Application of HEC-HMS to the investigation of soil erosion and sediment yield by surface runoff

By

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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...14/12/2020....................................

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EXECUTIVE SUMMARY

The soil erosion problem due to the surface runoff has been identified in Washpool Aldinga basin. To study the soil erosion, the HEC-HMS model was applied for simulating the soil erosion and sediment yield, and precipitation – runoff process in the sub-basin scale. This project aims to develop the application process of HEC-HMS to the erosion for a basin of area 47.9 km^2 located in Washpool Aldinga SA, to understand the parameters required to the erosion and sediment model in HEC-HMS, and to calculate the sediment load and sediment concentration of the selected basin.

To estimate the sediment yield from the HEC-HMS model a precipitation-runoff model is required. Therefore, before the simulation of the erosion model a hydrological model was created. Data required from the field to simulate the HEC-HMS model was used from the published recourses due to the lack of time and resources. To simulate the precipitation-runoff model, the SCS unit hydrograph was used as the transform method, and SCS Curve Number method was used as a loss method based on Hydrologic Soil Group (HSG). From the simulation of the precipitation-runoff model, the peak discharge of 3.4 m^3/s was obtained. To simulate the erosion and sediment model in HEC-HMS, the Modified Universal Soil Loss Equation (MUSLE) was selected based on land cover, 94.6% of the study area is impervious. The total sediment load from HEC-HMS for nine hours of rainfall was 11.8 tonne and the total sediment concentration was 1.92 gm/l.

An example case study with this result can illustrate the application process of HEC-HMS to the soil erosion and sediment yield due to precipitation. Also, this study provides a guide to use HEC-HMS for the estimation of sediment deposition and concentration at the outlet of the catchment.

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LIST OF ABBREVIATION

HEC-HMS	Hydrologic Engineering Centre-Hydrologic Modelling System
USACE	The U.S Army Corps of Engineers
GIS	Geographic Information System
SCS-CN	Soil Conservation Service – Curve Number
USLE	Universal Soil Loss Equation
RUSLE	Revised Universal Soil Loss Equation
MUSLE	Modified Universal Soil Loss Equation
SCS-UH	Soil Conservation Service – Unit Hydrograph
UNBRW	Upper North Bosque River Watershed
SWAT	Soil & Water Assessment Tool
DEM	Digital Elevation Model
CN	Curve Number
LA	Los Angeles
USGS	United States Geological Survey
OM	Organic Matter
UCA	Unit Counting Area
NRCS-USDA	Natural Resources Conservation Service – United States Department of Agriculture
TSS	Total Suspend Solid
USDA	United States Department of Agriculture
SA	South Australia
ARR	Australian Rainfall Runoff
HEC-RAS	Hydrologic Engineering Centre – River Analysis System
HSG	Hydrologic Soil Group

CHAPTER 1: INTRODUCTION

1.1 Background

Soil erosion involves a three-step process. These are soil particle detachment, transport, and deposition. Soil erosion and sediment deposition are complementary processes during the detachment of soil particles from a higher elevation to deposition of sediment on lower elevation plains or flood plains(Stefano et al. 2000). The erosion process is influenced by topography, land use, soil type, vegetation type, and the size of the watershed. A detachment of soil particles is influenced by precipitation and surface overflow. Runoff-water is the erosive agent for the transportation of the detached particles (Hajigholizadeh, Melesse & Fuentes 2018). Soil particles are carried by surface runoff (sheet erosion), concentrated flow (rill erosion), and deposition of sediment due to the decrease of the slope of the terrain and flow velocity (Lal 2001; Nouwakpo et al. 2016).

On a global basis, soil loss due to erosion (caused by water) is among the top ten complex environmental issues (Eswaran, Lal & Reich 2001; Liangyi & Baoli 2002; Mbajiorgu & Adegede 2019). Soil erosion caused by water has two effects, 1) on-site effects, and 2) off-site effects (Morgan 2009). On-site effects are described by various factors such as the depletion of soil nutrients, decline of infiltration capacity, and surface sealing (Erkossa et al. 2015). Whereas, off-site effects, include the passage of sediments and agronomic contaminants into waterways. This can cause sediment deposition in dams and watercourse, and downstream flooding due to increased flow and destruction to property (Morgan 2009).

1.2 Sediment yield predictions and HEC-HMS

The precise evaluation of soil erosion and sediment deposition is a challenging process because only some part of the eroded soil transported from the higher elevation to the outlet of the basin. The remaining part of the detached soil can deposit on valley slopes, depressions, and floodplains. The effectiveness of this deposition is depending on the slope of the catchment(Charlton 2007). To compute the sediment yield, the integration of the hydrological process with the erosion process at the watershed is required. The modelling approach is used to accomplish this integration.

Hydrological models describe the fundamental components (precipitation and surface runoff) of the erosion model. The erosion model converts these initial conditions into erosion and sediment transport processes (Jetten, Govers & Hessel 2003). The different hydrological models, for example, HEC-HMS, HEC-RAS, and SWAT can be applied to analyse the erosion and sediment transport process due to surface runoff. HEC-HMS version 4.6 is one of those modelling systems which has the capacity to compute the surface erosion analysis based on the hydrological model (USACE, H 2016). To parameterization, the erosion process GIS tool is important, which is integrated into the HEC-HMS version 4.6.

1.3 Scope and objectives

The main goal of this thesis is to contribute to the understanding of the application of HEC-HMS to the investigation of soil erosion and sediment transport process. Globally, HEC-HMS has been applied to the hydrological modelling for many basins, However, the application is comparatively less in erosion. The work in this project is expected to guide erosion and sediment modelling in HEC-HMS. The goal of this study is as follows:

1. To conduct an example case study of erosion and sediment yield by the application of the HEC-HMS model for a basin located in Onkaparinga council at Washpool Aldinga.
2. To understand the method and parameter selection for the erosion and sediment transport model in HEC-HMS.

3. To check the HEC-HMS in erosion and sediment process by the estimation of sediment deposition in a basin (Washpool Aldinga).

1.4 Thesis outline

This thesis includes five different chapters. Chapter 1 provides the introduction including background, sediment yield predictions and HEC-HMS, scope and objectives, and thesis outline. Chapter 2 presents the review of available literature, focused on soil erosion, surface runoff, and erosion components. Chapter 3 outlines the HEC-HMS and its application to the erosion and sediment process. This chapter is focused on understanding the input parameters for soil erosion and sediment transport modelling. Chapter 4 provides an example case study application of HEC-HMS to the erosion and sediment transport modelling. A grouping of selected methods and parameters are presented, this consists of developing a hydrological model operating the SCS curve number method as loss method, erosion model using MUSLE, and sediment model using Laursen-Copeland method. This chapter helps to understand the process of the application of HEC-HMS to erosion and sediment modelling. Chapter 5 provides conclusions.

In the appendices section, detailed procedure (steps) of HEC-HMS for the erosion and sediment modelling and additional information including calculations and parameters tables can be found.

CHAPTER 2: LITERATURE REVIEW

2.1 Soil surface erosion and types of erosion.

Soil erosion is extensive and the main environmental issue to the world's terrestrial ecosystems (Sun et al. 2014; Yang, D et al. 2003). On a global basis, around 33 % of the agricultural land has been destroyed due to erosion for the last forty years (Pimentel et al. 1995). Soil erosion can destroy physical infrastructures, and reduce the water quality and agricultural productivity (Nearing et al. 2005; Sun et al. 2014). Soil erosion due to rainfall-runoff is a severe form of erosion, this type of erosion has destructive impacts including land degradation and non-point pollution (Jin et al. 2008; Sun et al. 2014).

Soil erosion due to precipitation flow is defined as the wearing away of the soil from the land surface due to precipitation, runoff, snowmelt, and irrigation(Blanco & Lal 2008). The overland flow due to precipitation is the key driving agent to the water erosion. It describes the transportation of the soil particles involving organic and minerals particles along the path of flowing water and deposition of sediment particles at the lower end of the land surface (Jamison, Smith & Thornton 1968).

There are different types of soil erosion due to precipitation these are splash erosion, inter-rill erosion, rill erosion, and gully erosion (Blanco & Lal 2008; Morgan 2009). The first phase of erosion is splash erosion; raindrops hit the soil on the top of the ground then the splash of the soil particles starts. Splash erosion is caused by the momentum during raindrop striking the soil surface. Inter-rill erosion is mostly due to a thin sheet of water flows over the soil surface; this type of erosion is a function of precipitation amount and basin slope; erosion starts when rainfall intensity exceeds the infiltration capacity of the soil. 70% of the total erosion is produced by splash and inter-rill erosion (Blanco & Lal 2008). Rill erosion appears due to the intensity of flow in small channels or rills. The transportation of soil particles in rill erosion is faster than in inter-rill due to the concentrated flow. This type of erosion is the function of soil erodibility and delivered capacity of water flow. Gully erosion is advanced form of rill erosion, it creates V-shaped or U-shaped channels. Gully erosion can remove the entire soil profile from the field. Gully erosion is divided in two types: ephemeral and permanent. Ephemerals are superficial channels controlled by routine tillage (i.e., cultivation of land) operations. However, permanent gullies are large and wide, hard to control by tillage.

2.2 Erosion process by surface runoff

Soil erosion due to surface runoff involves a three-phase process, the separation of the soil particles, transfer of detachment particles by erosive agent, and sediment deposition, which occurs when an erosive agent has no longer energy available to carry the particles (Morgan 2009). Soil particle's detachment from the land surface depends on precipitation and flow discharge (Figure 2.1). Surface runoff occurs due to precipitation exceeds losses, which exists of a thin layer of water. Shear stress of soil surface due to the surface runoff exceeds the cohesive strength of soil, results in soil particles detachment (Merritt, Letcher & Jakeman 2003). The detached and transported amount of sediment is controlled by the capacity of rainfall, runoff water, and downslope of the watershed. Therefore, the sediment yield is depending on terrain slope and transport capacity of runoff. The concepts of detachment capacity and transport capacity are generally used to explain the quantity of sediment deposition (Bennett 1974; Nearing, Lane & Lopes 1994). The detachment capacity is defined as the maximum detachment rate due to the water having no sediment, the transport capacity is described as the maximum quantity of sediment transported by surface runoff without net deposition occurred (Nearing, Lane & Lopes 1994).

Image removed due to copyright restriction.

Figure 2.1: Soil erosion process. a) Falling raindrop, b) Separation of soil particles after hitting of a raindrop on the ground surface.

Source: (Bardy et al, 1999)

2.3 Sediment yield

Sediment yield specified the amount of soil particles deposited at the outlet of the basin. Sediment sources are mainly the types of surface erosion, channel and stream bank erosion and the amount of the eroded sediment depends on the soil types, terrain data, cover factor, precipitation, and flow (Onstad 1984). Sediment deposition at the basin outlet is generally estimated by multiplying total upstream erosion with sediment delivery ratio. The mathematical forms are shown in equation (2.1), (Julien 2010; Yang, CT 1996).

$$S_{DR} = \frac{Y}{A_T} \quad \text{……………………………………….. (2.1)}$$

Where, S_{DR} is sediment delivery ratio (dimensionless), Y is the average annual sediment yield per unit area and A_T is total soil erosion at measuring point from the basin upstream throughout inter-rill, rill, gully, and stream bank erosion process.

The S_{DR} can be described as the part of the sediment deposited downstream of the basin from the total erosion. Sediment yield from the basin outlet is generally lower in magnitude than the erosion estimated from hillslope plots (Edwards 1993; ROSEWELL 1996). The sediment delivery ratio is mainly empirical because it is challenging to find the major limitation on the erosion process due to the spatial variation of watersheds.

The maximum amount of sediment particles, carried by a flow based on a specific slope of the terrain is called sediment delivered capacity of the flow. (Merten, Nearing & Borges 2001). From the literature review, flow velocity and gradient of the terrain influenced the transport capacity of the flow. (Prosser & Rustomji 2000; Zhang, G-h et al. 2009). Infield, the measure of precise flow velocity is difficult in comparison to the remaining factors such as rainfall intensity and, length and width of the flow path, particularly in shallow and unconfined flow. However, the flow rate and slope gradient of surface runoff (due to rainfall), which are the main transporting agent and these are completely different from the stream flow conditions (Hessel & Jetten 2007).

2.4 Factors controlling surface erosion

The main components, which control the erosion process are the topography of the land, soil type, cover of the land, and precipitation (Blanco & Lal 2008; Morgan 2009).

2.4.1. Precipitation:

As already clear, Soil erosion is directly linked to the precipitation, some part of the precipitation force contributes to the detachment of soil particle and some parts contributes to the surface runoff, this applies specifically to the erosion due to overland flow (Morgan 2009). High rainfall intensity leads to higher overland flow and more soil erosion; therefore, the concentration, duration, and precipitation directly impact surface erosion. An only a certain amount of runoff will generate soil erosion and this is called a threshold value of erosion, below a threshold, there will have no erosion and sediment deposition (Morgan 2009).

2.4.2. The topography of land:

Topography can significantly impact soil erosion. The slope and size of the watershed affect flow generated due to precipitation. The topographic factor can be estimated by using the Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE), and Modified Universal soil Loss equation (MUSLE)(Hickey 2000; Zhang, X et al. 2018). Many studies revealed that soil erosion is proportional to the terrain slope (Nord & Esteves 2010; Zhang, X et al. 2018). However, soil degradation due to surface runoff is not linearly proportional to the slope gradient.

2.4.3. land cover

land cover is considered as the significant factor affecting runoff and erosion (García-Ruiz 2010; Nunes, De Almeida & Coelho 2011). Many researchers have revealed that in various environmental conditions, the overland flow and sediment yield process depends on vegetation cover, increasing vegetation cover can resist the erosion process, reducing the erosive capacity of rainfall due to adsorbing and intercepting the precipitation. To minimise the soil loss short and dense types of vegetation are more effective than the taller vegetation(Blanco & Lal 2008).

2.4.4. Soil properties and Soil texture:

Soil properties**:** Soil structure, soil texture, and organic matter are the predominant soil properties. It affects the soil erosion and sediment transport process.

Soil texture: clay soils are more cohesive than sandy soil, thus the soils with high sand content are more eroded. Clayey soils have high resistance to erosion in comparison to coarse-grained soil. However, after the detachment of the soil particles, clay particles are easily transported due to their smaller size. Silt particles are a highly eroded type of soil, infiltration rate is comparatively higher in silt particles than in clay soils. Infiltration rate increases with an increase in the size of the soil particles and vice versa (Blanco & Lal 2008; Wuest, Williams & Gollany 2006).

2.4.5. Soil structure:

soil structure describes the grouping of the soil particles such as clay, silt, sand, and organic matter content, it is also described as the arrangement of these particles separated by voids and gaps (Rai, Singh & Upadhyay 2017). Soil structure influences the water infiltration from the soil surface (Blanco & Lal 2008; Rai, Singh & Upadhyay 2017). Soils that are unstable, more removable, and sensitive to compaction are called poorly structured soil, this type of soils react as lower water infiltration and a higher rate of surface runoff.

2.5 Erosion model

The application of soil erosion studies is to estimate the soil loss and analysis of the source of erosion. According to Boardman and Favis-Mortlock (1998), the main goals of soil erosion are: to control the erosion and protect the soil resources, and to contribute to the understanding of the sediment transport process, deposition, and evolution of the landscape. Erosion models delivered the concepts of reality used to simulate. The selection of erosion model depends on several factors such as input data requirements, the objective of the model, scale output of the model, and basin characteristics (Hajigholizadeh, Melesse & Fuentes 2018)

On a global basis, the Universal Soil Loss Equation (USLE) is used as an empirical model as shown in equation (2.2).

$$A = R * K * LS * C * P \quad \ldots\ldots\ldots\ldots \quad (2.2)$$

Where, *A* is soil loss, unit is ton/[hectare.year], *R* is rainfall erosivity in (mm/ha.year), *K* is soil erodibility factor in (ton/ha, *R), LS* is a topographic factor, *C* is cover management factor and *P* is Practice factor and these are unitless.

