CHAPTER 4

METHODOLOGY

4.1 GENERAL

This research study focuses on the investigation of reservoir capacity loss due to sedimentation, internal Phosphate loading in the reservoir and the catchment processes through modelling approach. The research work started with a reconnaissance survey through which the general characteristics of the catchment area and the reservoir were collected. Several field investigations were conducted during 2009 to 2012 to collect primary data both in the catchment area as well as in the reservoir. The detailed procedure adopted in the study is explained below.

4.2 RECONNAISSANCE SURVEY

Reconnaissance survey was conducted during 2007 to obtain initial information regarding the details of the Krishnagiri reservoir and its catchment area (Figure 3.2). First field visit was carried out in the north east part of the watershed where Veppanapalli nadhi, Nachikuppam tributary and Markandanadhi flows. The width of the Veppanapalli nadhi is mostly narrow and traverses through forest and agricultural lands with bank erosion noticed in few places whereas Markandanadhi is relatively larger in width and runs from the highest elevation of 1050 m above MSL. The surplus of the Kamasandra tank located at the upper most part of the watershed in Kamsandra village flows into Markandanadhi River. All three rivers join
together at a place called Nedusalai and at about 1.7 km from Nedusalai an off take canal named Badathalab supply channel feeds Badathalab Tank (Big tank) near Krishnagiri town which has an ayacut of 335 ha. This was the only storage structure prior to the construction of Krishnagiri Reservoir in the catchment area. The terrain in general is found to have cultivated plains and valleys interspersed with sharply raising boulder hills. Many of the hills are spectacularly large and are often devoid of tree growth. During the reconnaissance survey of north eastern part, cultivated lands, fallow lands, barren land, stony wastes, water body, settlement and reserved forests were observed. The mountains are very steep in the middle part of the watershed (Figure 3.3).

During the second visit, the northwest and southern parts of the watershed were surveyed. With the help of GPS it was found that the elevation in watershed decreased from Hosur to Lower Ponnaiyar region from 1000 m MSL to 500 m MSL. In the entire watershed, steep slopes were found between Sulagiri and Melumalai where river Chinnar joins the Ponnaiyar River. The survey showed that the settlement from Chinnar subwatershed towards the north of the watershed has increased over the years. From Hosur towards Bengaluru, the built up area was the dominant land use. Another aspect of the survey included the identification of rain gauges in the watershed. Non-recording rain gauges are mostly deployed in the watersheds to measure the depth of rainfall except in Melumalai and KRP dam site. In addition to Melumalai and KRP dam site, two self recording rain gauges one in Veppanapalli and one in Sulagiri was installed for the present study. All the tributaries join together at a place called Ompalagutta and drain the river into Krishnagiri Reservoir. Central Water Commission, Government of India has installed a Gauging station at Gummanur, located 6 km upstream of the Krishnagiri reservoir where the daily flow volume and sediment concentration is monitored. The flow and sediment concentration data for the period 2001
to 2011 was collected from the station with the permission of the Chief Engineer, CPWD of Central Water Commission at Coimbatore, Tamil Nadu.

4.3 FIELD INVESTIGATIONS

The two automatic rain gauges installed at Veppanapalli and Sulagiri generated daily rainfall charts from 2008 to 2011. This has provided daily rainfall depth charts with 15 minutes duration for a period of four years (2008 to 2011) in the Krishnagiri reservoir catchment area where only non-recording rain gauges are available. In order to characterise the soils in the catchment area, in addition to the secondary data, soil samples from the entire catchment area were collected in an intensive survey. A predetermined route was followed to cover selected sampling locations in the entire catchment area starting from KRP reservoir through Sulagiri, Hosur, Malur, Kolar, Kamasandra, Veppanapalli, Krishnagiri and KRP dam. 46 soil samples were collected in the catchment area, stratified by the soil series map of Dhamapuri district prepared by the Agricultural Engineering Department of Government of Tamil Nadu. Soil samples were processed as per standard procedures (Loring & Rantala 1992) and analysed for particle size distribution and organic matter content. The bathymetry survey of the Krishnagiri reservoir was conducted during February 2012 along with in situ field measurements of the physical and chemical characteristics of the water and sediment.

