land cover types. Table 7 illustrates the parameters that are directly related to soil erosion parameters from the SWAT2012 database. The most important parameter is the curve number (CN2) of the land cover classes. CN2 based on the hydrological soil group. Only the CN2 values for the hydrological soil groups C and D are relevant for the watershed. The crop database includes many other parameters that affect plant growth, water and nutrient uptake and thereby indirectly control erosion. Studying those parameters and determining whether or not they fit the conditions and plant species in the study exceeds the scope of this study but should be tackled in future research.

Table 7. Extract of land use parameters from the SWAT 2012 database.

CPNM	CROPNAME	USLE_C	CN2C	CN2D	OpSchedule
AGRC	Agricultural Land-Close Ground	0.03	81	84	AGRC
FRSD	Forest-Deciduous	0.001	73	79	FRSD
FRST	Forest-Mixed	0.001	73	79	FRST
PAST	Pasture	0.003	79	84	PAST
RICE	Rice	0.03	81	84	RICE
URHD	Residential-High Density		72	79	URHD
URML	Residential-Medium Low Density		72	79	URML
WATR	Waterbody	0	92	92	WATR

Note: CPNM (crop name), USLE_C (Universal Soil Loss Equation crop value), CN2C (Curve Number value of hydrologic group C), and CN2D (Curve Number value of hydrologic group D)

4.1.6. HRU Definition

Slope classes were set to < 8 %, 8 – 15 %, 15 – 24 %, 24 – 40 % and > 40 %. The HRU definition was set to consider areas starting from 0 % for slope, soil and land use resulting in a total of 2302 HRUs and 193 sub basins. Figure 35 illustrates the final distribution of land use, soil and slope classes.

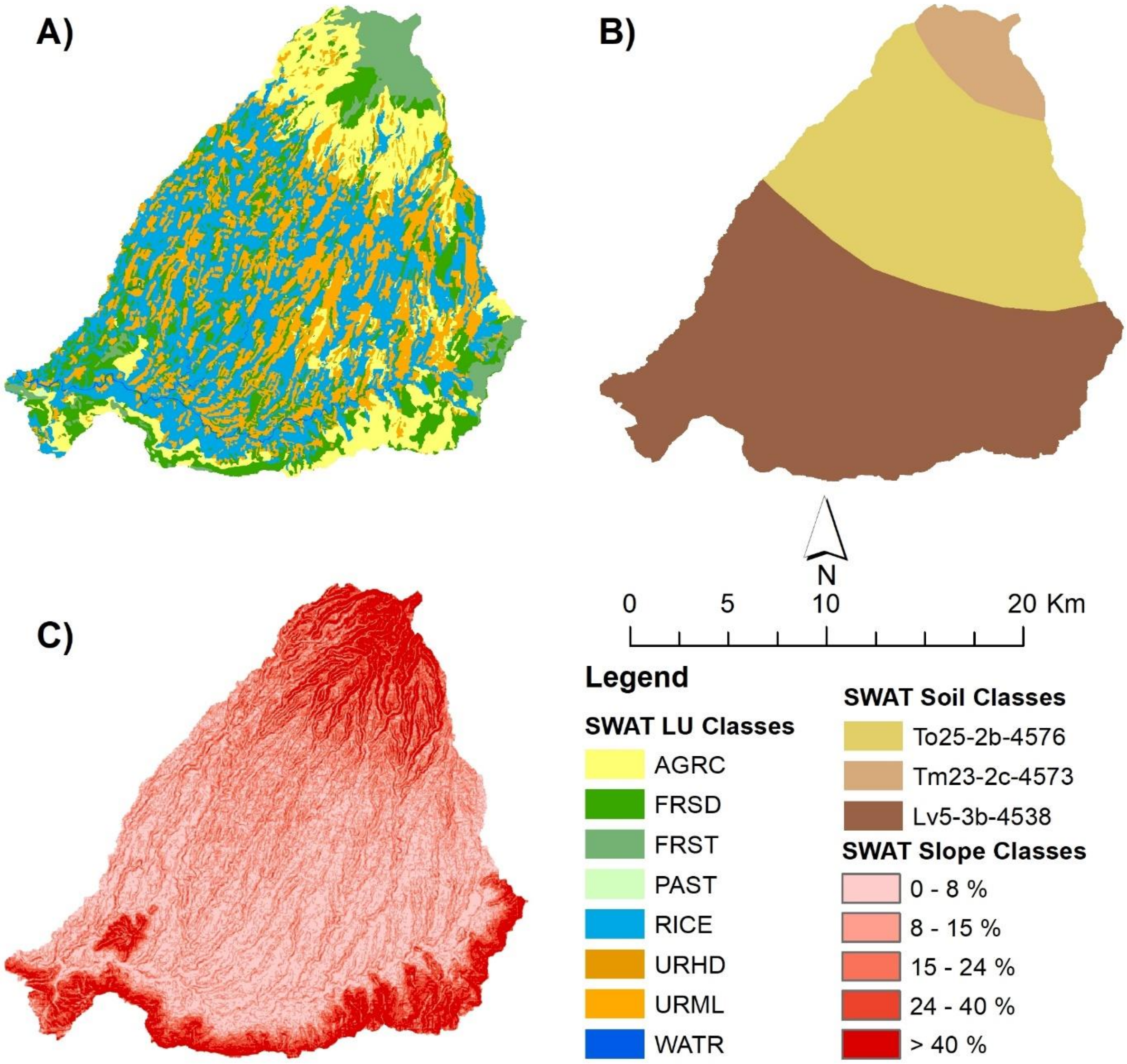

Figure 35. Land use, soil and slope definition in the SWAT project. a) Land use class distribution. b) Soil type class distribution. c) Slope class distribution.

4.2. Model Calibration

4.2.1. Calibration with SWAT-CUP

SWAT-CUP is a calibration tool that provides users the utility to perform automatic calibration of a SWAT model effectively and efficiently. The user selects a SWAT scenario for which the calibration will be generated and for which all input and output files are duplicated in the SWAT-CUP project folder.. The user also selects the parameters and allowed ranges during the calibration procedure. In the iterative process, these parameter ranges can be adjusted as seems fit or the suggested improved ranges for SUFI2 in SWAT-CUP can be applied.

Parameters can be adjusted for the total watershed or only for particular locations, for example only for certain soil layers, land covers, sub-basins, or management operations. The parameterization is an important procedure for the calibration process. Abbaspour (2015) explains the balance that needs to be achieved by having numerous number of parameters to represent the conditions within the watershed and acknowledging the limited spatial resolution of the model. One more key aspect that is necessary to be evaluated during the calibration is the problem of non-uniqueness of parameters. In inversely created models, meaning models that use numerous physical input parameters from calibration, similar output can be obtained with different sets of parameter inputs. It means the parameters that were generated from calibration probably have no base in the real world. Figure 36 illustrates the ‘Swiss-cheese-effect’ that shows calibration results and the goal function for a set of parameters plotted against another parameter. The peaks signify various well-fitting results of calibration which were all obtained with different parameter values.

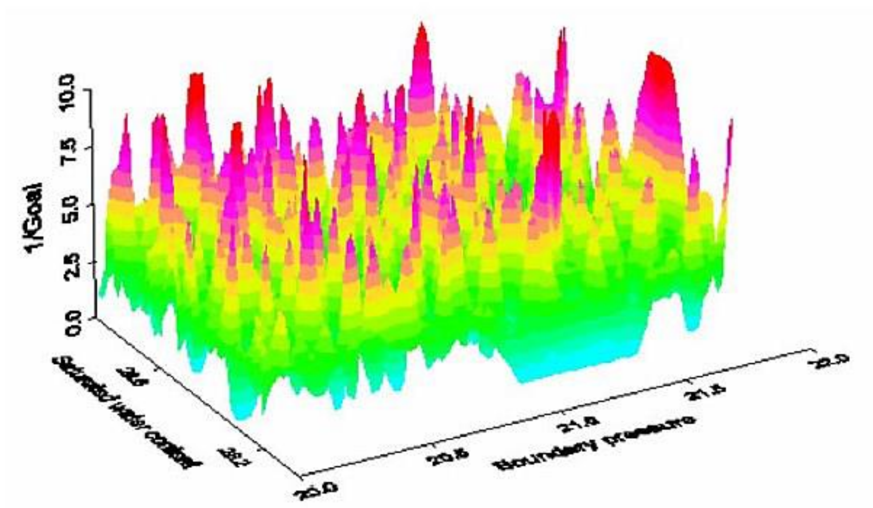

Figure 36. ‘Swiss cheese effect': A multi-dimensional objective function is “multi-modal” meaning about the availability of good solutions in many uncertainties similar with the mysterious holes in a cheese (Abbaspour 2015).