Mainly Precipitation and overland flow of this equation influence the erosion as shown in equation (2.2). This model purposed by Wishmeier and Smith in 1965, based on the thousands of collected samples throughout the USA in 20 years period. During the past three decades, researchers improved this model into a computerised version, for example, the Revised Universal Soil Loss Equation (RUSLE) is a computerised model of USLE (Renard 1997).

The Modified Universal Soil Loss Equation (MUSLE) is an advanced form of both USLE and RUSLE, MUSLE is developed by using runoff energy factor instead of the rainfall erosivity used in previous models (Renard 1997). MUSLE model estimates the sediment yield based on the runoff energy factor. Excepts runoff energy factors, the rest of the factors for USLE, RUSLE, and MUSLE.

CHAPTER 3: GUIDE TO THE APPLICATION OF HEC-HMS IN EROSION AND SEDIMENT YIELD

3.1 HEC-HMS

HEC-HMS is a reliable model developed by the US Army Corps of Engineers (USACE) to simulate the hydrological process of a dendritic watershed (Pak, JH et al. 2015). HEC-HMS is the easy and maximum used software for the modelling of the rainfall-runoff process. The HEC-HMS version 4.6 is capable to simulate the erosion and sediment yield process of the sub-basin (USACE 2016b). The HEC-HMS model is used in a wide range of watershed areas for solving various problems such as flood hydrology, erosion, and sediment deposition (Pak, JH et al. 2015; USACE 2016b). The HEC-HMS model for the basin is developed by dividing the hydrological model and erosion model into several components.

3.2 HEC-HMS application

HEC-HMS models have been tested for different watersheds throughout the world. It can simulate a single event or long-term continuous models and can be used for scale watershed to large watershed, Urban as well as a natural basin (Halwatura & Najim 2013; Pak, JH et al. 2015). The analysis of the hydrological process (such as precipitation, evapotranspiration, and infiltration) and erosion process depends on land cover, basin size, types of soil, and topography (Deng et al. 2015; Pak, JH et al. 2015). Researchers who used the HEC-HMS model in different watersheds with different methods obtained satisfactory results. Consistent with the previous studies, some of the application examples are shown below:

- Based on Oleyiblo et al. (2010) research, for the flood forecasting in Misai and Wan'an watersheds in China. In this study, the "initial and constant" (loss method), and "SCS UH" (transform method) was used, SCS UH defined as the Soil Conservation Service (SCS) derived a unit hydrograph (UH) based on averages of unit hydrograph developed from gaged rainfall and runoff for numbers of watersheds in US (Feldman 2000).
- . from the result of HEC-HMS, the prediction of peak discharge was accurate based on historical flood data (Oleyiblo & Li 2010).
- The study was conducted by Pak et al. (2015) for the modelling of surface soil erosion and sediment transport process in UNBRW in Texas USA. In this study, the MUSLE (for

rural or pervious ground) and build-up/Wash off method (for urban or impervious land) were used as erosion methods and the Laursen-Copeland method was used as sediment transport method (Pak, JH et al. 2015). Based on the result analysis, HEC-HMS is applicable for rural (pervious) and urban (Impervious) area.

- HEC-HME output and SWAT model output regarding the same basin as compared to calculate the better result between them. HEC-HMS predicts a comparatively effective result (Pak, JH et al. 2015).

From the review of literature, three applications of HEC-HMS including selected methods are shown in Table 3.1.

Table 3. 1: HEC-HMS application examples based on previous studies.

Source	**Location**	**Study Area (km^2)**	**Direct- Runoff (Transform) Method**	**Erosion Method**	**Sediment Transport Method**
(Pak, JH et al. 2015)	USA	921	Clark Unit Hydrograph	MUSLE	Laursen-Copeland
(Oleyiblo & Li 2010)	China	797	SCS UH	None	None
(Choudhari, Panigrahi & Paul 2014)	India	16	SCS UH	None	None

3.3 HEC-HMS modelling

To develop the HEC-HMS model first step need to define the characteristics of the basin and sub-basin. The basin is described based on watershed physical data and their system connectivity such as sub-basin, streams, and reservoirs. The precipitation is input from the metrological model. The erosion model in HEC-HMS simulates the result by the combination of basin component, meteorological data, and control specifications.

The HEC-HMS model comprises six different methods to represent the runoff process, erosion, and sediment yield. There are some different options for each method, the choice is depending on the types of watershed and goals required to be performed. In this study for the hydrological model, the SCS Curve Number method is the simple loss method to estimate runoff. The Curve Number (CN) depends on the hydrologic soil group and land cover of the watershed (Feldman 2000). The SCS unit hydrograph is used as a transform method (detail explanation see on chapter 4, section 4.6), flow before the peak discharge is not uniform through the watersheds due to variance of precipitation, length, and slope of the watersheds and the peak discharge is low in flat watersheds comparatively than in steeper watershed (Feldman 2000), based on this, the SCS unit hydrograph is used. The MUSLE method has been selected for the erosion simulation based on land used. It is used for pervious (rural) land (Pak, JH et al. 2015). HEC-HMS model can be developed based on the following components (USACE, H 2016):

- Basin model:

  The Basin model accomplished the physical description of watersheds. To simulate the runoff process, Hydrologic elements such as sub-basin, reach, sink, junction, and reservoir are composed of the basin model. The sub-basin used as a drainage basin where precipitation falls, and surface runoff obtained. The sub-basin outflow is estimated by subtracting the precipitation losses (infiltration, evapotranspiration, and storage)

- GIS Connection:

  GIS tool is available in HEC-HMS version 4.6 (which is used in this study), which can delineate the watershed. The integrated GIS tool is used to create a basin model from the digital elevation model (DEM). To delineate a watershed, assigned the terrain data component to the basin model and use some components from GIS tools such as compute flow direction, define the breakpoints, and identify a stream.

- Meteorological model:

  To simulate the simple event, only participation is required, and precipitation and evapotranspiration are required for the continuous simulation. Snowmelt is required for the watersheds in cold climates.
- Data input:
- Control specification:

  Control specification is used to specify the starting date, time interval, and ending date for the simulation.

  In this study, to estimate the sediment deposition of the watershed, HEC-HMS model is developed (shown in chapter 4). Selected methods and components (see Table 3.2 and 3.3).

Table 3. 2: Selected methods in the HEC-HMS.

Model Type	Surface method	Loss Method	Transform Method	Erosion method	Sediment Transport method
Event-based	Simple surface	SCS-CN	SCS Unit Hydrograph	MUSLE	Laursen-Copeland

Table 3. 3: Selected method in a meteorological model

Model Type	Precipitation	Evapotranspiration	Snowmelt
Event-based	Specified Hyetograph	None	None

3.4 Erosion model in HEC-HMS

Erosion and sediment transport component are optional in HEC-HMS. To access the features of sediment and erosion, one needs to activate the sediment component from the basin model manager. The detailed procedure of erosion and sediment transport model has been explained in appendix A 2. To test the erosion and sediment model in HEC-HMS, a model had been applied to the Upper North Bosque River (UNBRW) in central Texas USA. The UNBRW comprises 98% rural contains rangeland and dairy west application land. The outcome from HEC-HMS was better in comparison to the result from others model (Pak, JH et al. 2015).

3.4.1. Types of erosion method in HEC-HMS

Five surface erosion methods have been included in HEC-HMS version 4.6 (USACE, 2020). These are:

- Build up wash-up
- LA Debris Method EQ1
- Modified USLE
- Multi-Sequence Debris Prediction Method
- USGS Long-Term Debris Model

We can choose a different method for each sub-basin, or the same method for different sub-basin. Method selection depends on soil type, land use, and terrain data.

Build-up -wash-up method can simulate the erosion from an urban or impervious area(Pak, J et al. 2008).

The LA Debris Method EQ1 was applied to a small area watershed varies from 0.1 to 7.7 Km^2 had no peak flow data available (Pak, JH et al. 2009; USACE, H 2016). This method was set by the 349 observations of 80 watersheds in South California USA (USACE, 2020).

The application of MUSLE is based on surface runoff instead of precipitation, this method is more suitable in agricultural land (USACE, 2020). However, many users have used it in construction and urban areas (USACE, 2020). In this study, MUSLE has been selected to simulate the erosion model.

Multi-Sequence Debris Prediction Method (Pak et al., 2008) applies to the small watershed area range from 0.1 to 7.7 km^2 with no peak flow data available (USACE, 2020). This method was developed in Southern California from 80 debris basin cleanout data (1938 to 2002) (USACE, 2020). Likewise, LA Debris Method EQ1, this method also applies to the arid and semi-arid regions where it was developed (USACE, 2020).

USGS Long-Term Debris Model (Gartner, Cannon & Santi 2014) was established by using the hundreds of datasets of sediment accumulation from debris flow (USACE, 2020).

3.4.2. Selected erosion method: (MUSLE)

In this project, MUSLE method has been selected based on catchment data to erosion the model. The MUSLE is applicable for the pervious surface or rural area (Pak, J et al. 2008). The MUSLE has commonly used in the world (Banasik & Walling 1996; Sadeghi & Mizuyama 2007). It is based on the runoff energy factor (Williams 1975) and it can generate erosion from a single rainfall-runoff event (Pak, JH et al. 2015). This method was generated by using the individual storm data from minimum area of 0.012 Km^2 to more than 16.187 Km^2.

The mathematical equation of MUSLE to estimate the sediment yield from pervious land surface for a storm event (Williams, 1995) as shown in equation 3.1.

$$\text{Sed} = 11.8 \left(Q_{surface} * q_{peak}\right)^{0.56} * K * LS * C * P \ldots\ldots\ldots\ldots\ldots \text{(3.1)}$$

Where, Sed is sediment load in Tons, $Q_{surface}$ is the volume of surface runoff in m^3, q_{peak} is Peak discharge in $(\mathrm{m}^3/\mathrm{s})$, *K* is Erodibility Factor, the unit is (ton/ha, *R)*, *LS* is

Topographic factor, *C* is cover management factor, and *P* is Practice factor. The *LS, C,* and *P* are unitless.

The MUSLE can estimate the erosion from the single rainfall-runoff event as well as from a multi-year rainfall runoff simulation.

3.4.3. Input parameters for erosion model

A total of seven parameters are required to input for the erosion model. These parameters were estimated based on terrain, land use, and soil type of the catchment. The detailed procedure of how to model the erosion in HEC-HMS is shown in appendix A 2. The list of parameters:

- Erodibility factor *(K)*
- Topographic factor *(LS)*
- Cover factor *(C)*
- Practice factor *(P)*
- Threshold $\left(\frac{m^3}{s}\right)$
- Exponent
- Gradation curve

- **Erodibility factor *(K)***

Soil erodibility factor describes the resistance to soil erosion and is depends on soil properties, organic matter content (OM), bulk density, particle size, and shape, (Addis & Klik 2015; Duiker, Flanagan & Lal 2001; Morgan 2009). The value of K factor ranges from 0 to 1, with 0 indicate the least vulnerable to soil erosion and 1 indicate the high vulnerability to soil erosion (Gwapedza et al. 2018; Schulze et al. 2007).

Soil erodibility factor *(K)* can be calculated based on observed soil parameters such as organic matter content (OM), texture, coarse fragments, structural class, and permeability (Addis & Klik 2015; Parwada & Van Tol 2017; Wischmeier & Smith 1978) by using Wischmeier's nomograph (Wischmeier, 1971). The nomograph is based on equation (3.2). The nomograph is shown in appendix B 4.

$K = 2.77 * 10^{-7}(12 - OM)M^{1.14} + 4.28 * 10^{-3}(s - 2) + 3.29 * 10^{-3}(p - 3)$ ……. (3.2)

$M = [(100 - C)(L + Armf)$ …… …….. (3.3)

Where, *C* is the percentage of clay (<0.002 mm), L is the percentage of silt (0.002 mm to 0.05 mm), $Armf$ denotes the percentage of very fine sand (0.05mm to 0.1mm), OM is the

percentage of organic matter content, *S* is code of the structure size, type, and grade based on field observation and *P* is code of the permeability.
Source: (Addis & Klik 2015; Pérez-Rodríguez, Marques & Bienes 2007)

- **Topographic factor *(LS)***

The topographic factor (LS) is defined as vulnerability to erosion. The *LS* factor depends on the length and slope of the terrain. Generally, the value of (LS) ranges from 0.1 (flat slope) to 10 (steep-slope). The (LS) is the combination of slope length (L) and slope steepness (S). (Van Remortel, Maichle & Hickey 2004; Zhang, H et al. 2017).

LS=L*S……………………………………... (3.4)

Where,

$L = \left(\frac{\lambda}{22.13}\right)^{m}$ ……………………………… ………………….. (3.5)

$m = \beta/(1+\beta)$, m is a dimensionless exponent.

$\beta = (sin\theta)/[3.(sin\theta)^{0.8} + 0.56]$, β varies with slope gradient and slope angle

$S = 10.8sin\theta + 0.03$, for $\theta < 9\%$ ………………………………. (3.6)

$S = 16.8sin\theta - 0.5$, for $\theta \geq 9\%$

Where λ is slope length in meter and θ is slope angle.

The λ in equation (3.5) is defined as the distance from the origin point of overland flow to deposition points: (Wischmeier & Smith 1978; Zhang, H et al. 2017).

To find the connection between the S factor and soil loss at moderately sloped land, an example has been taken from the review of the literature. From the previous studies, on northern Germany. The accuracy of the S factor is influenced by the accuracy of the digital elevation model (DEM)(Ouyang & Bartholic 2001). A rectangular plot of 1.3 Km^2 was selected for the case study and 1m, 5m, 10m, 25m, and 50m horizontal resolution were included. Different algorithms such as maximum and minimum slope gradient, different order finite difference was used. This study shows the effects of topography on the S factor, horizontal resolution, and vertical accuracy of DEM and algorithm. The outcomes from these case studies were(Liu et al. 2009):

- The precision of the S factor to the given resolution of DEM is influenced by the algorithm, mostly the lower resolution of DEM is influenced.
- The precision of the S factor declines with horizontal resolution.

- 1m resolution of maximum downhill slope gradient and 5 m to 100 m resolution of maximum slope gradient are the most appropriate algorithm.
- S factor is also influenced by vertical precision.
- The accuracy of the S factor is influenced by terrain complications.

Mostly the precision of the S factor is depending on the horizontal resolution. The precise value of the S factor depends on the selection of the appropriate algorithm(Liu et al. 2009).

- **Cover factor *(C)***

The cover factor *(C)* defines the impact of vegetation on soil erosion. A higher value of cover factor indicates to the most vulnerable of soil erosion and vice-versa. Generally, the value ranges from 1 to 0.1. The value of cover factor for the bare ground is 1 which is more vulnerable to erosion whereas, *C* for thick vegetation cover or fully mulched land is 0.1 which is significantly low vulnerable to erosion, the *C* factor for the forest with the dense tree is 0.0001 (Scharffenberg 2016).

- **Practice factor *(P)***

The Practice factor (*P)* shows the ratio of soil loss based on conservation practice to the soil loss based on certain cultivation. The P-value range from 0 to 1. The lower value 0 indicates higher erosion resistance capacity whereas higher value 1 represents lower erosion resistance capacity(Parveen & Kumar 2012). Generally, the assumption of P-value is 1 due to insufficient data of existing contour location(Lu et al. 2001).

Based on the review of literature, examples show the value of the practice factor. Table 3.4 (Kim & Julien 2006) shows the *P*-value based on cultivation method and slope (shin,1999) and Table 3.5 (Morgan 2009) shows the *P*-value of rangeland and forest land in the western USA. The practice factor can be calculated according to the relationship between contouring and slope of the crop field(Kim & Julien 2006).