4.4 SOURCES OF DATA

The details of the data collected from various sources are summarised in Table 4.1. The topography of the catchment is usually represented by the Digital Elevation Model (DEM). Shuttle Radar Topographic Mission (SRTM) data were downloaded from the Consortium for Spatial Information with a spatial resolution of 90 m x 90 m. The drainage network in the catchment area reflects the runoff potential and the routing
Toposheets from Survey of India were collected and used for delineation of the drainage network in GIS environment and combined with the stream network derived from the DEM. The subsurface characteristics of the catchment area can be captured through the soil profiles. The Soil atlas map of Krishnagiri and Dharmapuri district prepared by Agricultural Engineering Department of Government of Tamil Nadu was collected and georeferenced in GIS. The required soil map for the catchment area was then clipped from the district soil map. The runoff from the catchment to the outlet depends on the land use and land cover pattern in the catchment area. First level land use and land cover classification map for the year 2007 was prepared by IRS, Anna University for the entire Dharmapuri district. This map was collected and used in this study. The meteorological data of the two Climatic stations located at Bengaluru and Melumalai were downloaded from the Global Weather Data and India SWAT dataset (http://globalweather.tamu.edu). In addition, daily rainfall data from 1998 to 2011 was obtained from the State Surface and Groundwater data Centre, Tharamani Government of Tamil Nadu and Karnataka State Natural Disaster Monitoring Centre, Bengaluru. The daily inflow into the reservoir along with the sediment concentration in the stream flow was obtained from the Central Water Commission, Cauvery and Southern rivers organisation, Coimbatore for the Gummanur River gauging station. Figure 4.1 shows the general methodology adopted for water, soil samples and data analysis in the study.
Table 4.1 Secondary sources of data collected for the present study and the Organisations

<table>
<thead>
<tr>
<th>Type of Data</th>
<th>Source</th>
<th>Scale / Resolution</th>
<th>Station / region</th>
<th>Description/Properties</th>
<th>Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topography</td>
<td>SRTM</td>
<td>90 m x 90 m</td>
<td>Krishnagiri Watershed</td>
<td>Digital Elevation Model and slope</td>
<td>-</td>
</tr>
<tr>
<td>Hydrography</td>
<td>Survey of India</td>
<td>1:50000</td>
<td>Topo sheet numbers: 57H/9, 57 H/13, 57 H/14, 57 L/1, 57 L/2, 57 L/3 and 57 L/7</td>
<td>Drainage network</td>
<td>-</td>
</tr>
<tr>
<td>Soil</td>
<td>Soil Atlas Dharmapuri district</td>
<td>1:20000</td>
<td>Dharmapuri and Krishnagiri District</td>
<td>Soil classification and physical properties</td>
<td>-</td>
</tr>
<tr>
<td>Land Use</td>
<td>IRS Anna University</td>
<td>-</td>
<td>Krishnagiri Watershed</td>
<td>Land use classification</td>
<td>2007</td>
</tr>
<tr>
<td>Hydrology</td>
<td>Global Weather Data and India SWAT Dataset</td>
<td>Daily</td>
<td>Melumalai and Bengaluru</td>
<td>Precipitation, temperature, Relative Humidity, wind speed, Solar radiation</td>
<td>1979-2011</td>
</tr>
<tr>
<td></td>
<td>State Surface and Groundwater data Centre, Tharamani</td>
<td>Daily</td>
<td>Krishnagiri, KRP dam, Melumalai, Sulagiri, Hosur, Royakottai, Denkanikottai</td>
<td>Precipitation</td>
<td>1980-2011</td>
</tr>
<tr>
<td></td>
<td>Karnataka State Natural Disaster Monitoring Centre, Bengaluru</td>
<td>Daily</td>
<td>Malur, Masti, Kolar, Bengaluru, Bangarpet, Bethamangala</td>
<td>Precipitation</td>
<td>1980-2011</td>
</tr>
</tbody>
</table>
Figure 4.1 Plan of work
4.5 BATHYMETRY SURVEY

The bathymetry survey of the reservoir was conducted during 2012. The water level during the survey period was 480.3 m above MSL (14.3 m depth). River Discharge Monitoring System (Q liner), an acoustic Doppler velocity profiler used to measure discharge was deployed to measure the spot depth at various locations of the Reservoir in this study. The Q liner has a Doppler current profiler mounted on a miniature catamaran measuring 93 cm x 46 cm x 23 cm (l x w x h) weighing 11.5 kg including profiler and batteries. The aquapro sensor mounted to the bottom of the boat is intended for measuring the velocities and depth which acts as both transducer and receiver. This sensor propagates four beams at 2 MHz and has sufficient energy to penetrate the water column but reflected from sediment water interface. The first three beams are used for velocity measurement while the fourth beam is configured as a high accuracy echo sounder for accurate depth measurement (Q Liner user manual 2005). A very narrow beam combined with a very short pulse gives accurate high resolution for depth measurement. A special algorithm is inbuilt to discriminate the false echoes. Returning echoes are taken through a digital matched filter which gives quality of depth measurement between 0 (no match) and 255 (perfect match) levels. Any echo that has a quality figure between 50 and 100 is accepted as good measurement.