SUFI2

SWAT-CUP provides four algorithms for data optimization. One of the algorithms that commonly is used is the Sequential Uncertainty Fitting (SUFI2). This algorithm generates optimization utilising an uncertainty analysis and global search procedure. Parameter sets within the boundaries for each parameter that are defined by the user are created in SUFI using a Latin sampling. Then a particular number of model runs are generated (this simulation performed 300 iterations). During each of the iterations, a different set of parameters is tested. Lastly, the uncertainty and the goodness-of-fit of the selected parameter ranges are determined. This process is repeated until satisfactory results regarding goodness-of-fit are reached, while considering model uncertainty (Abbaspour 2015).

Uncertainty

Abbaspour (2007) also explains that calibration and uncertainty are strongly correlated. Therefore, calibration without uncertainty is misleading and meaningless. The different uncertainties held by the input parameters and by the conceptual model parameters result in uncertainties of the output variables. The user acknowledges this by accepting solution bands and parameter ranges for the results instead of single curves and values. The user determined the range of parameters which are simulated in SWAT-CUP. Then the result is a range of solutions that indicated in 95 % probability distributions bands. 95PPU (95 Percent Prediction Uncertainty) bands are the range of probability between the 2.5th and the 97.5th percentiles of the aggregate probability distribution of the results of generated iterations. The aim of the calibration procedure is to determine an as small as possible number of parameter ranges, which cover the majority of the observed data inside the range of the 95PPU band. The p-factor indicates the percentage of measured data which are inside the range of the 95PPU band. For river discharge calibration the recommendation for the p-factor is that it should reach more than 70 %. Beside p-factor, there is also r-factor which is important in order to assess the model uncertainty. It is calculated from the width of the 95PPU band, which means the average distance from the 2.5th percentile X_L to the 97.5th percentile X_U, the number of observed data points k and the standard deviation σ_X of all observations:

$$r - factor = \frac{\frac{1}{k}\sum_{n=1}^{k}(X_U - X_L)}{\sigma_X} \tag{19}$$

It is recommended to achieve an R-factor below 1 for the calibration. According to Abbaspour (2015) for the sediment calibration, a higher r-factor and a lower p-factor can be accepted.

Objective Function

In order to perform the optimization process, the user can select between various objective functions. Three of the efficiency criteria that are commonly used in watershed modelling and available in SWAT-CUP are the percent bias error index PBIAS, the Nash-Sutcliffe model efficiency coefficient (NSE) and the coefficient of determination R^2.

PBIAS is expressed as

$$PBIAS = 100 \cdot \frac{\sum_{i=1}^{n}(O_i - S_i)}{\sum_{i=1}^{n}(O_i)} \tag{20}$$

With

O_i : observed data at time step i.

S_i : simulated data at time step i.

$\overline{O}$: average of the observed data.

NSE is expressed as

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \tag{21}$$

R^2 is expressed as

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \overline{O})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(S_i - \overline{S})^2}}\right)^2 \tag{22}$$

R^2 ranges from 0 to 1, where 1 means that the dispersion of the simulated data is equal to the dispersion of the observed data. According to Krause, Boyle and Bäse (2005), this coefficient has one but a main weakness that only dispersions are measured because a continuous under or over estimate by the model will still express good R^2 values.

Nash-Sutcliffe model efficiency was developed for hydrological simulations and ranges from –∞ to 1, with 1 expressing a perfect fit. Similar to R^2, it is not very sensitive to constant under or over estimations of the model. The fact that the differences between observed and simulated data are squared causes the coefficient to overestimate large values and reduce the impact of low values. Therefore, Krause, Boyle and Bäse (2005) concluded that the optimization algorithms based on NSE would mainly fit the model to peak flows.

The model quality can also be assessed with the PBIAS, one of the error index models. PBIAS evaluates the simulated flows tendency whether to be smaller or larger than the observed data; the optimal value is 0.0, the negative values show an under-estimation and positive values show an over-estimation. Therefore, PBIAS is an indicator for the general model under or over estimation. Lower absolute PBIAS values provide better performance than higher values (Yapo, Gupta & Sorooshian 1996).

The main interest in this research is peak flows fluctuation because soil erosion mainly occurs during the rainy season. Therefore the NSE was selected as the objective function and PBIAS and R^2 are adopted as other signs for model efficiency. However, the main indicator is still the graphical comparison of the simulated and the observed hydrograph.

Uncertainty measurement of the studied data is also considered in the assessment of the goodness-of-fit. It is important to set the expected error of the measurement in the SWAT-CUP input files. For hydrological calibration, it is suggested 10 % for a measurement error and a higher value may be appropriate for sediment.

Sensitivity

The SWAT-CUP can be used to analyse global sensitivity that describes the sensitivity of the objective function to the parameter change. The analysis of sensitivity provides only an estimation of the model sensitivity, as it is carried out while other indicators are changing simultaneously. An analysis of multiple regression is utilised for that matter. A t-test is generated for each variable: The t-value is expressed as the coefficient regression of a parameter divided by its standard error. The variable is most likely sensitive if the regression coefficient of the variable is significantly larger than the standard error. Then the p-value investigates the hypothesis that the variable is sensitive. In this test suffix v_ means the existing parameter value is to be replaced by a given value and suffix r_ means an existing parameter value is multiplied by (1+ a given value). A high p-value means that the probability of the variable being sensitive is low. The results of the global sensitivity analysis for the calibration point of the monthly flow data is illustrated in Figure 37. The five most sensitive parameters in the calibration were CN2, SOL_AWC, GW_REVAP, GWQMN and GW_DELAY. Other of the parameters were excluded from the calibration because of their low sensitivity. The final set of parameters that were used in the model calibration is further explained in the next chapter.

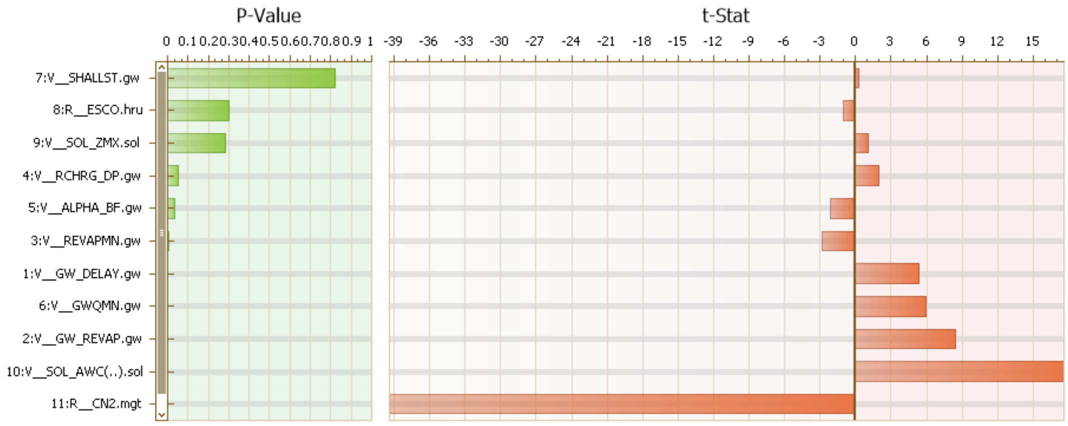

Figure 37. Global sensitivity plots of Keduang sub-watershed.

4.2.2. Observed Data

Daily discharge data of Keduang River was taken from measurements of the Watershed Management Technology Centre, which is one of research centres under Ministry of Environment and Forestry of Indonesia. The discharge data available is from 1991 to 2016, however the data that can be used is only from 2007 to 2016 due to data quality and the availability of precipitation and weather data. Calibration and validation periods for the discharge of more or less equal length were selected independently for Keduang sub-watershed within the years that precipitation input data and discharge measurements were available. Table 8 illustrates the particular calibration and validation period for Keduang sub-watershed. The observed data, similar to the weather data, is not consistent and few months are missing for calibration and validation periods. However, SWAT-CUP has the ability to exclude missing data points from the objective function.