Table 3. 4: Practice factor values based on cultivation and slope.

Slope (%)	Contouring	Strip cropping	Terracing
0.0-7.0	0.55	0.27	0.10
7.0-11.3	0.6	0.30	0.12
11.3-17.6	0.8	0.40	0.16
17.6-26.8	0.9	0.45	0.18
26.8 >	1	0.50	0.20

Table 3. 5: Practice factor values for Western USA.

Erosion control practice	P-factor value
Contouring: 0-1° slope	0.60*
Contouring: 2-5° slope	0.50*
Contouring: 6-7° slope	0.60*
Contouring: 8-9° slpoe	0.70*
Contouring: 10-11° slope	0.80*
Contouring: 12-14° slope	0.90*
Level bench terrace	0.14
Reverse-slope bench terrace	0.05
Outward-sloping bench terrace	0.35
Level retention bench terrace	0.01
Tied ridging	0.10-0.20

∗ Use 50 % of the value for contour bunds or if contour strip cropping is practiced.

- **Exponent.**

The exponent in erosion is used to distribute the sediment concentration in time-series sedigraph. The sediment concentration can be calculated by using a power function (Haan, Barfield & Hayes 1994; Pak, JH et al. 2015) is shown in equation (3.7). The value of exponent is generally range from 0.5 to 1(Pak, JH et al. 2015).

$C_t = K^i Q_t^b$ ……………………………………………………….. (3.7)

Where,

C_t = Sediment concentration at time t, K^i is constant calculated from runoff, Q_t is discharge from the sub-basin. b= exponent entered by a user.

From the review of literature,

1. Based on the sediment rating curve, the effects of exponent on sediment concentration and discharge (Asselman 2000) is describes by equation (3.8).

$C = aQ^b$ ………………………………………………………… (3.8)

This is the most used power function in the sediment rating curve (Asselman 2000).

Where,

C is sediment concentration (mg/l), Q is discharge (m^3/sec), coefficient "a" and exponent "b" both are the regression coefficient.

According to Peters-Kummerly (1973) and Morgan (1995), the coefficient "a" indicates an index of erosion severity whereas, the exponent "b" indicates the erosive power of the river.

2. According to C T Haan et al., 1994, The exponent can be calculated based on flow rate and basin area (Haan, Barfield & Hayes 1994). An example has been explained in literature "Design Hydrology and Sedimentology for small catchment".

$Q_T = aA^b$ …………………………………………….. (3.9)

Where,

Q_T= T-year flood magnitude, A= basin area and a and b are constants.

The constants can be estimated based on stream data of two location.

Table 3. 6: Hydrological data for the exponent.

Return period (T)	Area (km^2)	Discharge ($\frac{m^3}{s}$)
10	1.8	31
10	5.9	93

Source: (Haan, Barfield & Hayes 1994)

From the equation (3.9),

I) 93 $= a(5.9)^b$

II) 31 $= a(1.8)^b$

The exponent b can be estimated from the ratio of (i) and (ii).

$\frac{93}{31} = \left(\frac{5.9}{1.8}\right)^b \therefore b = 0.94.$

- **Gradation curve**

The gradation curve in HEC-HMS describes the distribution of total sediment load into different grain size classes at the outlet of the sub-basin. The gradation curve is the particle size distribution curve, and it is input as a diameter-percentage function from the Paired Data Manager in HEC-HMS. The detailed procedure to input the particle size distribution table in HEC-HMS is shown in figure A 5 in appendix A 2.

To determine the particle size distribution of the soil, the sieve analysis and sedimentation analysis are commonly used. The sedimentation analysis is also called hydrometer analysis. The hydrometer analysis is used for the fine soil particles which have a size less than $75\ \mu m$ and sieve analysis is used for the coarse grain soil particles(Terrain & Craton). The wet sieve analysis and dry sieve analysis are used to find the particle size distribution of size more than $75\ \mu m$.

3.5 Sediment model in HEC-HMS

As the rate of surface runoff increased, the erosive energy increase which leads to further erosion. The sediment transport capacity of sub-basin can be calculated based on flow parameters and sediment characteristics (Scharffenberg 2016).

From the review of literature, based on Modelling Surface Soil Erosion and Sediment Transport Processes in Upper North Bosque River Watershed (UNBRW). Total sediment load obtained from HEC-HMS are divided into four grain class such as clay, silt, sand, and gravel. However, during the model calibration clay, silt and sand were taken as total suspended solids (TSS) and assumed to eliminated gravel (Pak, JH et al. 2015). Thus, the sum of clay, silt and, sand particles from the result of HEC-HMS was compared with observed TSS (Pak, JH et al. 2015).

3.5.1. Selection of the transport potential method (Laursen-Copeland)

In HEC-HMS, flow capacity to drive the sediment will be calculated from the transport potential method. This method is used for non-cohesive sediments. A total of seven transport potential method are available in HEC-HMS. In this study, Laursen-Copeland method has been selected.

From the literature review,

To estimate the total sediment load in the ping river in Thailand, different sediment transport method was applied. The stepped mountains and valleys are the major characteristics of the river catchment. The elevation range of the river basin is 330 to 2000 m, 70% of the river basin was covered by tropical forest, and more than 27% of the river basin was covered by agricultural area (Bidorn et al. 2016).

Some of the required data were collected from the Royal irrigation department and insufficient data were collected from hydrologic surveys. Surveys were conducted on nine events from 2011 to 2013 at two different stations, which were located at 70 and 230 km downstream (Bidorn et al. 2016). Flow velocities suspended sediment, river cross-section, and bedload sample concentration were the hydrologic survey data. To collect the suspended sediment, an inverted and corked bottle was used at the proportional depth of 0.2, 0.4, 0.6, and 0.8 between the water surface and riverbed. The GIF filter was used to retain the particle from the collected suspended sediment, GIF filter retained the particle greater than 0.45 μm. Based on these data, each method had been tested to evaluate the sediment estimation for the ping river basin. Among these methods, the result of total sediment load from the Laursen-copeland method shows the best estimation (Bidorn et al. 2016).

3.5.2. Specific Gravity for Sediment model

The specific gravity of soil particles ranges from 2.6-2.7 (Yu et al. 1993). Generally, the average specific gravity of natural soil is close to 2.65 (Yu et al. 1993). Therefore, in erosion and sediment modelling, specific gravity is assumed to be 2.65 (USACE 2016a). However, the specific gravity of soil particles should be determined whenever possible from the field.

From the review of literature, there are two methods, vacuum and boiling methods generally used to remove the air from the soil sample(Mebust 2015). A previous study (Mebust 2015) had conducted a test to estimate the specific gravity of a soil sample based on the boiling method. In this test, 50 gm of dried soil sample was kept in a 500 ml pycnometer and filled 2/3 part with distilled water. The mixture of soil and water was boiled on a hot plate for 2 hours. Then soil sample was cooled in an insulated cooler. The pycnometer was filled with added water and soil mixture and weighed. Then the pycnometer was filled with distilled water and weighed. The specific gravity of the soil was estimated by equation (3.10).

$$G_s = \frac{M_0}{M_0+(M_a+M_b)} \quad \text{(3.10)}$$

Where,

G_s= specific gravity of soil sample, M_0 = dry weight soil sample, M_a= flask and water weight, M_b = weight of flask, water, and soil.

The specific gravity obtained from this experiment was 2.68 (Mebust 2015).

3.5.3. Dry density for Sediment model

The dry density of soil is the ratio of the mass of dried soil to its total volume (sum of pore and solid volume) and can be calculated by the equation (3.11). The value of dry density of soils range from 1100 -1600 Kg/m^3 (Yu et al. 1993).

$$\rho_b = \frac{M_s}{V_t} = \frac{M_s}{V_s+V_l+V_g} \quad \ldots\ldots (3.11)$$

Where,

ρ_b = Dry density of soil, M_s = Dried mass of soil, V_t= total volume of soil sample.

Soil dry density (ρ_b) is related to the particle dry density (ρ_s), is shown in equation (3.12).

$$\rho_b = (1 - p_t)\rho_s \quad \ldots\ldots (3.12)$$

Where,

ρ_s = particle density and $(1 - p_t)$ is the total porosity.

Based on previous studies (Arvelo 2004), the relationship between values of maximum dry densities, soil type and characterization of the different soil samples has been explained. To estimate the maximum dry density, a proctor test was chosen. In these studies, eight types of soil samples (using a total weight of 38329.5 gm) were taken and classified based on the Unified Soil Classification system. Classified soils were divided into two categories based on sieve analysis, coarse-grained soil, and fine-grained soil. The soil less than 50% passing through the No. 200 sieves is coarse-grained soil and the soil more than 50% passing through No. 200 is fine-grained soil. The sample was washed to remove fine particles before conducting sieve analysis. Then the sample was tested by proctor test based on ASTM Test Designation D-698 (ASTM,1999). Dry unit weight measured from the Proctor Test were plotted to the moisture content 5%, 7%, 9%, and 11%, then the maximum dry density of each soil type to the corresponding moisture contain were estimated. Once the experiments were finished, the data were analysed to find the relationship between estimated dry densities and soil characteristics. The result based on this experiment was the soil containing clay minerals had higher dry density than those having silt (Arvelo 2004).

CHAPTER 4: CASE STUDY APPLICATION OF HEC-HMS IN SOIL EROSION AND SEDIMENT YIELD

4.1 Study Area

This project aims to illustrate the soil erosion and sediment yield due to precipitation through the sub-basin by using HEC-HMS. Typically, it requires the following information:

- A digital elevation model (DEM) terrain data.
- The precipitation runoff model.
- Soil data
- Land use data
- Appropriate erosion and sediment modelling methods.

This case study was conducted on the Washpool Aldinga basin located in the Onkaparinga city council of South Australia. The outlet of the basin is considered at Easting = -35.318101°; Northing = 138.446857°. The study area of the basin is 47.9 km^2 as shown in figure (4.1).

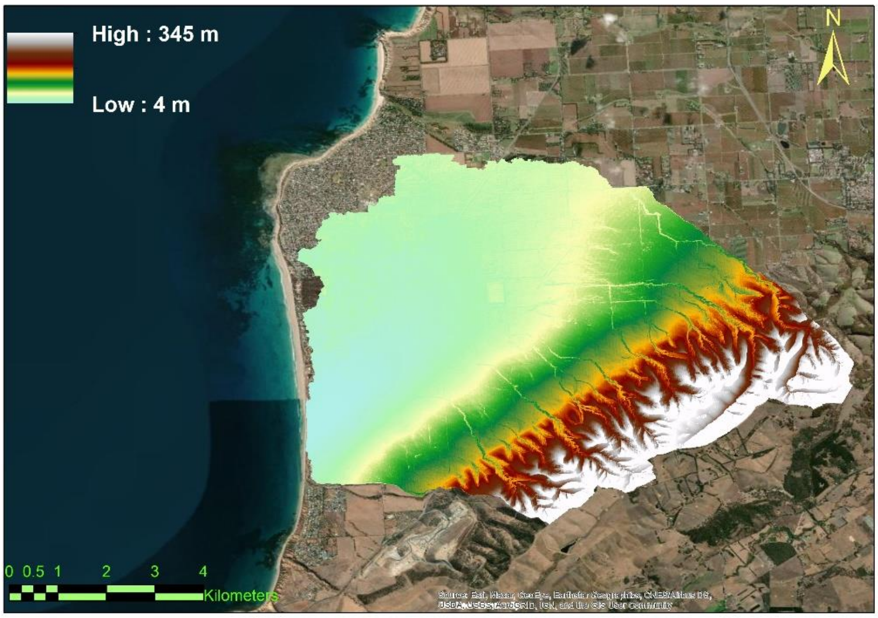


Figure 4. 1: Location of the washpool Aldinga basin.

The selected basin is mostly covered by vegetation including Woody native vegetation, Orchards vineyards, Irrigated Non-Woody, Dryland agriculture and slightly covered by urban area based on Nature's Map SA, website: http://www.naturemaps.sa.gov.au. The land cover map as shown in figure (4.2) was generated from ArcGIS and Nature's Map SA. The basin's elevation ranges from 4 m to 345 m as shown in figure (4.5), which was estimated from Google Earth. The average basin slope is 1.6%, the detailed calculation is shown in appendix B1. The soil textures for this basin are clay loam, loam, and sand this classification is based on USDA soil triangle (Brown, 1998). The major use of the land in the study area agriculture, horticulture (cultivation), livestock farming (based on Nature's map of SA) is shown in figure (4.3), website: http://www.naturemaps.sa.gov.au. Therefore, most area of the basin is an impervious area (estimated 94.6%).

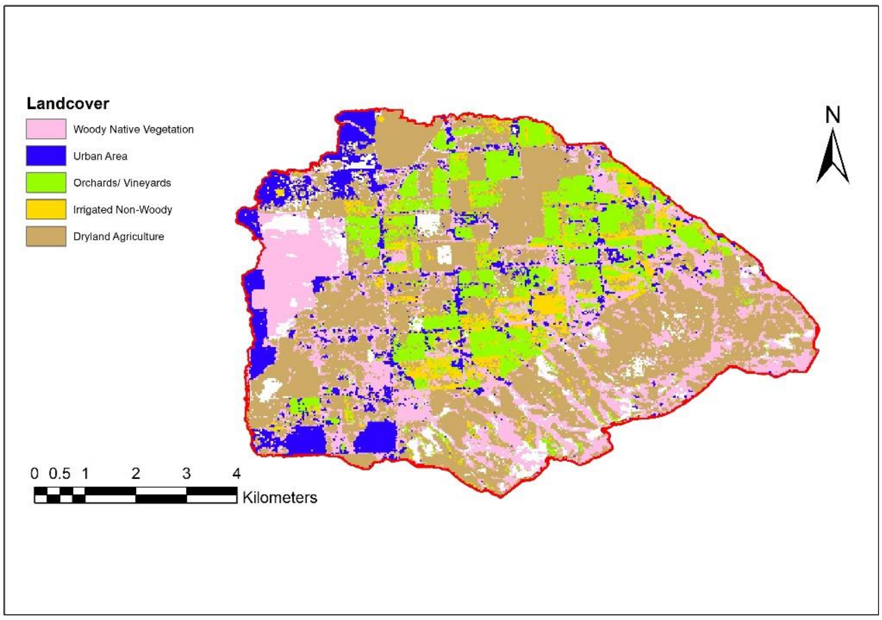


Figure 4. 2: Land cover map of the basin.

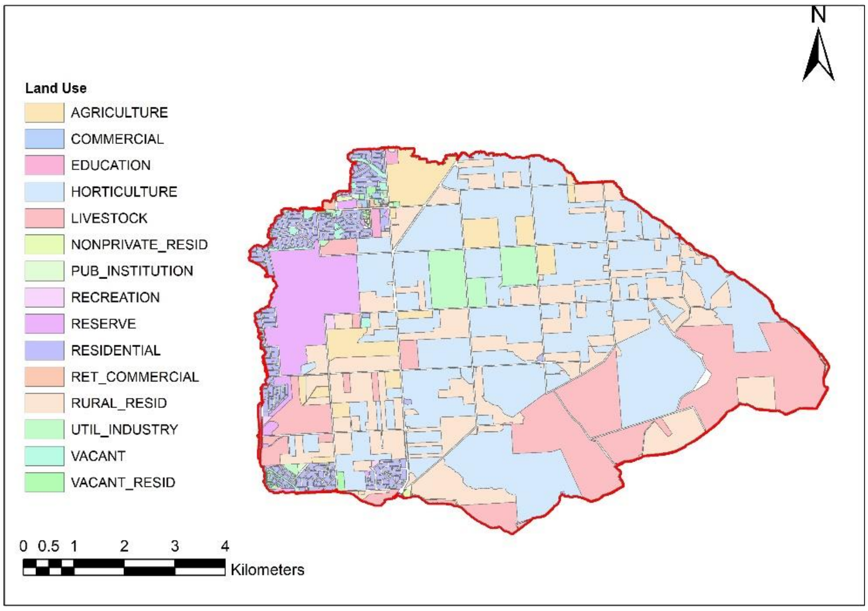


Figure 4. 3: Land use map of the basin

4.2 Table of parameters and methods for erosion modelling in HEC-HMS

Table 4. 1: Selected Methods and input parameters for erosion model:

Method	Parameters	Selected value.	Description
MUSLE:	Erodibility *(K)*	0.49	. K values range from 0 to 1. With 0 indicates least vulnerability to soil erosion and 1 indicates high vulnerability to soil erosion (Gwapedza et al. 2018; Schulze et al. 2007).
	Topography *(L*S)	0.8	LS depends on the length and slope of the catchment. LS values range 0.1 to 10. O.1 for flat slop and 10 for steep slope.
	Cover factor *(C)*	0.03	C factor depends on the vegetation cover over the land surface. Values range from 0.0001 dense tree canopy, 0.1 for covered soil to 1 for bare ground.
	Practice factor *(P)*	1	The practice factor depends on the specific soil conservation practice. Practice factor equals to 1 has been taken in this modelling.
	Threshold (m^3/s)	1	The minimum runoff can cause erosion. If Maximum discharge is below the threshold discharge, catchment will have no erosion in HEC-HMS.
	Exponent	0.6	This value is used to plot the sediment load versus time and time interval
	Gradation Curve	Create a Table	In the model, the table of grain size in mm and percentage finer is used in paired data manager. Gradation curve can generate each grain size sediment load.

Source: (USACE 2016b), (Gwapedza et al. 2018; Schulze et al. 2007).

The selected value in Table (4.1) has been justified under section 4.4 below.

Table 4. 2: Selected Methods and parameters for sediment routing modelling in HEC-HMS:

Method	Parameters	Estimated value.
Laursen-Copeland	Specific Gravity	2.65
	Clay Dry Density (kg/m^3)	481
	Silt Dry Density (kg/m^3)	1041
	Sand Dry Density (kg/m^3)	1490
	Fall velocity (selected, Rubey)	-
	Grade scale (Selected, Clay Silt Sand Gravel)	-

Source: (Pak, J et al. 2015; USACE 2016b).

Table 4. 3: Selected Methods and parameters for hydrology model:

Method	Parameters	Value
Canopy Method: Simple canopy	Initial storage (%)	0
	Maximum storage (mm)	16
	Crop coefficient	1
	Evapotranspiration	-
Surface Method: Simple surface	Initial storage (%)	
	Maximum storage (%)	
Loss Method: SCS Curve Number	Initial abstraction (mm)	23
	Curve number	67
	Impervious (%)	5.4
Transform Method: SCS Unit hydrograph	Graph type	-
	Lag time (minute)	288

Source: (USACE 2016b), ARR DATA HUB: http://data-legacy.arr-software.org/

4.3 Catchment delineation

The basin was delineated based on a 5m*5m resolution Digital Elevation Model (DEM). The DEM was generated from the data provided by data set SA from the website: https://elevation.fsdf.org.au/. To delineate the catchment, the required physical characteristics of the sub-basin are elevation, slope length, and slope (calculations shown in Appendix B1). The detailed process of the catchment delineation in HEC-HMS is shown in Appendix A1.

Elevation difference = 341 m

Slope length= 21 km

Slope= 0.016

All sub-basin within the catchment were merged into a single sub-basin. The catchment delineation is shown in figure 4.4 and the elevation map of the delineated catchment is shown in figure (4.5).

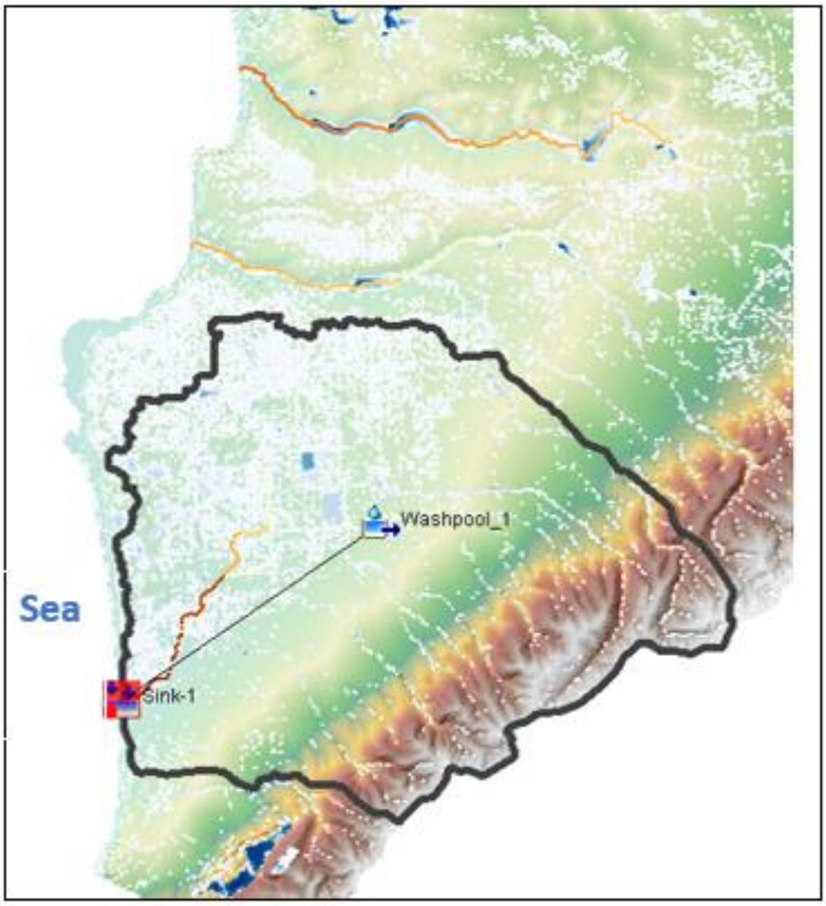


Figure 4. 4: Wash Pool Aldinga catchment delineation.

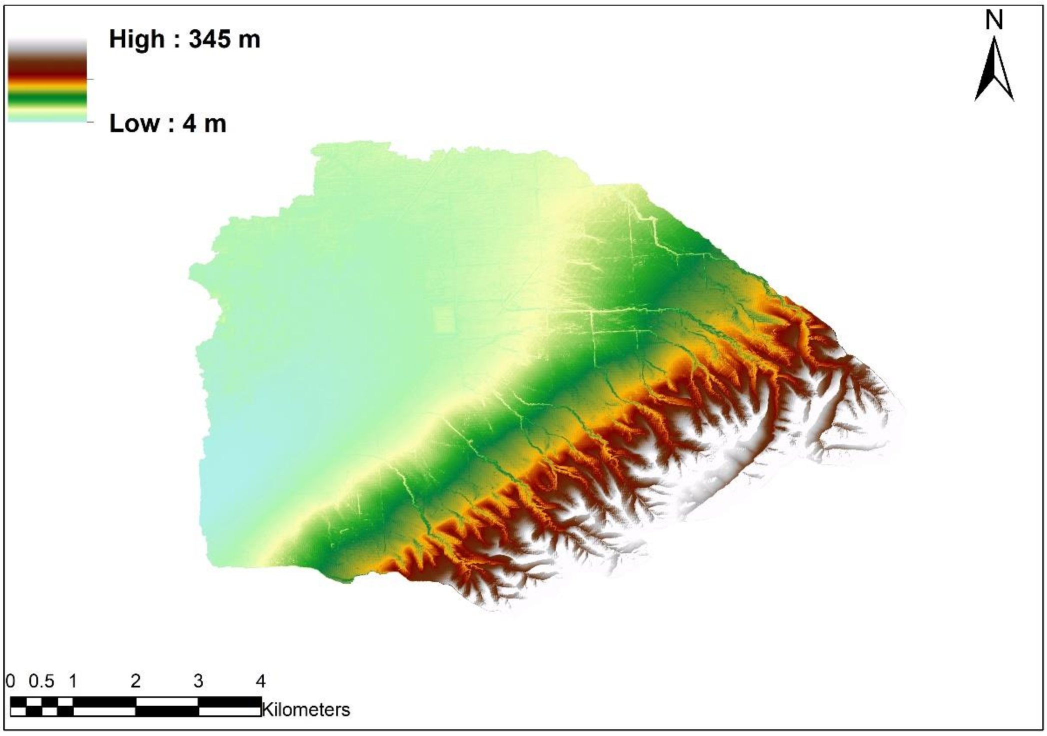


Figure 4. 5: Elevation map of the delineated catchment

4.4 Estimation of parameters for MUSLE, and development of erosion model in HEC-HMS

The MUSLE was used as an erosion method based on the land use of the study area (most of the area is pervious). The MUSLE was applied to estimate the sediment load for the pervious surface (Pak, J et al. 2008).

The MUSLE (see equation 3.1, in chapter 3) method and required parameters are explained in section 3.5, chapter 3. The process of the erosion modelling in HEC-HMS is shown in appendix A2, the estimation of the parameters for the erosion model is given below.

4.4.1 Estimation of Erodibility Factor *(K)*

The *K* factor describes the resistance capacity to soil erosion. It can be calculated based on observed soil parameters such as organic matter content (OM), texture, coarse fragments, structural class, and permeability (Wischmeier & Smith 1978).

To estimate the erodibility in this case study, Morgan K factor calculation table was used (see appendix B3). Based on Nature Map's SA, clay loam, loam, and sand are the key types of soil in the basin. Estimated average K factor as shown in table 4.5. The area covered by soil type was estimated from the google earth (Google Earth) and Nature Map's SA (http://www.naturemaps.sa.gov.au). Firstly, the soil type associated with the study area was categorised from the Nature Maps and the catchment area of the respective soil type was estimated from google earth.

Table 4. 4: Average K factor for the corresponded soil type:

Soil Type	Area covered (%)	Average (K) factor
Clay Loam	32	0.68
Loam	39	0.67
Sand	29	0.04

The required erodibility factor was estimated by calculating the weighted average value given in table 4.4. The table was created based on less than 2% OM content, average OM content, and more than 2% OM content. Hence, K= 0.49 was used in the erosion model.

4.4.2 Estimation of Topographic Factor *(LS)*

The *LS* factor shows the vulnerability to erosion due to the length and slope of the terrain. The detailed explanation is shown in chapter 3, section 3.4.3, equations 3.4, 3.5, and 3.6. The estimated *LS* factor based on the basin data (calculation shown in, Appendix B1) is shown in table 4.5. The calculated value of m is 0.02, however, the value of m = 0.2 was selected based on gradient $(\theta) \leq 0.017$ (Zhang, H et al. 2017), (shown in appendix B1).

Table 4. 5: Input parameter to the LS factor

λ (m)	Slope (°)	Gradient $(\boldsymbol{\theta})$	m	L	S	LS
21000	0.93	0.016	0.2	3.93	0.205	0.8

4.4.3 Estimation of Cover Factor *(C)*

The *C* factor is the influence of vegetation on soil erosion, the risk of soil erosion is higher with a high *C* value and lower with a low *C* value. The range of *C* value is 1 to 0.1 (Scharffenberg 2016).

To estimate the cover factor, Table 4.6 was created from the Morgan (see a table in appendix B 5) table. The required cover factor was estimated by calculating the weighted average of the *C* values given in table 4.6. Hence estimated cover factor for the erosion model is 0.03.

Table 4. 6: vegetation type and C value**.**

Vegetation Type	**Description**	**Area in (%)**	**C value**
Dryland Agriculture	Use for dryland cropping and grazing	42	0.01
Orchards/Vineyards	Grapes, citrus, and stone fruits.	15	0.08
Woody Native	Generally greater than 1 m tall. Example, hop-bush shrublands, woodlands, and eucalypt forest.	29	0.001
Irrigated Non-woody	Pasture, grassed reserves, and golf course	8.6	0.1
Urban	Mix vegetation example, garden, road, house, and street trees.	5.4	0.01

In this table, C values were estimated by matching the relevant crop from the table of Morgan. R. (2005)(Morgan 2009). The detail table is shown in appendix B 5.

4.4.4 Estimation of Practice Factor *(P)*

The *P*-value range from 0 to 1. The lower value 0 indicates higher erosion resistance capacity whereas higher value 1 represents lower erosion resistance capacity(Parveen & Kumar 2012). Generally, the assumption of P-value is 1 due to insufficient data of existing contour location(Lu et al. 2001).

In this case study, practice factor (*P)*= 1, was used. The explanation of the practice factor is shown in chapter 3, 3.5.

4.4.5 Threshold

The threshold is the minimum overland flow rate that can cause erosion, there will have no erosion with the flow rate less than the threshold value. In this study, the threshold flow was selected $1\ \mathrm{m}^3/\mathrm{s}$, due to the limitation of HEC-HMS version 4.6, this version has not been designed for the watershed associated with runoff discharge less than $1\ \mathrm{m}^3/s$. During the modelling for the small catchment (area less than 0.5 km^2), with the threshold discharge less than $1\ \mathrm{m}^3/s$ there was no erosion analysis in HEC-HMS on that catchment. Later, a larger basin (47.9 km^2) was chosen to conduct the case study.

4.4.6 Exponent

The value of the exponent is applied to plot the sediment concentration in time-series for the erosion model (see equation 3.8, chapter 3)**.** The explanation shown in chapter 3, 3.5, the exponent value ranges from 0.5 to 1 (Pak, JH et al. 2015). Based on previous studies (Pak, JH et al. 2015; Scharffenberg 2016), the value of exponent b=0.75 was used for the erosion model.

4.4.7 Gradation Curve

In HEC-HMS, for the erosion model, the gradation curve (particle size distribution curve) is associated with the grain size classes of the soil particles at the outlet of the basin. The process to input the gradation curve in the erosion model is shown in Appendix A 2.

To estimate the gradation curve, a particle size distribution table was developed based on the soil texture of the study area and the grain classes of corresponded soil texture from the USDA soil triangle (this triangle is shown in Appendix B 6), (see table 4.7).

Table 4. 7: Particle distribution table

Soil texture	Area in (%)	Based on the USDA Soil triangle		
		Clay (%)	Silt (%)	Sand (%)
Clay loam	32	30	40	30
Loam	39	20	40	40
Sand	29	2	2	96

The average weighted value of percentage finer for each grain classes (clay, silt, sand) was estimated from Table 4.13, the size (diameter) of each grain class was chosen from the table of (Brown,1998) shown in Appendix B 6. Based on that analysis, a gradation table (see in table 4.8) was developed to input in the erosion model. The table was developed in the form of a diameter-percentage function.

Table 4. 8: Diameter-percentage function table in HEC-HMS.

Particles	Diameter (mm)	Percent finer (%)
Clay	0.002	17.98
Silt	0.050	28.98
Sand	0.250	53.04

4.5 Estimation of parameters for the development of sediment model in HEC-HMS

In this case study, the Laursen-Copeland method was used as a transport potential method, this method is applied for non-cohesive sediments. The explanation of this method is shown in chapter 3, in section 3.6.1. The process of sediment modelling in HEC-HMS is shown in appendix A 3. The estimation of required parameters for the sediment model is shown below.

4.5.1 Specific Gravity

The values of specific gravity are associated with the mineralogy and chemical composition of the soil(Roy & Bhalla 2017). The range of typical value of specific gravity is shown in table 4.9. Based on previous studies of sediment modelling by HEC-HMS (Pak, JH et al. 2015), HEC-RAS, and Table 4.9, specific gravity = 2.65 was used for the sediment model. Explanation of specific gravity is shown in chapter 3, in section 3.6.