Table 8. Calibration and validation period.

Sub-basin	Calibration Period	Validation Period
Keduang	2007 – 2013	2014 – 2016

Measurements of suspended sediment concentrations in Keduang Sub Watershed outlet were also available from the Watershed Management Technology Centre. Those, however, were not available as daily measurements but only available for particular dates from 2007 to 2016. Since the flow model was generated with set a model output with a monthly resolution, the obtained simulated sediment concentrations are also monthly averages. Observed values measured in the same month were averaged to make the data comparable to the model results. The distribution of measured data over the year is very uneven: during some month, ten or more measurements were taken and during others only one or two. Thus, it has to be acknowledged that most of these averaged sediment values cannot perfectly represent the value of the month.

4.2.3. Hydrological Calibration

The calibration of the model was performed in several phases. The Keduang sub-watershed was calibrated for river discharge at a monthly time step using SWAT-CUP. Calibration was only carried out at the discharge station

Parameterization

In general, groundwater related parameters which are largely unknown for the basin were adapted in the calibration. These parameters were calibrated on a sub-basin level. Land use and soil parameters were largely excluded from the calibration process because the effect of soil types and land use on erosion in the model would not be affected by the calibration. As described in section 4.2.1, due to the issue of non-uniqueness of parameters, land use and soil parameters obtained from a calibration are most likely not to be correct. Using such calibrated parameters might shift the impact of different soil and land use classes in an incorrect manner. The main assumption in this study is that the land use and soil parameters obtained from various sources (BIG, FAO, SWAT database, literature) are to a certain degree uncertain, but still valid. Otherwise, it will be difficult to draw a conclusion about land use and soil using this model.

The parameter ranges generated in SWAT-CUP are illustrated in Table 9. The 300 iterations were performed with these ranges. Parameters that display a very low sensitivity (p-value above 0.7) were excluded in this calibration step.

From the analysis of weather input (section 4.1.3), it was found that the low resolution of weather stations is a constraint for the model. While some of the obtained groundwater parameters may be more accurate than the default values in SWAT, it can be assumed that, partly, their change compensates for the inaccuracy of the climate input. It was therefore concluded that parameters found in the calibration should be expanded to the sub-basin covered by the same weather and precipitation stations. If the parameters represent physical properties of the area, it is also more likely that they also fit the neighbouring sub watershed. The final values for all parameter acquired from calibration are listed in Table 10.

Table 9. Parameters incorporated in the discharge calibration.

Parameter Name	Description	Range
Groundwater Parameters:	Groundwater related parameters, that are defined for each HRU in the ‘.gw’ input files. These parameters were adapted on a sub-basin level.	
GW_DELAY	Groundwater delay [days].	0 – 50
GW_REVAP	Groundwater evaporation coefficient. Determines if groundwater may move upwards from the shallow aquifer and evaporate.	0.02 – 0.20
REVAPM	Threshold water depth in the shallow aquifer for groundwater evaporation to occur [mm].	0 – 500
RCHRG_DP	Fraction of water that percolates to the deep aquifer from the root zone.	0.0 – 0.2
ALPHA_BF	Baseflow recession constant [1/days]. Determines response in groundwater flow to groundwater recharge. A low value signifies a slow response, a high value a fast response.	0.0 – 1.0
GWQMN	Minimum groundwater depth in the shallow aquifer for return flow to occur [mm].	0 – 2000
SHALLST	Initial groundwater depth in the shallow aquifer [mm].	0 – 2000
HRU Parameters:	Parameters defined for each HRU in the ‘.hru’ input files.	0 – 3000
CN2	Moisture condition II curve number	0 – 0.2
ESCO	Evaporation compensation factor. Determines if the model can extract water for evaporation from lower soil layers.	Set to 0.01 to increase evaporation.

Parameter Name	Description	Range
Soil Parameters:	Soil related parameters that are defined for each HRU in the '.sol' input files. These parameters were only adjusted for the Mollic Andosols in the northern parts of the basin. Those are actually Ochric Andosol and their soil available water capacity and maximum rooting depth are most likely higher than the very low values defined for Mollic Andosols in the database.	
SOL_ZMX	Maximum rooting depth [m].	0.1 – 0.3
SOL_AWC	Soil available water capacity.	0.02 – 0.2

Table 10. Parameter values obtained from discharge calibration.

Parameter	Keduang sub-watershed fitted values
GW_DELAY	27.916668
GW_REVAP	0.161300
REVAPM	19.166666
RCHRG_DP	0.082333
ALPHA_BF	0.828333
GWQMN	190.000000
SHALLST	1490.000000
CN2	0.019667
ESCO	0.001317
SOL_ZMX	0.116333
SOL_AWC	0.159500

4.2.4. Sediment Calibration

The sediment calibration was not carried out using SWAT-CUP, because the available observed data of sediment concentration are limited to only a few data points per sub-watershed. The model output was instead compared to the measured values graphically and parameters were adapted manually.

The first observation from comparing observed and modelled sediment concentrations showed a high in-channel sedimentation predicted by the model in Keduang sub-watershed. This process is determined by the settings for sediment routing. While sediment routing does not affect the sediment yield on the erosion sites, it strongly affects the sediment output of the outlet. In-channel deposition is expressed by the sediment delivery ratio (SDR), which describes the
ratio of the amount of sediment that reaches the outlet of a sub-basin to the amount of sediment that enters the main channel from the land surface of the sub-basin. The sediment delivery ratio is strongly affected by the selected mode for sediment routing.

With the default parameters for SPEX, SCON and the peak flow rate factor PRF (see section 3.3.3), the Bagnold method resulted in very low sediment delivery ratios for the Keduang sub-watershed. By changing those factors, the sediment delivery ratio could be changed from less than 10 % to over 90 % in all sub-basins. The high sensitivity of these parameters is further illustrated in Figure 38.

Different sets of values for SCON, SPEX and PRF were tested in order to receive sedimentation ratios from the model. Only when that objective is met, can the simulated sediment concentrations be compared to the measured ones. The predicted sediment delivery ratio for the default and best fit/selected settings are shown in Table 11.

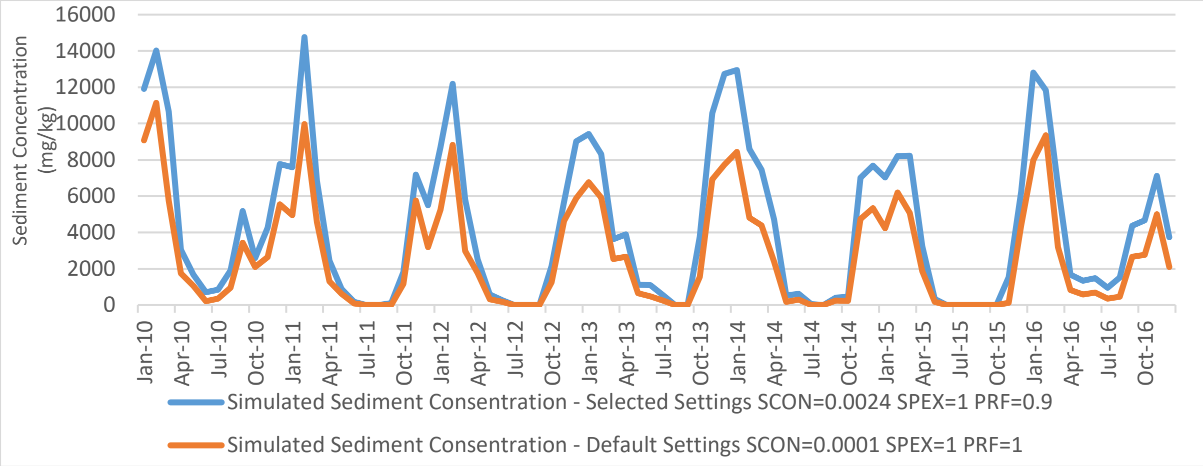

Figure 38. Sediment concentration at the Keduang watershed outlet depending on settings for SCON, SPEX and PRF.