Table 4. 9: The values of specific gravity based on soil type.

Type of soil	Specific gravity
Sand	2.65-2.67
Silty sand	2.67-2.70
Inorganic clay	2.70-2.80
Soil with mica or iron	2.75-3.00
Organic soil	1.00-2.60

source:(Bowles 1992; Roy & Bhalla 2017)

4.5.2 Dry density

The dry density of soil particles is associated with the soil texture in general, the dry density depends on the dried mass and total volume of soil (See Eq. 3.11 in Chapter 3 for calculation details). The typical values of dry density of different soil are shown in table (4.2).

4.5.3 Fall velocity

Generally, the basin elements such as reaches, and reservoirs require the calculation of fall velocity and it depends on the selected transport potential method. In HEC-HMS, four methods are available to calculate fall velocity(USACE, H 2016). These methods include Rubey (1993), Toffaleti (1968), Report 12 (interagency committee, 1957), and Van Rijn (1993). In HEC-HMS, the default selection is Rubey.

4.6 Precipitation- runoff model in HEC-HMS

The precipitation–runoff model is the initial condition for simulation to the erosion and sediment model. In this study, the HEC-HMS hydrology model is prepared using nine-hour rainfall data during the period 00:00 to 09:00. Selected methods and input parameters of the hydrology model are shown in table 4.3. In this study, the surface method, loss method, and transform method are specified for the simulation of the rainfall-runoff model. The canopy method is an optional method and generally used for continuous simulation (USACE 2016b).

Surface method:

In this study, a simple surface method was selected. The maximum surface storage depends on the net precipitation, land use, and terrain slope (Feldman 2000; Ibrahim-Bathis & Ahmed 2016). The study area has a slope of 16.2%, based on this slope surface storage was selected 9 mm from table 4.10 (Ibrahim-Bathis & Ahmed 2016). Initial storage was specified 0%.

Table 4. 10: Surface storage

Description	Slope	Surface storage
Paved impervious area	NA	3.18-6.35
Flat, Furrowed Land	0-5	50.8
Moderate to gentle slopes	5-30	6.35-12.70
Steep, Smooth Slope	>30	1.02

Source: (Ibrahim-Bathis & Ahmed 2016)

Loss method:

I used the SCS Curve Number method among the eight different methods available in the loss method. Input parameters for this method are shown in table (4.3). Generally, the SCS Curve Number method is associated with land use and soil type(USACE 2016b). Initial abstraction is 23 mm, it was taken from Australian Rainfall and Runoff Data Hub-Results based on the corresponding location. The impervious area is 5.4%, which was estimated from google earth. The Curve Number (CN) was calculated based on hydrological soil group and land use. The hydrological soil group (see on table 4.11) and Land Cover pattern (see on table 4.12) were processed together based on the TR55 table provided by the United States Department of Agriculture (1986) (Cronshey 1986). The CN is 64, which was estimated as a weighted average.

Table 4. 11: Soil texture and hydrological soil group (HSG).

Soil Texture	**Area (%)**	**HSG**
Clay loam	32	D
loam	39	B
sand	29	A

(Feldman 2000; Ibrahim-Bathis & Ahmed 2016).

Table 4. 12: Curve number for different land cover.

Land cover	**Area (%)**	**Hydrologic Soil Group**			
		A	**B**	**C**	**D**
Urban	5.4	49	69	79	84
WoodyNative Vegetation	15	45	66	77	83
Orchard/Vineyards	29	32	58	72	79
Irrigate Non-Woody	8.6	39	62	74	82
Dryland Agriculture	42	60	72	80	84

Source: (Cronshey 1986; Feldman 2000; Ibrahim-Bathis & Ahmed 2016)

Transform method:

The SCS Unit Hydrograph was selected among the seven different transformed method. Lag time was calculated as an input parameter based on time of concentration (T_{lag} =288) min. The SCS Unit Hydrograph method depends on the area, length of the mainstream, and slope of the catchment (Feldman 2000).

In the meteorologic model, time-series data, control specification, and, paired data are the boundary condition (USACE, H 2016). The meteorological model was set up using the rainfall data derived from the ARR Data Hub. The precipitation data were manually entered into the time-series model (shown in table 4.12) and Specified Hyetograph was selected as the precipitation method. The meteorological model received the precipitation data from the time-series data.

The control specifications were used to fix the time of the simulation run. The start time was 00:00. The time interval of the rainfall event was 30 minutes. To estimate the shape of the unit hydrograph total time of rainfall storm was considered 24 hours, precipitation after 9 hours was considered 0 mm. However, the actual time of the rainfall storm was 9 hours (shown in table 4.13). The diameter-percentage functions were selected to create a paired data table. The paired data is depended on the structure and types of soils. The detail of paired data is shown in table 4.1.

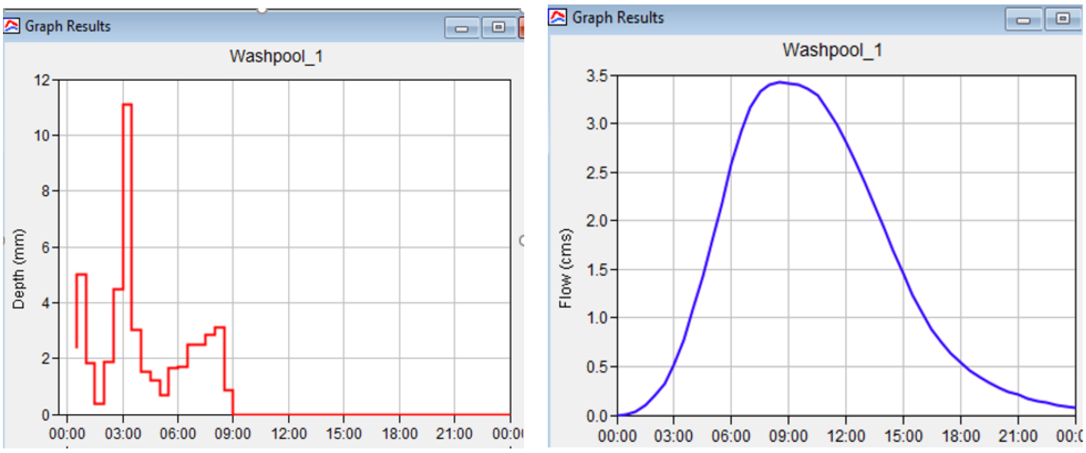
Table 4. 13: Precipitation data

Time (hours: minutes)	Precipitation (mm)
00:00	-
00:30	2.37153
01:00	5.00871
01:30	1.84023
02:00	0.38640
02:30	1.86921
03:00	4.49190
03:30	11.08002
04:00	3.03324
04:30	1.52145
05:00	1.19301
05:30	0.66654
06:00	1.67118
06:30	1.68084
07:00	2.49228
07:30	2.50677
08:00	2.83038
08:30	3.12984
09:00	0.87423
09:30	0.00000

4.7 Result and Discussion

4.7.1 Results:

Flow result is the main boundary condition for the HEC-HMS erosion model. The input precipitation and discharge obtained from the model are shown in figure 4.6. The Peak discharge (3.4 m^3/s) for 10% AEP occurs at 08:00 hours. The detailed value from the model is shown in the table in appendix C1.



a) Precipitation b) Discharge

Figure 4. 6: a) precipitation and b) discharge (flow hydrograph) for 10% AEP from HEC-HMS.

Sediment yield at the outlet of wash-pool Aldinga basin:

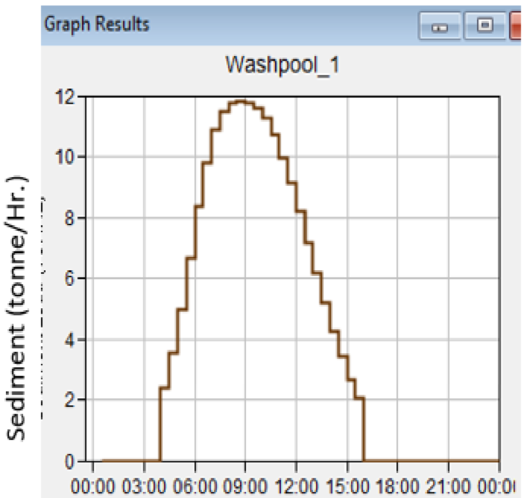
Using the MUSLE as the erosion method, Laursen-Copeland as the sediment transport method, and SCS curve number as the loss method in HEC-HMS, the sediment yield at the outlet of wash-pool Aldinga basin was calculated for the event for 9 hours. The value of peak flow and runoff volume for the estimation of sediment yield was used from the hydrological model.

Sediment yield was calculated according to the average values of K, LS, P, and C factors (shown in table 4.1) of the wash-pool Aldinga basin. The Threshold value for the MUSLE method in the erosion model was set to 1 m^3/s, the required exponent factor for the erosion calculation was estimated 0.6, and the Gradation curve was set based on the Diameter-Percentage function is shown in section Appendix A2 (see figure A6). Furthermore, specific gravity, dry density of clay, sand, and silt (shown in table 4.2) were also used for the calculation of sediment yield and sediment concentration.

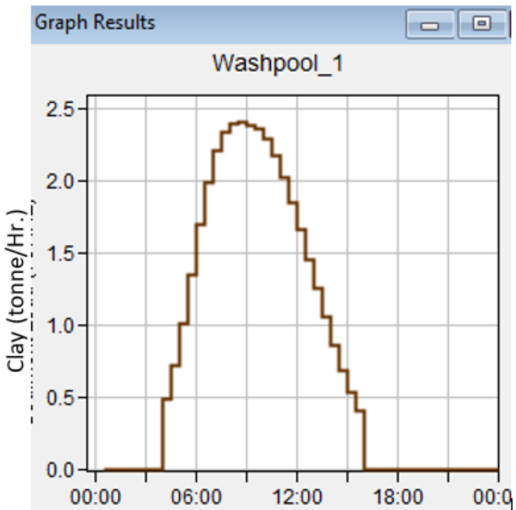
The results obtained using these methods and factors are presented in figure 4.7 (graph obtained from the model) and figure 4.8 (graph plots in excel). The detailed values of total sediment load, sediment load of each component (clay, sand, silt), and sediment concentration are shown in the result table in appendix C1. The estimated maximum sediment load was 11.8 tonne or 13 tons, while the maximum sediment concentration was 1917.18 mg/l during the 9 hours rainfall event (see 4.14). The sediment yield and sediment concentration increase gradually as the flow discharge rises, sediment concentration is high approaching the end of the simulations depends on catchment flow rate and sediment load.

Table 4. 14: Maximum Sediment yield

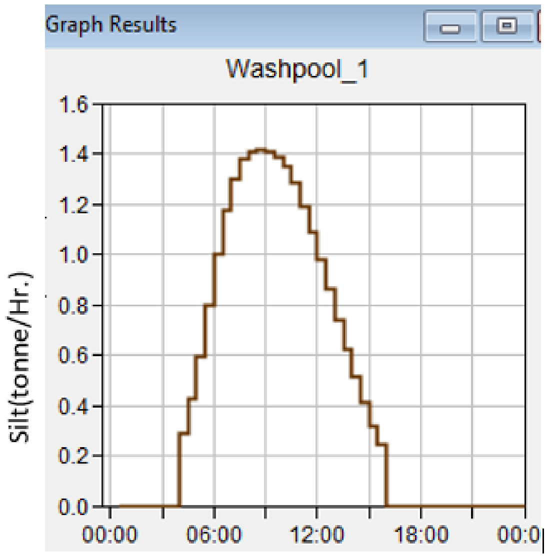
Time interval	Flow	Maximum Sediment Load				Sediment
Hr: min	m^3/s	Total (tonne)	Sand (tonne)	Clay (tonne)	Silt (tonne)	(mg/l)
08:30-09:00	3.4	11.8	8	2.4	1.4	1917.18



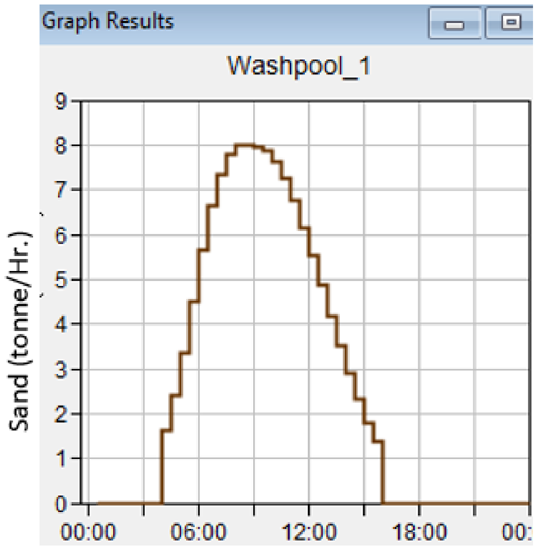
a) Sediment Load (Total).



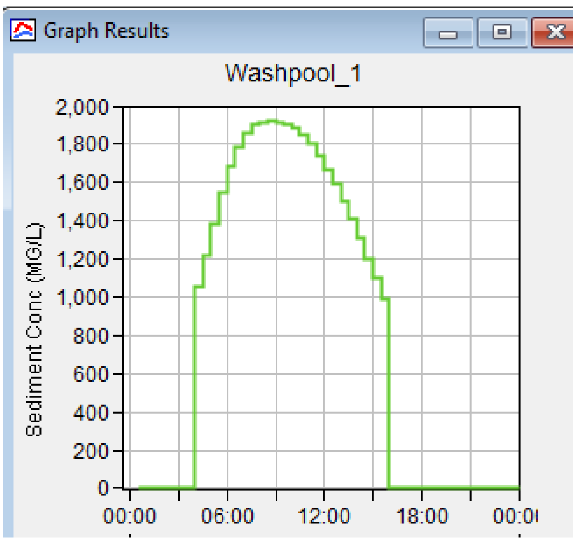
b) Sediment Load (Clay



c). Sediment Load (Silt).