By using the ‘best fit settings’, the model predicts the highest sedimentation ratios in Keduang sub-basin, compared to the default river reaches. This appears to be correct because, as shown in the geological map in Figure 10 recent fluvial deposits are dominant in Keduang sub-basin. The majority of geology type in the Keduang is Qlla that generally consist of the andesitic component.

The settings for SPEX SCON and PRF that best reflect the specifics of the watershed and where the simulated sediment concentrations fit the measured are shown in Figure 38. For the Keduang sub-watershed, the simulation fits the measured values well. However, too much weight should not be put on the fit of measured and simulated sediment concentrations because of the extremely limited available data which might simply not be representative. Other possible issues might regard the simplicity of the sediment routing method. Floodplain deposition is not included in this method and the texture of the transported sediment is not tracked. Undoubtedly, the predictions of upland sediment yields by SWAT are also quite uncertain due to the many uncertainties in the input parameters.

Other changes of erosion related parameters are described in the sections about land use and soil input. Those were, however, largely based on findings from the literature review and are therefore not part of the calibration process.

Table 11. Resulting sediment delivery ratios from different settings for sediment routing

Method	**Bagnold Method SDR [%]**	**Bagnold Method SDR [%]**
Parameter Settings	**Default Settings** SPEX =1 SPCON=0.0001 PRF=1	**Best Fit Settings** SPEX =1 SPCON =0.0024 PRF=0.9
Average Sediment Yield [t/ha]	259.27	325.02
Upland (North of Main River)		
Reach 9	40.8	41.0
Reach 10	78.2	76.9
Reach 14	58.2	60.8
Reach 15	100.0	100.0
South of Main River		
Reach 169	95.3	93.8
Reach 172	84.8	68.2
Reach 192	100.0	100
Reach 120 (Keduang watershed outlet)	100.0	99.8

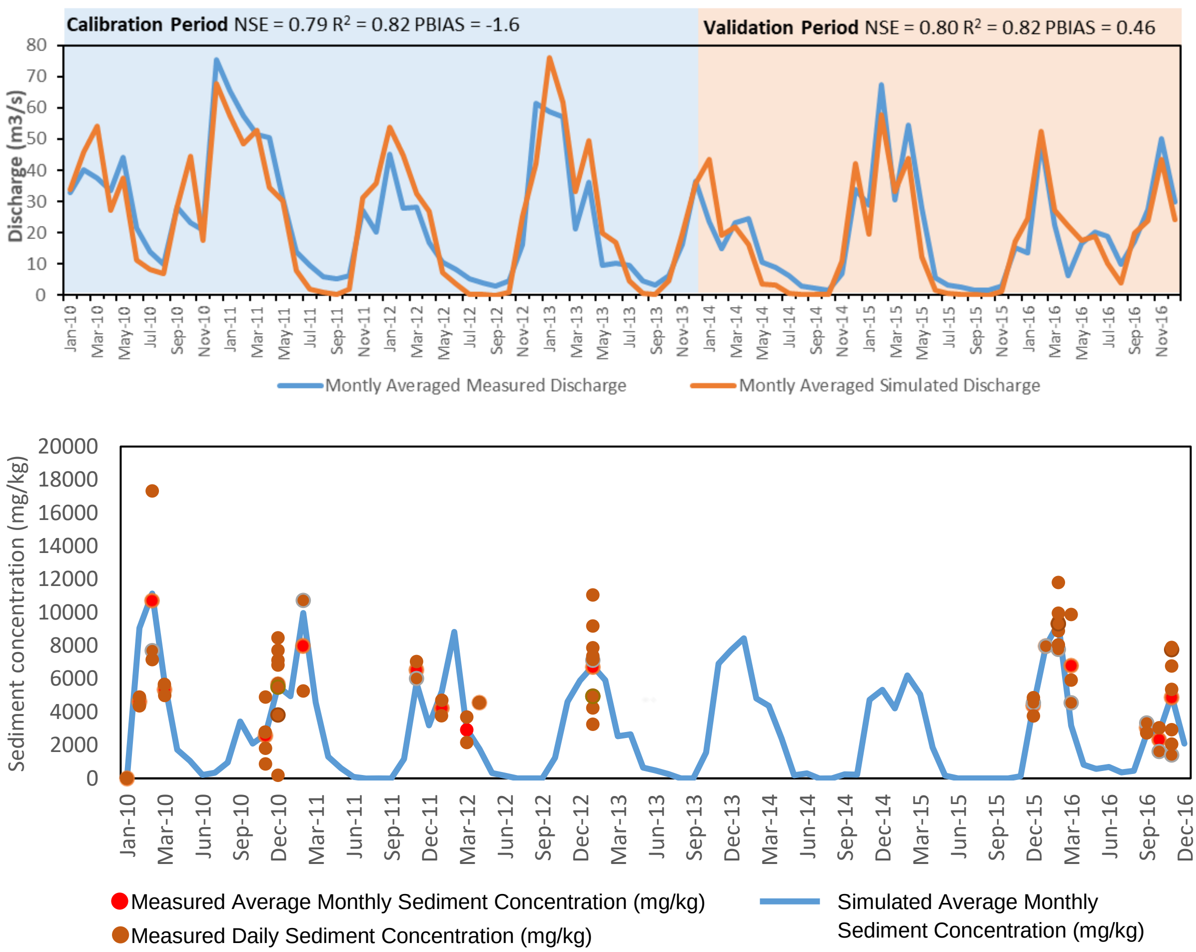

Figure 39. Keduang calibration results. Top: discharge calibration. Bottom: sediment calibration.

4.2.5. Discussion of calibration results and model uncertainty

The resulting simulated discharges and sediment concentrations at the calibration and validation points are shown in Figure 39. Parameter changes from the calibration in Keduang sub-basin were applied here. The simulated and measured sediment records were compared to evaluate this approach. The few available sediment measurements indicate that the model projects the erosion yield well.

In general, the discharge calibration was generated successfully. This explains that the model setup does not contain large flaws that affect discharge. For the validation period of Keduang River, acceptable to good results were obtained for R^2, NSE and PBIAS at the calibration points for calibration and validation periods. The p- and r-factors are listed in Table 12. The proposed values of p > 0.7 could not be reached in the Keduang sub watershed. The small number of parameters used in the calibration leads to a narrow 95PPU band, which causes the p-factors to be too low. Including more sensitive parameters such as SOL_AWC and CN might have increased the r-factor. This was rejected because it would have shifted these parameters away from their physical meaning (due to parameter non-uniqueness). Since the calibration parameters were changed in the model to the obtained best fit values, uncertainty is neglected in the further analysis of the model output in any case.

Regarding the sediment output, for which no calibration could be carried out, uncertainty is assumed to be very high. Uncertainties regarding the accuracy of many input variables that affect soil erosion is high and many of these parameters are very sensitive.

Table 12. p and r-factors from the discharge calibration.

Sub-watershed	**p-factor**	**r-factor**
Keduang	0.29	0.41

5. RESULTS AND DISCUSSION

In this part, the simulated soil loss is analyzed concerning its spatial distribution in the watershed and the temporal distribution over the series of the year. The impact of soil, land use and topography are compared and discussed to the findings from literature study. Finally, a simple scenario to determine the possible advantages from the use of soil conservation practices is implemented in SWAT.

5.1. Erosion Sensitive Areas

In order to determine the sources of soil erosion in the SWAT model, a map was created showing the average annual soil yield from each HRU in the period from 2007 to 2016 (see Figure 41). The prediction of average erosion rate is 7.9 t/ha/year and the maximum estimated loss is 1,189.3 t/ha/year for one HRU in sub basin number 20. Based on HRU polygon, 15 % of the Keduang watershed experience a higher soil erosion than the approximate amount of soil that is formed in a year (approximately 10 t/ha). Within the basin, the sub basin with the erosion rates more than tolerable rate is located in 25 sub basins and the sub basin number 9 experience the highest erosion, where the rate is more than 35 t/ha. This result is supported by the finding from other research. According to Tjakrawarsa and Pramono (2012), Keduang sub-watershed deliver the highest annual loads of sediment to Wonogiri Dam, during 1994-2002 circa 29 ton/ha/year, which increased significantly in the period of 2009-2010 to around 45 ton/ha/year. Furthermore, erosion gullies and badlands were found in particular area in the Keduang sub-watershed by Donie (1995). On the high gradients in the Upland area of Keduang watershed, a severe erosion risk is estimated by the SWAT model as well.

For larger areas of the sub watershed, losses are estimated to be 13 – 37 t/ha/year. A soil loss of 20 t/ha/year corresponds to an average soil loss of 0.5 mm/year. Assuming a soil formation rate of 1 mm/year and an average bulk density of 1.3 t/m^3 this is calculated as follows:

$$Soil\ Loss = \frac{20\ t/ha}{1.3\ t/m^3} \cdot 0.1 \frac{m^3 \cdot mm}{ha} - 1mm = 1.5mm - 1mm = 0.5mm$$

Over an extended period of time, this seemingly minor soil loss of 0.5 mm per year will still cause severe damage, especially when considering that in large parts of the basin soils are already very shallow (Alfisol are widespread in the southern areas of the Keduang watershed).

Concerning the spreading of soil erosion in the Keduang watershed, the easiest distinguishable sign is related to gradient level of slope. On slopes below 8 %, the vulnerability of soil erosion is generally low. With increase of slope, the vulnerability of soil erosion is increasing too, especially on rice fields and agricultural areas. Annual precipitation is another aspect and the upland area of Keduang watershed receives higher annual precipitation (Figure 25) and also have the highest vulnerability of soil erosion risk according to the SWAT model. The impact of higher annual precipitation becomes especially obvious when comparing soil loss in the upper area of Keduang watershed. Soil type and land use are largely similar in the upper area. When comparing the areas with the similar slope class 0-8%, erosion is still estimated to be higher in the northern area, than in southern area (see Figure 41). This is due to the fact that precipitation input from Jatipurno and Girimarto SKT rain gauges are higher than from Keduang and Jatiroto stations.

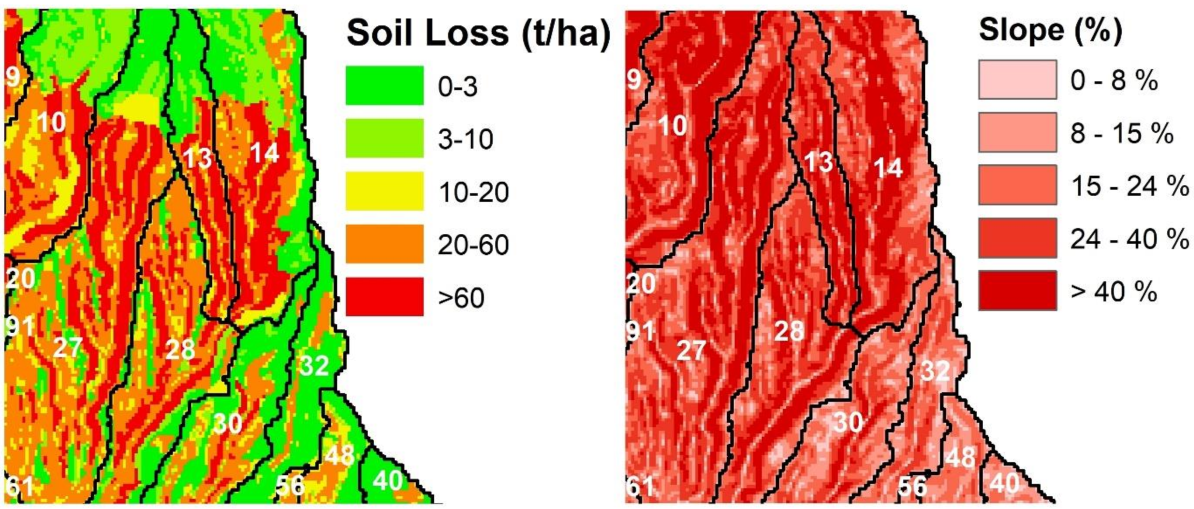

Figure 40. The impact of rainfall on soil loss in sub-basin number 13, 14. Left: Soil loss predicted by SWAT. Right: Slope classes in the two sub-basins.

Similar results can be observed based on the slopes of sub basins in the Keduang watershed. An important assumption related to the model setup can be concluded from these observations: even though the weather stations were selected to fit the average precipitation in each sub-basin, the change between areas of low and high rainfall intensity is not adequately represented in the model. This problematical fact might also to some extent bias the model output for soil erosion and the impact of soil and land use. Therefore, it is essential to have high resolution weather input for modelling the soil erosion in a catchment with diverse precipitation or climate such as Wonogiri Dam catchment.

In order to further validate the results, it is important to compare the results with other studies. In their study, Basuki, Tyas Mutiara and Wijaya (2015) estimated an average annual soil yield of 50.1 tons/ha/year from the Keduang watershed in 2011. The model output is an annual average of 58.07 tons/ha/year for the same period. The very high soil loss that the model calculates for Keduang River is also supported by another formula such as Utomo-Mahmud and Bols (53.9 ton/ha/year and 98.9 ton/ha/year respectively.

Basuki, Tyas Mutiara and Wijaya (2015), Wuryanta (2014), and Pramono (2012) determined the distribution of soil erosion hotspots in Wonogiri Dam catchment including the Keduang sub-watershed basin using USLE and a multi criteria analysis. Erosion hotspots (> 50 t/ha/year) were identified in the upper area / northern area of Keduang sub-watershed. While in the southern area of the watershed, the results of three studies are quite similar, and predicted soil yields were less than 25 ton/ha/year. It can be assumed that the selection of different precipitation stations is affecting the model output. The high erosion estimated from upland is thus most likely caused by the high precipitation from Girimarto SKT and Jatipurno weather station. Other factors that cause differing results are most likely the altered input parameters for land use and soil. Even though this research in general used similar input data (a slightly modified soil map and the similar land use data), modifications of input parameters (e.g. USLE_C factors and rock content) highly likely contribute to the various results in the model output.