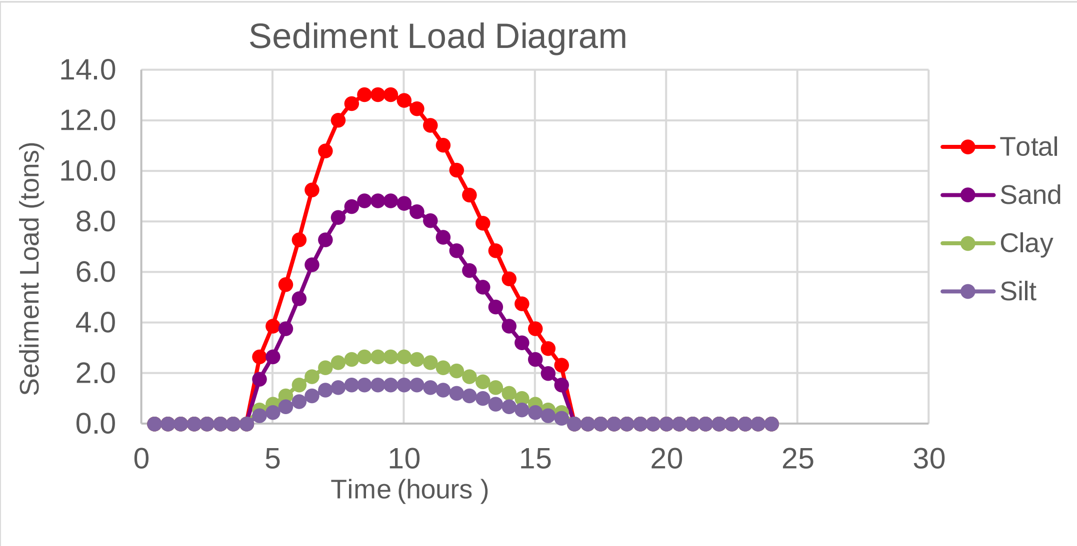
d) Sediment Load (Sand)



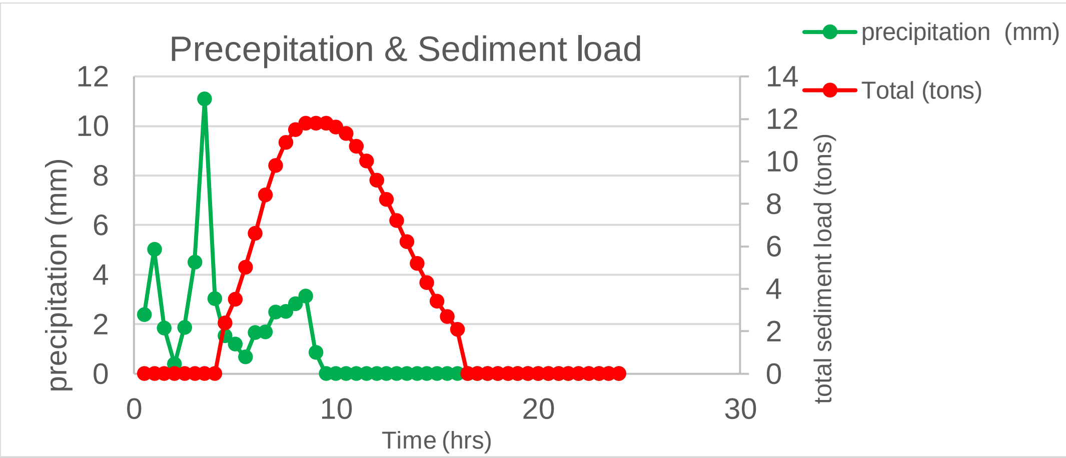
e) Sediment Concentration

Figure 4. 7: Simulated Sediment yield from HEC-HMS a) Total sediment yield, b), c), d) are sediment of clay, silt, and sand respectively from the wash-pool Aldinga basin. e) Sediment concentration at the outlet of wash-pool Aldinga basin.

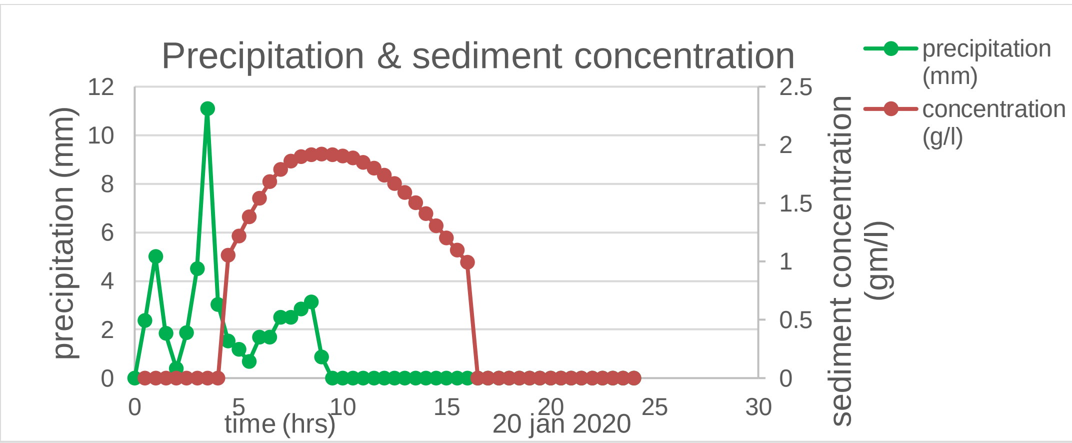
4.7.2 Discussion:



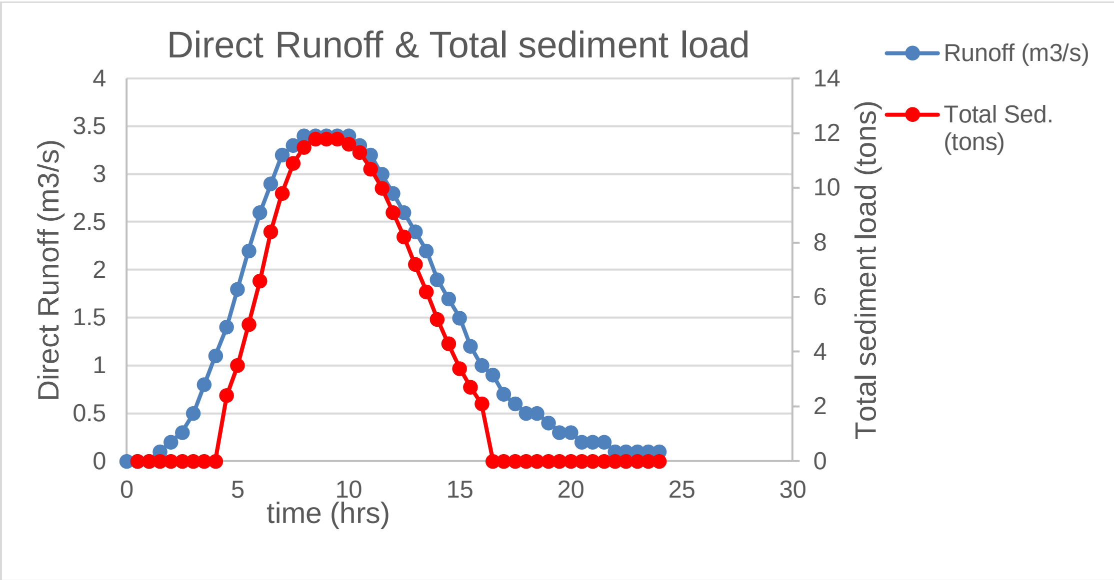
a) Individual particles sediment yield



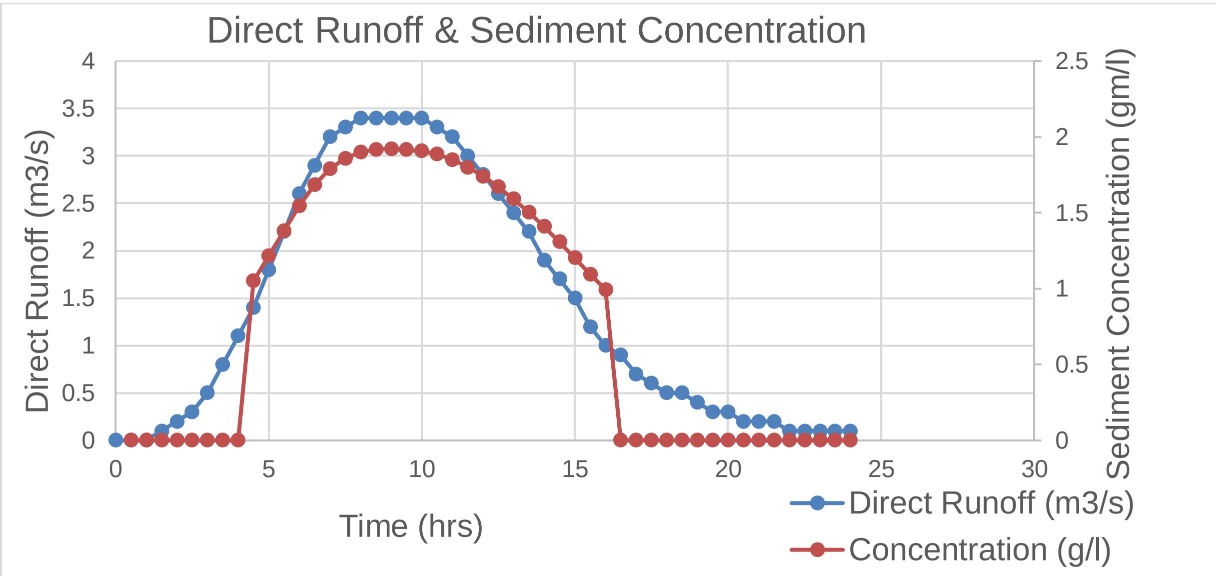
b) Precipitation and total sediment load



c) Precipitation and sediment concentration



d) Discharge and total sediment load



e) Discharge and Sediment concentration**.**

Figure 4. 8: Graphs of the results table from the HEC-HMS model. Sediment load and Sediment concentration curve combine with precipitation and discharge. a) individual particles sediment yield, b) precipitation and total sediment load, c) precipitation and sediment concentration d) Discharge and total sediment load, e) Discharge and Sediment concentration.

During this project, I found HEC-HMS is an easy and user-friendly software. However, the fine resolution of DEM that is 1 m* 1m of the basin took a longer time to simulate. I started a project with the small cliff basin (area 1200 m^2), HEC-HMS could not be able to produce the erosion because of threshold discharge of this basin was less than 1 m^3/s. Therefore, HEC-HMS cannot be applicable for the small catchment. Thereafter, I started my project with the larger catchment (47.9 km^2) and got the sediment deposition and sediment concentration at the outlet of the catchment.

In this study, an example case study of soil erosion and sediment yield by the application of HEC-HMS was performed, the result is that the soil erosion (sediment yield and sediment concentration) is increased with an increase in flow rate. Flow rate is the initial boundary condition that was obtained from the hydrological modelling. Also, soil erosion and sediment transport process are most sensitive to the factors such as soil erodibility (K), length and steepness factor (LS), land cover factor (C), and practice factor (P). Furthermore, soil erosion and sediment yield were estimated by selecting the MUSLE method in the erosion model and the Laursen-Copeland method in the sediment model. The input parameters for erosion (K, LS, C, P) and sediment (specific gravity and dry density) model were estimated mostly based on the review of the literature.
The result of the total sediment yield in HEC-HMS was divided into three sediment types such as clay, silt, and sand. The distribution of each sediment load is based on the input gradation curve in the erosion model.

CHAPTER 5: CONCLUSIONS AND FUTURE RECOMMENDATION

Conclusions

In this project, an example case study performed a better understanding of the whole process of application of HEC-HMS to the soil erosion and sediment yield. Following are the main conclusions found from this study:

- HEC-HMS is free available software, easy to use. When the method for erosion and sediment model is selected, and parameters estimated then the model can simulate and understand very easily. However, I found that model simulation took too long time for the fine resolution (1 m*1 m) DEM, and the model performed better, and faster for the 5 m*5 m resolution DEM.
- The HEC-HMS model cannot simulate erosion for the small catchment which has the runoff discharge below $1\ \mathrm{m}^3/s$. I found that there was no erosion produced in HEC-HMS modelling in a catchment area less than 0.5 km^2 and runoff discharge below $1\ \mathrm{m}^3/s$, that condition had been mentioned to HEC-HMS developers, they replied, HEC-HMS has not been designed for the watershed associated with runoff discharge less than $1\ \mathrm{m}^3/s$.
- HEC-HMS model found the total sediment load, sediment load of each grain class, and sediment concentration within the time-series at the outlet of the basin. 11.8-tonne total sediment load and 1.92 gm/l total sediment concentration were estimated from the HEC-HMS for nine hours precipitation storm, these results illustrate the applicability of HEC-HMS in erosion and sediment yield.

Recommendations:

Based on limitation, results, and experience during this project, the following recommendations are made:

- In the present study, input parameters for the model were selected from published resources. For a future project, conduct the field test and laboratory test to use precise data for reducing uncertainty.
- Conduct the model calibration and validation for both hydrological and erosion and sediment yield model for better performance.

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APPENDICES

Appendix A1: Guide to the use of HEC-HMS

To simulate the HEC-HMS model, several steps include:

- **Find the decision required:**

  Decide what decision is required based on the research goal. For example, in an erosion and sediment transport study, the decision requires is the estimation of sediment load and sediment concentration.

- **Find Out the required data**

  After the decision, this step will set the use of selection and application methods. For example, in erosion and sediment transport studies, the HEC-HMS required precipitation runoff, land use, topography, and soil properties of the extended location. While particle size distribution of soils plays some role to calculate the sediment load. However, it cannot influence decision making. Thus, decision-making is based on rainfall-runoff, land use, terrain, and type of soil.

- **Define the relevant watershed information required:**

  The simulation methods in HEC-HMS are data-driven and they are applicable to watersheds of all sizes for the analysis. For example, to analyse a watershed with an area of thousands of square kilometres can be divided into sub-watersheds with an area of hundreds of square kilometres.

- **Select the relevant method**

  In HEC-HMS, several alternative methods available, need to select the proper method based on decision making. For example, chose the relevant method for the erosion model Each method influenced by its input parameters. In this study, (MUSLE) has been selected as an erosion method, this method is applicable for the pervious (rural) areas (Pak, JH et al. 2015).

- **Fit and verify the model**

  Input the estimated value of parameters for the selected method to fit the model before the model run. In this study require parameters are estimated from the published resources. However, to estimate the precise parameter we can conduct experiment and observation and calibration.

- **Generate boundary conditions and initial conditions:**

  In HEC-HMS, boundary conditions are generated based on the rainfall data and the initial conditions are created based on the calibration process. The hydrology model in HEC-HMS is the main model, it simulates the precipitation overflow process of the watersheds. Hydrology models need to be calibrated before simulating the surface erosion and sediment transport model.

- **Modelling by HEC-HMS**

  The detailed procedure of the HEC-HMS modelling can be shown in the User's Manual(USACE 2016b).

- **Check and sensitivity analysis**

  After the HEC-HMS modelling, the result needs to be checked and compared to the expected result. If the result from HEC-HMS is considerably different, input parameters for the selected methods need to be reviewed. At this point, sensitivity analysis can be applied to the result.

Appendix A 2: Catchment delineation in HEC-HMS

- **Import DEM**

1. Open HEC-HMS create a new project from file menu and set to the metric unit.
2. Go to components menu and select the terrain data manager to create the terrain data as shown in figure A1. To delineate the catchment terrain data will need to be linked with basin model. Go to components menu, create a basin model from the basin model manager as shown in figure A1.

Figure A 1: Create terrain data

Save the imported terrain data, selected terrain data will be converted by HEC-HMS into a geo TIF.

- **Catchment delineation:**

1. Go to GIS menu, check the co-ordinate system and unit. Select the pre-process sinks, this process generates two new layers sink location and sink fill, these can be turn off and on from map layer window. To open the map layers, select the view menu.
2. Go to GIS menu, select Pre-process Drainage, this generates two new layers, Flow Direction and Flow Accumulation. Flow direction displays the direction of flow from one grid cell to the next. And the flow accumulation displays the number of upstream grid cells.
3. Go to GIS menu, select identify streams. Put the threshold value for the stream delineation. Small value will create a more sub-basin. Under the same GIS menu, Select the break points manager to insert outlet in the catchment near about to an identified stream.

4. To delineate the catchment, go to GIS menu select delineate elements. Final displays will be a link of combined sub-basin, sink, reach and outlet of the catchment.