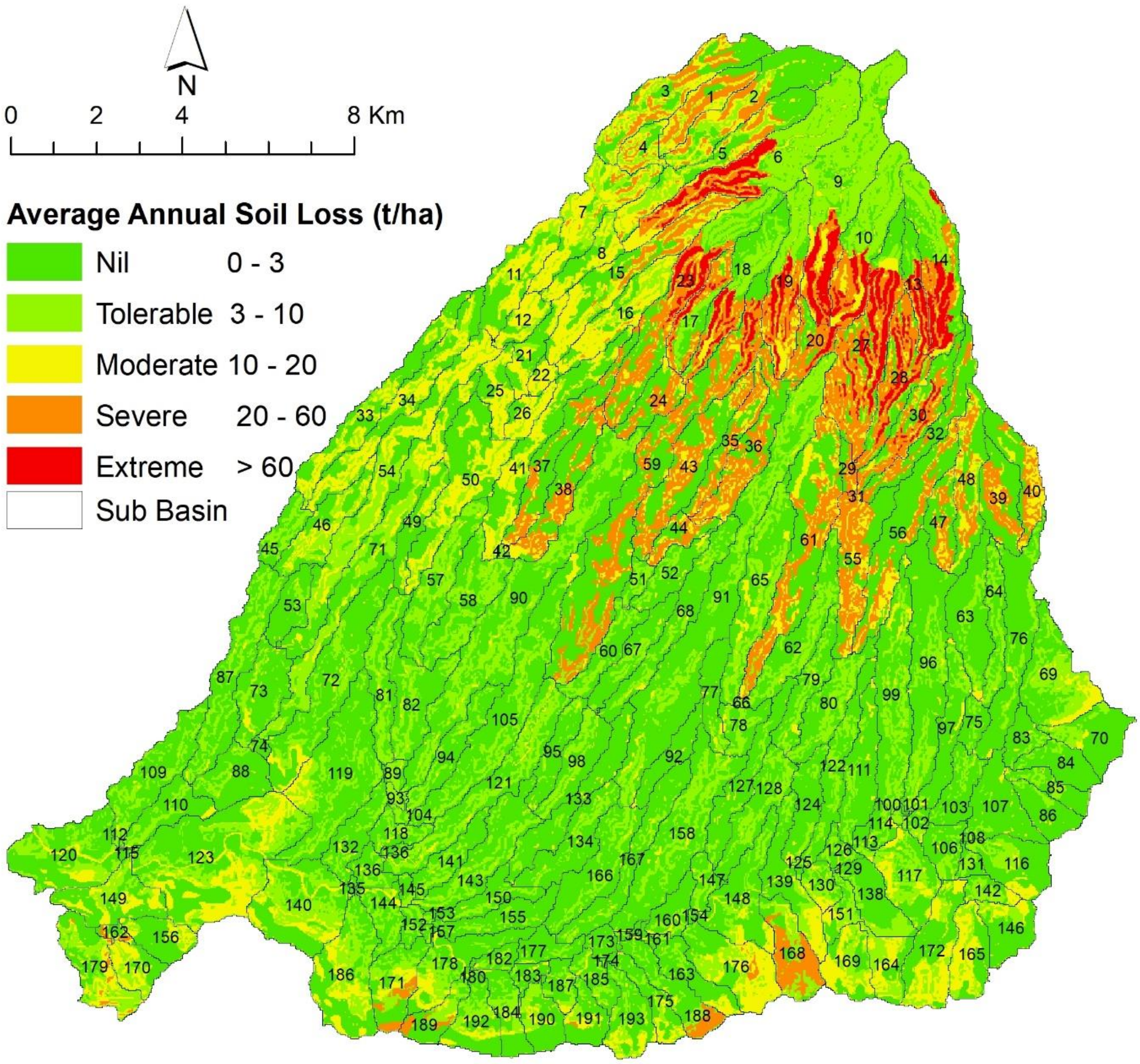

Figure 41. Average annual soil loss predicted by SWAT model for Keduang watershed from 2007 to 2016. In these figures, soil formation is not considered. Soil loss below 10 t/ha is balanced out by soil formation (see section 3.3).

5.2. Impact of Land Use and Soil and Topography

The mean of annual soil loss from the different land use types is illustrated in Figure 42. The highest erosion (15.2 t/ha and 10.6 t/ha) is predicted on agricultural land close grown and rice field. This observation is largely due to the location of agricultural land and rice fields on the hillslopes that are too steep for cultivation. This is also shown by the strong correlation of the topography factor USLE_LS and the sediment yield (see Figure 45). The agricultural practices in the dry field that

SWAT predicts on these land use classes is most likely another factor causing these extremely high soil losses in the model.

The average soil loss from forest ranges from 0.4 t/ha in the forest area that is dominated by deciduous tree (teak) to 1.1 t/ha in the forest areas that is dominated by pine forest. The crop specific parameters are not responsible for this ranking since the average value of CN for FRSD (Forest deciduous) as well as FRST (Forest mixed) are similar than those of other land use that have the high CN values In literature, AGRC (agriculture) fields were generally described to be the most erosion sensitive. The average annual surface runoff in the areas dominated by bean production is significantly higher than in the dry parts of the basin where mainly corn is grown, which might be causing this dissimilarity.

Therefore, when comparing natural land cover (forests and water area) with cultivated land classes (agricultural and rice field), the model accurately represents the effect of vegetative / natural protection on soil loss, even on steep slopes.

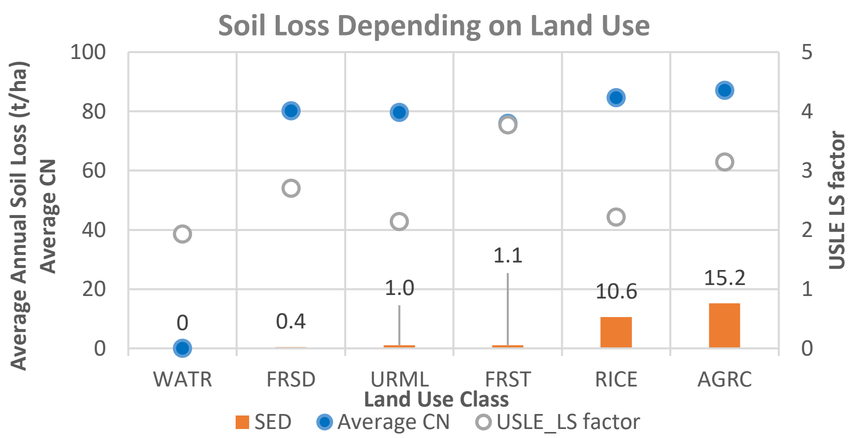

Figure 42. Average annual soil loss from the different land use classes from 2007 to 2016. The average USLE_LS factor for each land use class is illustrated as an open circle.

5.2.1. Impact of Soil Type and Rock Content

In order to enhance understanding of the impact of soil type and land use on soil erosion the average monthly sediment yields from several HRUs in Keduang watershed were illustrated and compared. Figure 43 plots average soil loss from HRUs within 8-15 % slope class with different soil types in Keduang watershed with the land use agricultural land. The average slope of the 179 HRUs is 11.5 % and the average slope length of all HRUs is 53.5 m. The graph illustrates that the soils from the Tertiary origin for which the rock content was set to 20 % have a considerably lower erosion rate (approximately 1 to 15 t/ha) than the Quaternary Entisol and Inceptisol for which the rock fragment was set to 10 % in that slope class. Compared to the impact of land use and slope, the diverging properties of the soil types, such as soil erodibility factor, hydrological soil group and available water capacity, are not significant for two types of soil (Entisol and Inceptisol) but significant for Alfisol.

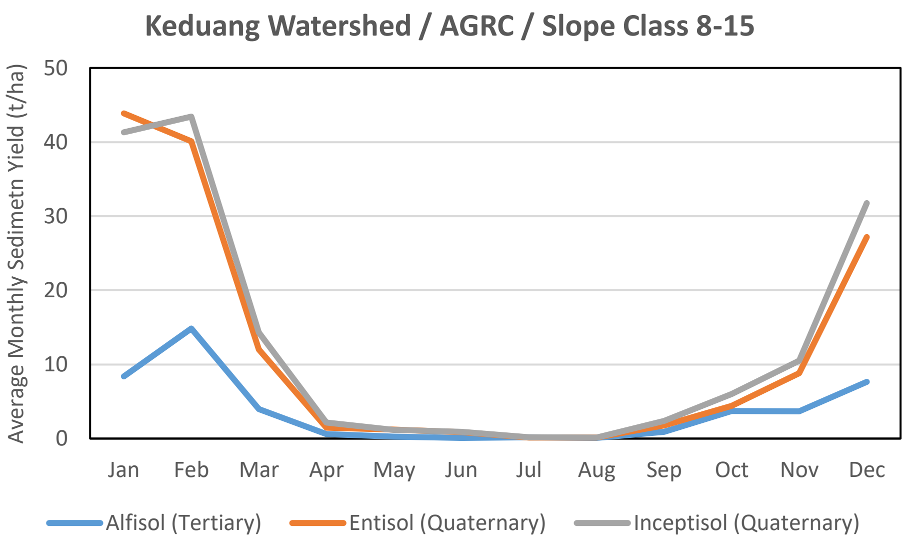

Figure 43. Impact of various rock content and soil types in the SWAT model.

5.2.2. Impact of Agricultural Land Use

The effect of various land use types was compared in a similar way (see Figure 44). The comparison can be performed because soil erosion on the agricultural area is practically low during some months especially from May to August. The average soil erosion of the agricultural area HRU for soil type Alfisol and slope 8-15% is 3.7 t/ha between 2007 and 2016 (Figure 44) and for soil type Inceptisol with the same slope range experience higher erosion rates, circa 12.8 t/ha (Figure 45). For this reason, the slope has a very strong impact on the erosion. HRUs with similar average slopes (from 8 % to 15 %) and equal slope lengths (60.97 m) were selected.

It clearly can be observed that rice field depicts the highest erosion loss followed by agricultural land, urban area and forest. The findings from the literature regarding the susceptibility of fields with different land use to erosion were thereby successfully implemented in the model. The significantly higher projected average soil loss from rice fields in the watershed stems from the concentration of rice fields in the region with lower precipitation and less erodible soils (high rock content) in the watershed. The accuracy of the land use map should however not be overestimated since it is only based on Landsat satellite images which area delineated visually by BIG.

The fact that erosion is the highest during the rain period after tillage before the crops reach a certain size is reflected for rice in the model. Similarly, for the agricultural dry field, erosion is predicted to increase over the course of the rainy season.. In general, however, in spite of the lack information regarding management practices and despite using crop parameters that were not adapted to local crop species, the implementation of different land use in the model can be considered successful.

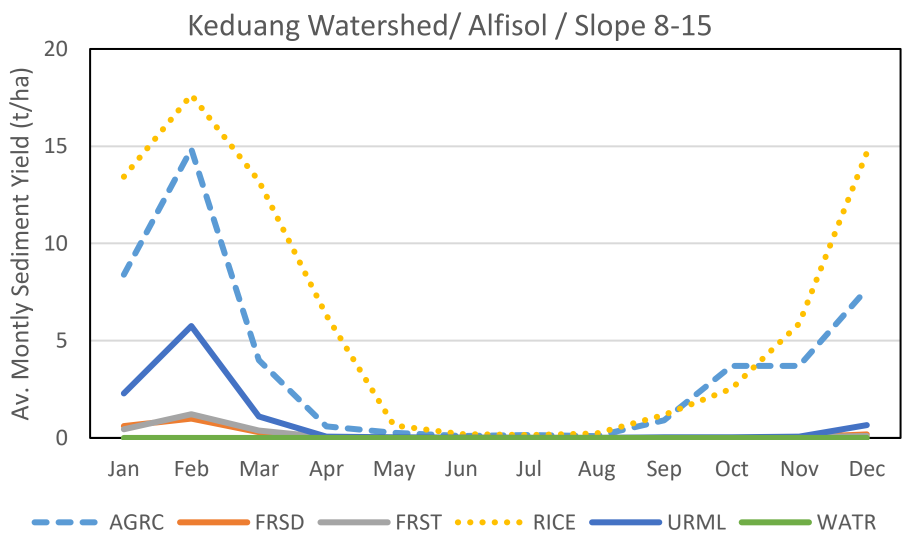

Figure 44. Impact of different land use, Alfisol and slope 8-15% on soil erosion. AGRC (agriculture), FRSD (forest deciduous), FRST (forest mixed), RICE (paddy), URML (urban area) and WATR (water body)

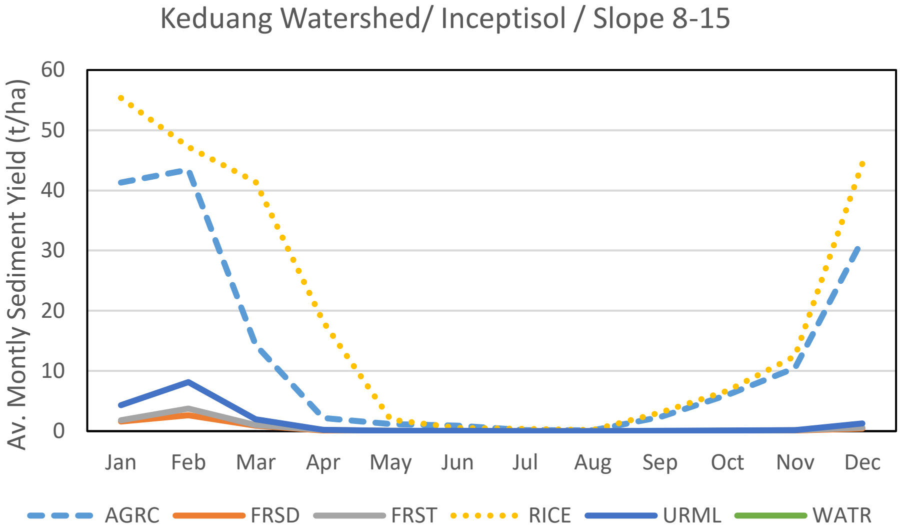

Figure 45. Impact of different land use, Inceptisol and slope 8-15% on soil erosion. AGRC (agriculture), FRSD (forest deciduous), FRST (forest mixed), RICE (paddy), URML (urban area) and WATR (water body)

5.2.3. Impact of Topography

The impact of slope for different land use types is shown in Figure 46. The average annual soil loss depends on the slope, for HRUs with the soil type Inceptisol in Keduang watershed it is illustrated in the Figure 46. It clearly can be observed, that with increasing slope, the soil erosion increases strongly for all land use types especially rice fields and agricultural area. The step shape of the graphs is highly likely influenced by the classes of rock fragment defined for the soil type (0% / 10% / 20%).

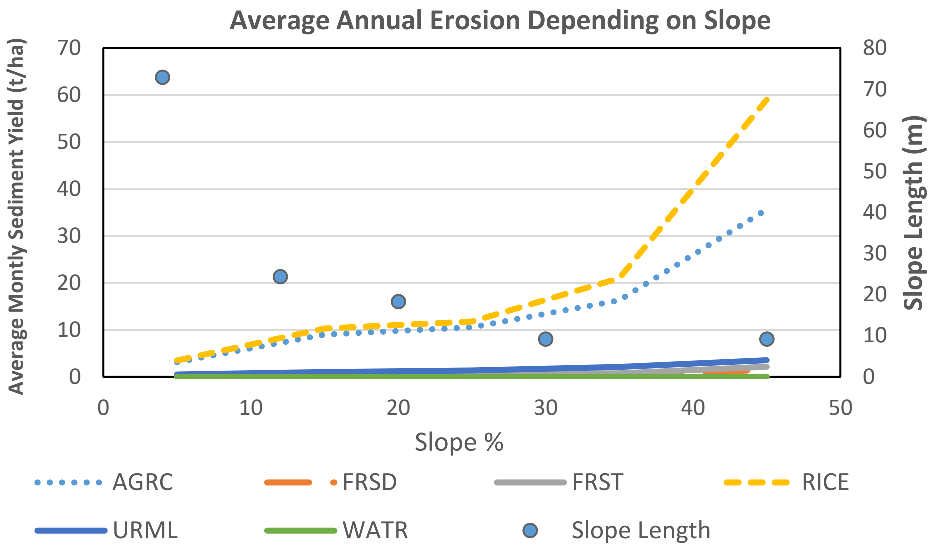

Figure 46. Impact of slope on soil erosion.

5.3. Soil Conservation

One of the most important factors for soil erosion which was not incorporated in the SWAT model is the practice of soil conservation measures. Those can be generated in the SWAT model by modifying the USLE_P (support practice factor). The effect of the construction of bench terrace is explained in this section.

The implications of the construction of different terraces were studied by Panagos et al. (2015). In consideration of social, economic and technical aspects of the maintenance and construction of bench terrace, the authors recommend their extensive use in Europe. Panagos et al. (2015) estimated a USLE_P factor of 0.2 for well-maintained reverse slope bench terraces based on interpolated terraces dataset at 1 km resolution. The negative effect is caused by the removal of grass as cover crops from the fields, which is reflected in this value.

Bench terraces were initially not included in the model, as their distribution in the watershed is unknown. In order to determine the possibility of advantages of an area with the construction of bench terraces on steep hillslopes in Keduang watershed, the USLE_P factor was modified in the model. For all agricultural area and rice field in the slope classes 8-15 %, 15-24 %, 24-40 % and > 40 % the USLE_P factor was set to 0.2.

The model estimates a reduced average soil loss based on HRU of 3.2 t/ha instead of 7.9 t/ha. The maximum soil yield is reduced from 1189.3 t/ha to 382 t/ha. Figure 47 illustrates the comparison of soil erosion map between default and modified USLE P. Although this is a very simple scenario, it shows that the implementation of soil conservation practices such as reverse side of bench terrace can reduce soil erosion significantly. In view of the current situation in the Keduang watershed, the efforts in this practice are clearly important to be encouraged and promoted by stakeholders.