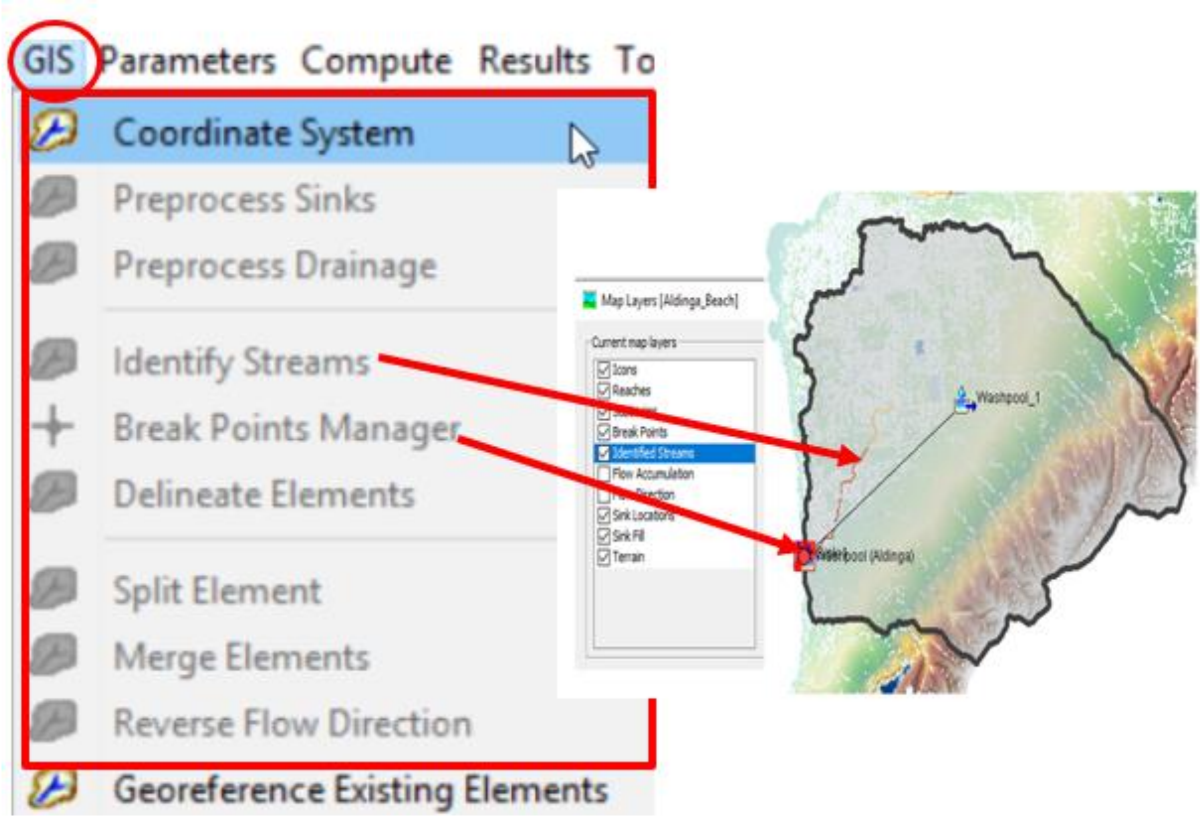


Figure A 2: Parameter in GIS menu and catchment delineation**.**

Appendix A 3: Detail process of Erosion modelling in HEC-HMS

1. Open HEC-HMS, go to basin model, and select yes from sediment option. By default, erosion and sediment transport features are deactivated in HEC-HMS. To active the component features user should select yes under sediment from the basin model icon is shown in figure B1.

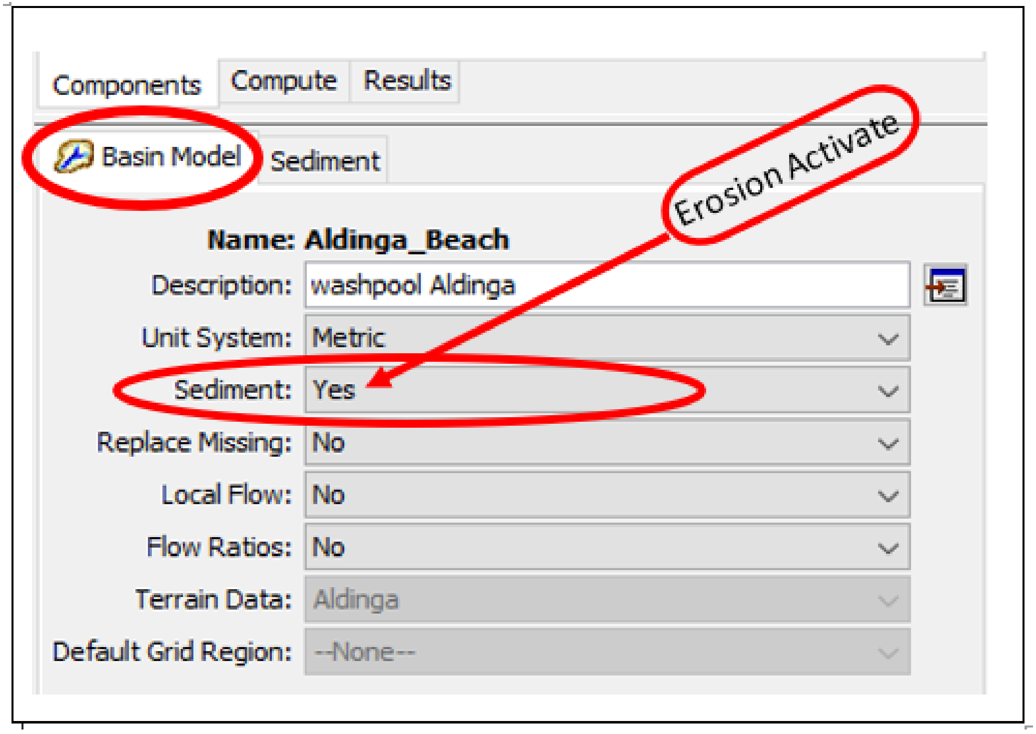


Figure A 3: Activation of erosion and sediment model in HEC-HMS.

2. From the component editor, select the sub-basin option. Go to the erosion method and click the Modified USLE among the five different erosion methods is shown in figure B2. If click on the None-method, there will be no erosion and sediment discharge in the sub-basin.

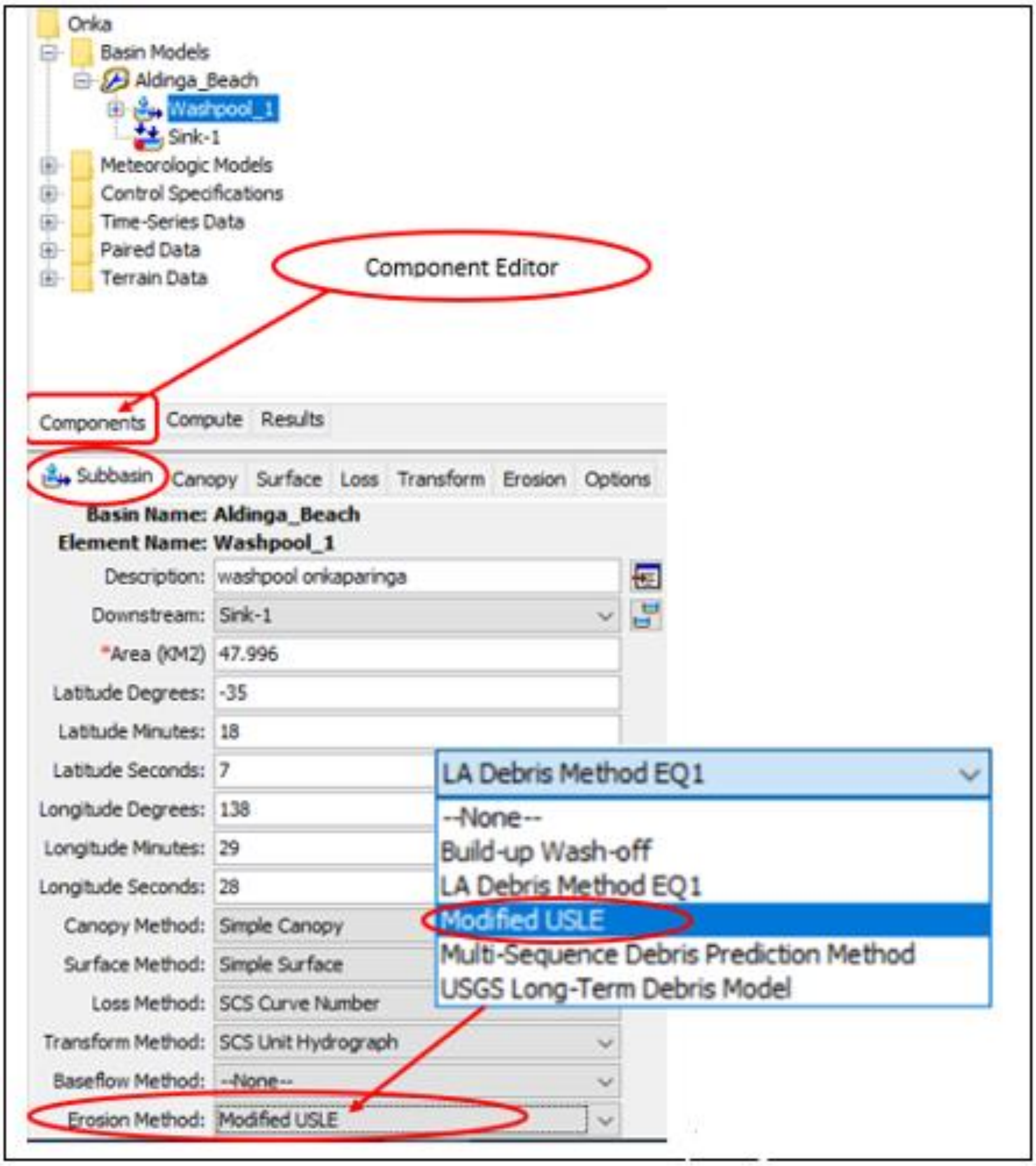


Figure A 4: Selection of erosion method.

3. From the component editor, open the erosion model by click on the erosion component. Enter all the estimated parameter values, estimated values are shown in figure B3. To create a table for the gradation curve, go to the component's menu select the paired data manager and click on the diameter-percentage function. Enter the values for diameter and percent finer is shown in figure B4.
4. Save the input parameters for the erosion model.

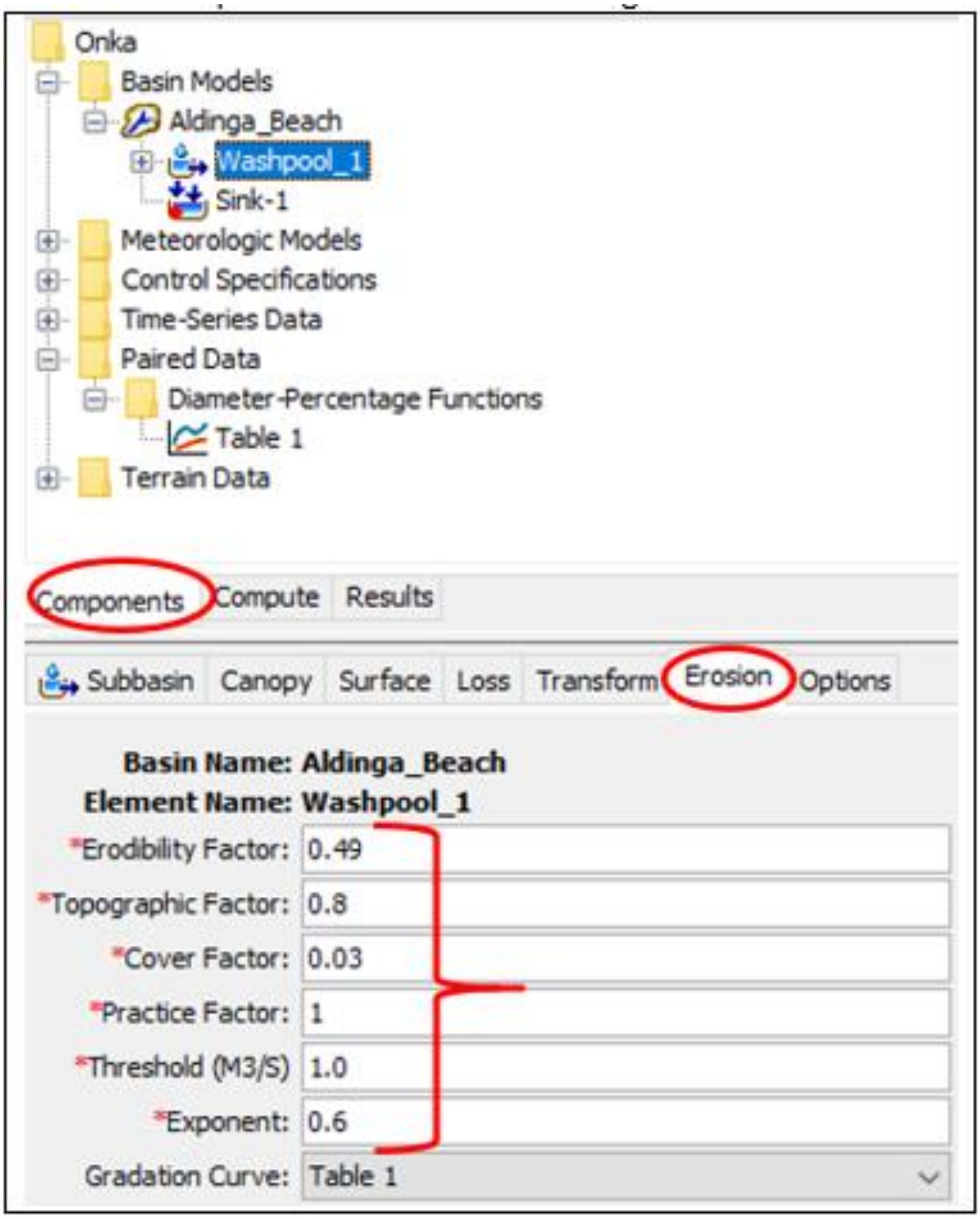


Figure A 5: Input erosion parameter.

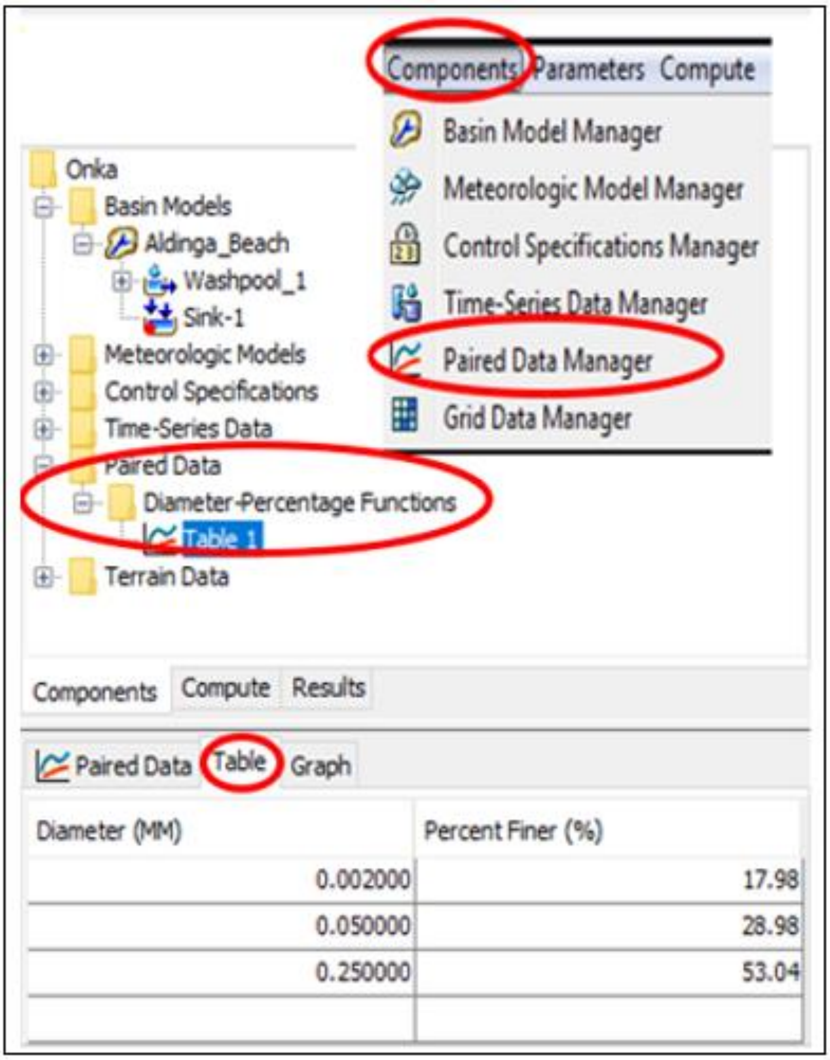


Figure A 6: Input Gradation Curve (Table).