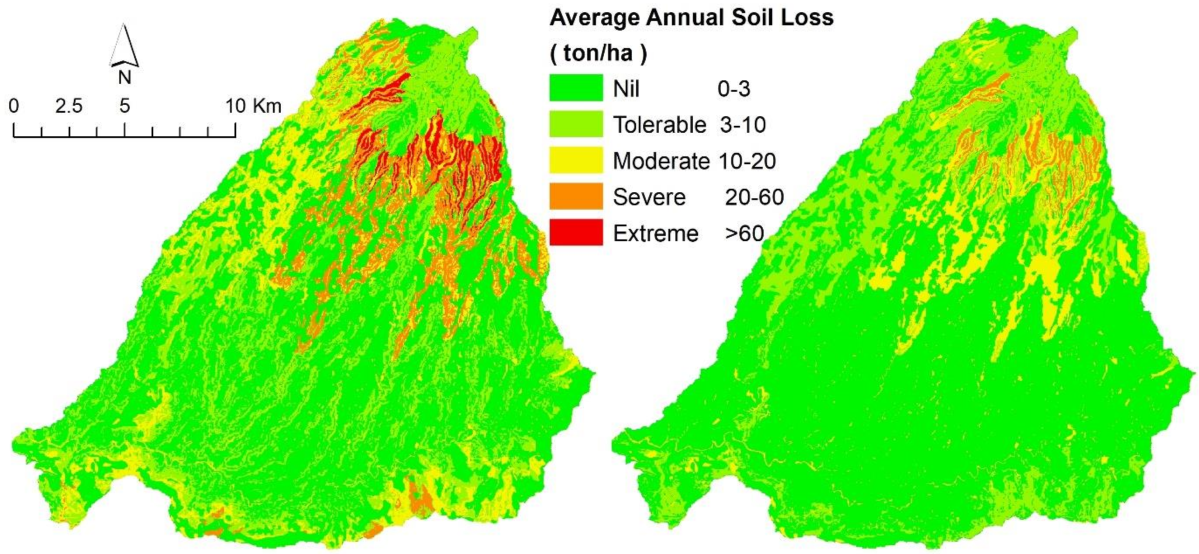

Figure 47. Left: Soil erosion map without conservation practices (USLE_P = 1) Right: Soil erosion map with conservation practices.

6. CONCLUSION

The purpose of this research was to evaluate the vulnerability of soil erosion in Wonogiri Dam catchment especially Keduang watershed by utilising the SWAT model. In order to suitably set up the SWAT model, land use, soil types, DEM and management operations were studied by a literature review. Moreover, the processes and governing factors of soil erosion by water were also evaluated and compared to their performance in the SWAT model.

The data input, such as a soil map and land use map, were analysed and linked to available soil and land use parameter databases. Several parameters were modified based on findings from literature (soil rock content, USLE_C factor). For most soil properties and land use classes a high inaccuracy has to be assumed. Not only because the databases were not built specifically for the tropical area, but also because most parameters are likely to vary within the research area.

The location of weather and precipitation stations proved to be a very sensitive step in the SWAT model setup. The weather stations were selected to fit the average annual precipitation in the Keduang watershed. In some cases, the coordinates of the weather stations were changed to a minor degree in order to control their assignment to a certain sub watershed. The model output of discharge could successfully be calibrated at Keduang watershed outlet. Land use and soil parameters were excluded in the calibration process in order to avoid a shift away from their physical meaning.

As the next process, the output of suspended sediment was compared to available measurements from the Keduang suspension station. Due to the limited consistency of the measurements, no calibration was carried out for sediment. Instead, observed and simulated sediment data were compared graphically. In this step, two settings for sediment routing were tested and the estimated sediment delivery ratios were analysed. In some sub watersheds, the sediment delivery ratio is estimated to be almost 100 % independently of the settings for sediment routing. In other sub watersheds, however, the sediment delivery ratio can be varied from < 10 % to more than 90 % by changing the main parameters for sediment routing SCON and SPEX. Therefore, these results indicate that the accuracy of sediment routing in this SWAT model is low. As a result, an important point for next studies can be drawn. Currently, several types of research on modelling of soil erosion with SWAT include the highly sensitive parameters SCON and SPEX in the sediment calibration. However, sediment delivery ratios are rarely reported. The findings from this research propose that sediment delivery ratios should be discussed and reported to evaluate SWAT erosion models.

The comparison of observed and simulated suspended sediment concentrations showed acceptable fits considering the high uncertainty of input parameters for sediment. The uncertainty of input parameters that affect soil erosion in SWAT model creates a high uncertainty in the model output. The MUSLE formula consists of several empirical factors that represent different impact factors for soil erosion which are multiplied with each other. The range of some of these factors is very large which makes them highly sensitive. For instance, a rock content of 5 % in soil reduces soil loss approximately 20 % in the model compared to a rock content of 0 %. The high uncertainty caused by limited data available of some of these factors, therefore cannot be stressed enough. Another weakness of the MUSLE is the fact that gully erosion cannot be incorporated in this erosion model.

In spite of the high model uncertainty, the severity of the situation in the Wonogiri Dam catchment especially from Keduang watershed is reflected in the model's estimation of soil erosion. An average estimated soil loss of 7.9 t/ha from the land surface of the Keduang watershed was determined for the period from 2007 to 2016, which is below the soil formation rate in the watershed. Areas of severe erosion are wides-pread in the north upland sub watersheds where the slopes are relatively steeper than in the southern part of the watershed. Extreme soil erosion rates of more than 60 t/ha/year are estimated for many sub watershed of the Keduang watershed.

In order to determine the impact of topography, land use and soils on the estimated erosion, several HRUs were selected and average monthly soil loss was compared. It was determined that slope is the most dominant factor for erosion, followed by land use, rock fragment and soil type. However, for future studies, it is important to include crop species in the SWAT model because most published studies on erosion modelling in Keduang watershed have so far not been including specific crops. By implementing operation schedules and defining CN values for different operations, the progression of erosion rates over the course of the year for specific land use can be adjusted in SWAT. In combination with the use of a detailed land use map, this might improve the accuracy of model predictions significantly.

Well maintained reverse side bench terrace were implemented and simulated in SWAT by setting the USLE_P factor to 0.2 for agricultural land and rice field sloping more than 8 %. This practice is already used in the Keduang watershed and parts of Wonogiri Dam catchment Area. The model output suggests that this conservation practice could decrease average erosion rates from the land surface (based on HRU) of the basin from 7.9 to 3.2 t/ha. Increasing efforts in soil conservation are in any case essential to improve the livelihood of the Wonogiri Dam catchment farmers by improving food security.

APPENDICES

A. Explanation of Geology Symbols

Symbols	Age	Formation	Explanation
Qa	Holocene	Alluvium	Clay, mud, silt, sand, gravel, pebble and cobble
Qaf	Holocene	Alluvium Fan Deposit	Pebble, gravel, intercalation of sand and mud
Qb	Holocene	Ojo Formation	Black clay, mud, silt and sand
Qlla	Holocene	Nitopuro Formation	Generally consist of andesitic components
Qvjb	Upper Pleistocene	Breccia of Jobolarangan	Volcanic breccia, intercalations of andesitic lava
Qvjl	Upper Pleistocene	Lava of Jobolarangan	Andesitic lava flows from Jobolarangan Mountain (Old Lawu)
Qvjt	Upper Pleistocene	Tuff Jobolarangan	Lapilli tuff and pumiceous breccia
Qvl	Holocene	Lawu Volcanic Rocks	Volcanic breccia, lava and tuff
Qvsl	Upper Pleistocene	Lava of Sidoramping	Andesitic lava flows were issued from Sidoramping, Puncakdalang,Kukusan and Ngampiyungan
Tma	Miocene	Tertiary Intrusive Rocks	Andesite
Tmd	Miocene	Tertiary Intrisive Rocks	Dacite
Tmj	Lower Miocene	Jaten Formation	Quartz sandstone, tuffaceous sandstone, siltstone, claystone, marl and marly limestone
Tmn	Middle Miocene	Nglanggran Formation	Volcanic, breccia, sandstone, alternating of both in places

Symbols	Age	Formation	Explanation
Tms	Lower Miocene	Semilir Formation	Tuff, dacitic pilmice breccia, tuffaceous sandstone and shale
Tmw	Middle Miocene	Wuni Formation	Agglomerate with tuffaceous sandstone and coarse grained sandstone intercalations
Tmwl	Miocene-Pliocene	Wonosari Formation	Reef limestone, calcarenite, wilh intercalations of conglomeratic limestone, calcareous claystone
Toma	Oligo-Miocene	Arjosari Formation	Polymit conglomerate, sandstone, siltstone, limestone, claystone, sandy marl, pumiceous sandstone
Tomd	Oligo-Miocene	Dayakan Formation	Alternations of sandstones and claystones
Tomi	Oligo-Miocene	Intrusive Rocks	
Tomm	Oligo-Miocene	Mandalika Formation	Dacite-andesitic lavas and dacitic tuff with dioritic dykes

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