Appendix A 4: Detail process of Sediment modelling in HEC-HMS

1. Open the HEC-HMS model and click on the basin model. Go to the component editor, click on the sediment option is shown in figure C1.
2. Click on the transport potential option, Select the Laursen-Copeland method among the seven different methods is shown in figure C1.

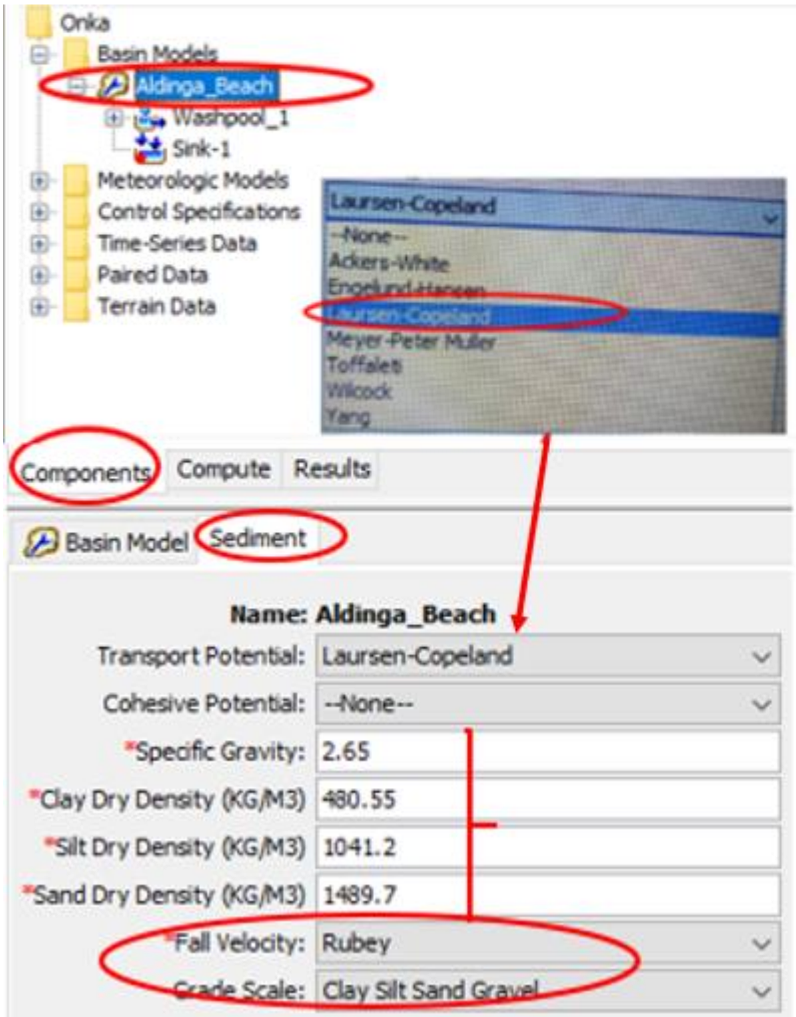


Figure A 7: Selection transport potential method.

3. Click the sediment option next to the basin model. Input all the estimated parameter values of specific gravity and particles dry densities as shown in figure C2. Click on fall velocity and select Rubey as the default selection out of four methods, Report 12, Rubey, Toffaleti, and Van Rijn. Click on Grade Scale and select Clay Silt Sand Gravel as shown in figure C2.
4. Save the sediment model.

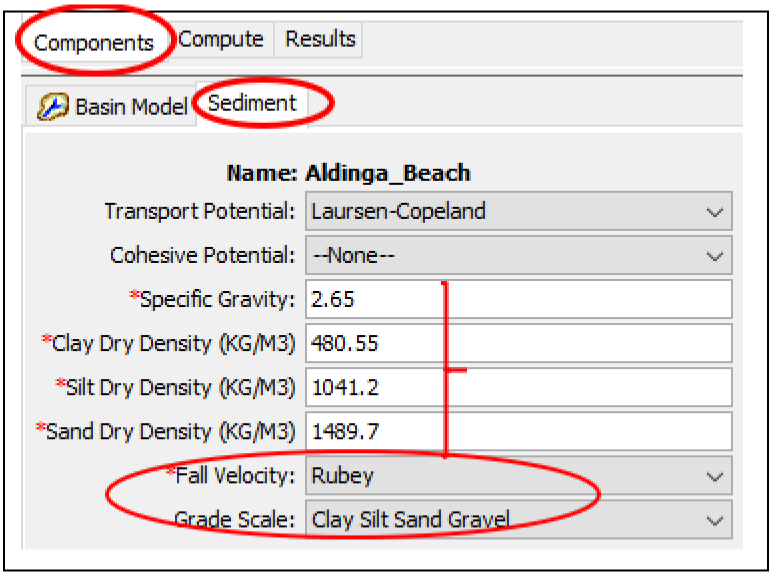
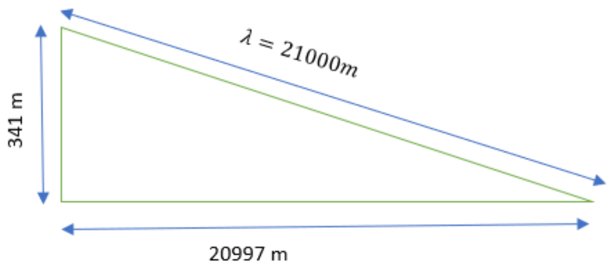


Figure A 8: Input estimated parameter values in sediment model.

Appendix B 1: Calculation of *LS* factor



$\tan\theta = \left(\frac{341}{20997}\right) = 0.016$,

$\theta = 0.93°$

$\lambda = 21000$ m, measured from google earth

Elevation difference= 341m, measured from google earth

L $= \left(\frac{\lambda}{22.13}\right)^{m}$

$m = \frac{\beta}{1+\beta} = \sin\theta/(3(\sin\theta)^{0.8} + 0.56)$ = 0.02, take m=0.2 for $\theta \leq 1.7\%$

$L = 3.93$

$S = 10.8\sin\theta + 0.03$ for $\theta < 9\%$

$S = 0.205$

LS=3.93 *0.205 = **0.8**

Appendix B 2: Time of concentration.

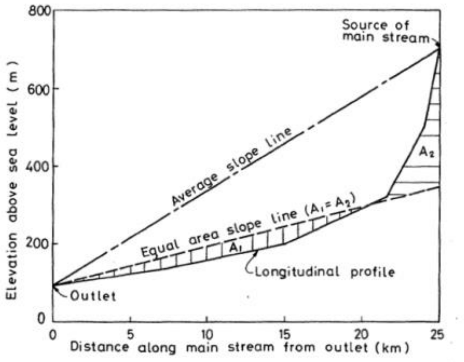
Design rainfall estimation: Duration

➢ **Time of concentration**

- The Bransby-Williams formula is the most commonly used in Australia:

$$t_c = \frac{F \times L}{A^{0.1} \times S^{0.2}}$$

F = conversion factor. F = 58.5 when A is km^2 and 92.7 when A is hectares (ha)
A = catchment area (either km^2 or ha)
L = length of mainstream (km) from the outlet to the catchment boundary
S = equal area slope (m/km)



Source: The Bransby- Williams formula.

Appendix B 3: Morgan *K* factor values

Textural Class	K Factor tonnes/hectare (tons/acre)		
	Average OMC*	Less than 2% OMC	More than 2% OMC
Clay	0.49 (0.22)	0.54 (0.24)	0.47 (0.21)
Clay loam	0.67 (0.30)	0.74 (0.33)	0.63 (0.28)
Coarse sandy loam	0.16 (0.07)	–	0.16 (0.07)
Fine sand	0.18 (0.08)	0.20 (0.09)	0.13 (0.06)
Fine sandy loam	0.40 (0.18)	0.49 (0.22)	0.38 (0.17)
Heavy clay	0.38 (0.17)	0.43 (0.19)	0.34 (0.15)
Loam	0.67 (0.30)	0.76 (0.34)	0.58 (0.26)
Loamy fine sand	0.25 (0.11)	0.34 (0.15)	0.20 (0.09)
Loamy sand	0.09 (0.04)	0.11 (0.05)	0.09 (0.04)
Loamy very fine sand	0.87 (0.39)	0.99 (0.44)	0.56 (0.25)
Sand	0.04 (0.02)	0.07 (0.03)	0.02 (0.01)
Sandy clay loam	0.45 (0.20)	–	0.45 (0.20)
Sandy loam	0.29 (0.13)	0.31 (0.14)	0.27 (0.12)
Silt loam	0.85 (0.38)	0.92 (0.41)	0.83 (0.37)
Silty clay	0.58 (0.26)	0.61 (0.27)	0.58 (0.26)
Silty clay loam	0.72 (0.32)	0.79 (0.35)	0.67 (0.30)
Very fine sand	0.96 (0.43)	1.03 (0.46)	0.83 (0.37)
Very fine sandy loam	0.79 (0.35)	0.92 (0.41)	0.74 (0.33)

* Organic matter content

Source:(Mine & PORGRAM 2012; Morgan 2009).

Appendix B 4: Soil erodibility Nomograph:

Image removed due to copyright restriction.

Source: soil erodibility nomograph (Wischmeier et al., 1971)

Appendix B 5: Cover factor values:

Image removed due to copyright restriction.

Source: (Morgan 2009)

Appendix B 6: USDA Soil triangle

Image removed due to copyright restriction.

Source: (Brown 1998)

Appendix C 1: Result table from HEC-HMS.

Time	Precipitation	Direct Runoff	Sediment concentration	
hrs: min	mm	m3/s	mg/l	g/l
00:00		0		
00:30	2.37	0	0	0
01:00	5.01	0	0	0
01:30	1.84	0.1	0	0
02:00	0.39	0.2	0	0
02:30	1.87	0.3	0	0
03:00	4.49	0.5	0	0
03:30	11.08	0.8	0	0
04:00	3.03	1.1	0	0
04:30	1.52	1.4	1051.16	1.05
05:00	1.19	1.8	1218.04	1.22
05:30	0.67	2.2	1382.95	1.38
06:00	1.67	2.6	1543.55	1.54
06:30	1.68	2.9	1683.35	1.68
07:00	2.49	3.2	1788.40	1.79
07:30	2.51	3.3	1859.37	1.86
08:00	2.83	3.4	1899.65	1.90
08:30	3.13	3.4	1917.18	1.92
09:00	0.87	3.4	1920.18	1.92
09:30	0	3.4	1915.38	1.92
10:00	0	3.4	1906.23	1.91
10:30	0	3.3	1886.47	1.89
11:00	0	3.2	1850.61	1.85
11:30	0	3	1800.21	1.80
12:00	0	2.8	1740.07	1.74
12:30	0	2.6	1670.61	1.67
13:00	0	2.4	1591.00	1.59
13:30	0	2.2	1503.51	1.50
14:00	0	1.9	1408.77	1.41
14:30	0	1.7	1307.19	1.31
15:00	0	1.5	1201.79	1.20
15:30	0	1.2	1096.08	1.10
16:00	0	1	993.32	0.99
16:30	0	0.9	0	0
17:00	0	0.7	0	0
17:30	0	0.6	0	0
18:00	0	0.5	0	0
18:30	0	0.5	0	0
19:00	0	0.4	0	0

19:30	0	0.3	0	0
20:00	0	0.3	0	0
20:30	0	0.2	0	0
21:00	0	0.2	0	0
21:30	0	0.2	0	0
22:00	0	0.1	0	0
22:30	0	0.1	0	0
23:00	0	0.1	0	0
23:30	0	0.1	0	0
00:00	0	0.1	0	0

Time	**Total Sediment load**		**Sand**		**clay**		**silt**	
hrs: min	TONNE	tons	TONNE	tons	TONNE	tons	TONNE	tons
00:00								
00:30	0	0	0	0.00	0	0.00	0	0.00
01:00	0	0	0	0.00	0	0.00	0	0.00
01:30	0	0	0	0.00	0	0.00	0	0.00
02:00	0	0	0	0.00	0	0.00	0	0.00
02:30	0	0	0	0.00	0	0.00	0	0.00
03:00	0	0	0	0.00	0	0.00	0	0.00
03:30	0	0	0	0.00	0	0.00	0	0.00
04:00	0	0	0	0.00	0	0.00	0	0.00
04:30	2.4	2.64	1.6	1.76	0.5	0.55	0.3	0.33
05:00	3.5	3.86	2.4	2.64	0.7	0.77	0.4	0.44
05:30	5	5.51	3.4	3.75	1	1.10	0.6	0.66
06:00	6.6	7.27	4.5	4.96	1.4	1.54	0.8	0.88
06:30	8.4	9.26	5.7	6.28	1.7	1.87	1	1.10
07:00	9.8	10.80	6.6	7.27	2	2.20	1.2	1.32
07:30	10.9	12.01	7.4	8.15	2.2	2.42	1.3	1.43
08:00	11.5	12.67	7.8	8.60	2.3	2.53	1.4	1.54
08:30	11.8	13.00	8	8.82	2.4	2.64	1.4	1.54
09:00	11.8	13.00	8	8.82	2.4	2.64	1.4	1.54
09:30	11.8	13.00	8	8.82	2.4	2.64	1.4	1.54
10:00	11.6	12.78	7.9	8.71	2.4	2.64	1.4	1.54

10:30	11.3	12.45	7.6	8.38	2.3	2.53	1.4	1.54
11:00	10.7	11.79	7.3	8.04	2.2	2.42	1.3	1.43
11:30	10	11.02	6.7	7.38	2	2.20	1.2	1.32
12:00	9.1	10.03	6.2	6.83	1.9	2.09	1.1	1.21
12:30	8.2	9.04	5.5	6.06	1.7	1.87	1	1.10
13:00	7.2	7.93	4.9	5.40	1.5	1.65	0.9	0.99
13:30	6.2	6.83	4.2	4.63	1.3	1.43	0.7	0.77
14:00	5.2	5.73	3.5	3.86	1.1	1.21	0.6	0.66
14:30	4.3	4.74	2.9	3.20	0.9	0.99	0.5	0.55
15:00	3.4	3.75	2.3	2.53	0.7	0.77	0.4	0.44
15:30	2.7	2.98	1.8	1.98	0.5	0.55	0.3	0.33
16:00	2.1	2.31	1.4	1.54	0.4	0.44	0.2	0.22
16:30	0	0	0	0.00	0	0.00	0	0.00
17:00	0	0	0	0.00	0	0.00	0	0.00
17:30	0	0	0	0.00	0	0.00	0	0.00
18:00	0	0	0	0.00	0	0.00	0	0.00
18:30	0	0	0	0.00	0	0.00	0	0.00
19:00	0	0	0	0.00	0	0.00	0	0.00
19:30	0	0	0	0.00	0	0.00	0	0.00
20:00	0	0	0	0.00	0	0.00	0	0.00
20:30	0	0	0	0.00	0	0.00	0	0.00
21:00	0	0	0	0.00	0	0.00	0	0.00
21:30	0	0	0	0.00	0	0.00	0	0.00
22:00	0	0	0	0.00	0	0.00	0	0.00
22:30	0	0	0	0.00	0	0.00	0	0.00
23:00	0	0	0	0.00	0	0.00	0	0.00
23:30	0	0	0	0.00	0	0.00	0	0.00
00:00	0	0	0	0.00	0	0.00	0	0.00