In the present work, the bathymetry surveys were conducted between February and March 2012. The water level in the reservoir during the bathymetry survey was 480.3 m above MSL (14.3 m). The Q liner was deployed from a 5 meter boat and the accuracy of the total depth measured is increased by averaging measurements over a period of time and in this case the measurement time was set to 30 to 45 seconds. Survey lines consisted of south-west, north-east, northeast-southwest, and northwest-southeast trending
tracks with an average offset of 30 to 40 m. The total track line distance covered during the surveys in the reservoir was 72 km (Figure 4.2).

Figure 4.2 Hydrographic survey range lines for collection of spot depth data in Krishnagiri Reservoir during February 2012
Navigation data for the survey were acquired from *Magellan path finder* Global Positioning System. The depth measured was corrected for the heading, pitch and roll by the *Q liner* review software. The data from both GPS and *Q liner* survey were exported to MS Excel spread sheet. The survey yielded 700 soundings spread over the entire reservoir water spread area. The data file was post-processed to generate a contour plot of the entire reservoir in MapInfo GIS environment. The network of traverses used in this study was closer than a traditional hydrographic survey method. This would minimise the interpolation errors during post-processing of data. In general, contouring algorithms perform better as data density increases. At the time of survey, the water level was 2.81 m below the FRL. Remote sensing imageries were used to obtain the water spread area of the reservoir between the water level at the time of survey and the FRL which is 483.11 m. The water spread boundary obtained through satellite imagery was overlaid with the contour map drawn from the bathymetry survey. The volume between any two adjacent elevations was determined by prismoidal formula and the resulting volumes were summed up to create a stage-storage curve.

The depth contours of the reservoir for the year 2007 conducted by the Institute of Hydraulics and Hydrology at Poondi (IHH 2007) and 2012 (present study) were processed using cut/fill tool in ArcGIS 9.3 to determine the areas and volumes of change between two bathymetric surfaces. This identified the areas and volume of the surface that have been modified by the removal or addition of sediments within the reservoir during this period.

### 4.6 SEDIMENTS

The physical and chemical characteristics of the sediments were assessed through field investigation and monitoring of the sediments. *In-situ* measurements were made for estimation of pH, temperature, DO, EC, and TDS using *YSI Professional plus* field probe in the Reservoir. Sediment deposits at various locations were sampled using a simple grab sampler (Figure 4.3).
Figure 4.3 Sediment sampling locations in Krishnagiri Reservoir
The samples were transferred immediately to air tight containers and transported to the laboratory under cold condition for further analysis. Samples were centrifuged to separate the pore water and sediments at 4000 rpm for 30 min in the laboratory. Pore water was carefully transferred to clean polythene vials and refrigerated until further analysis (Figure 4.4). Sediment samples were air dried in shade and homogenized by grinding with mortar and pestle.

**Figure 4.4 Internal Phosphate load estimation in Krishnagiri Reservoir**

Dry sediments were passed through 0.075 mm sieve to separate silt/clay particles. The chemical speciation of sediment Phosphate content was analyzed by sequential extraction procedure in the laboratory. The extraction
method given by Nurnberg (1994) and Kapanen (2008) was used to analyze the sediment phosphate fractions. Total Phosphate (TP) in sediment and the various inorganic forms of Phosphate such as soluble reactive Phosphate (SRP), calcium bound Phosphate (Ca-P), aluminium bound Phosphate (Al-P) and iron bound Phosphate (Fe-P) was estimated (Figure 4.5). The organic matter content in the sediment was analysed by loss on Ignition method (550 °C, 3h). The weight difference gave the organic matter present in the sediment and is expressed as percent of the sediment by weight.

![Figure 4.5 Sediment analysis procedures](image)

4.6.1 Laboratory Analysis

The following sequence of extractions was performed to estimate the P fractions in the sediment samples.
• 1 M NH₄Cl at pH 7 for 2h to be used to remove loosely sorbed P (NH₄Cl) in sediments.

• 0.11 M NaHCO₃ for 1h was used to remove Iron bound phosphorus (NaHCO₃-P) from sediments.

• 0.1 M NaOH for 16 h was used to remove Aluminium bound P (NaOH-P).

• 0.5 M HCl for 16 h was used to extract apatite P or calcium bound P (HCl-P).

• Total Phosphorus is determined after digestion of whole sediment sample with potassium per sulphate reagent and analysed by ascorbic acid method (APHA 1999).

• TP in pore water samples from the sediments were analyzed after the sample is digested by Persulphate digestion reagent, neutralized and analysed by the ascorbic acid method (APHA 1999).

4.6.2 Phosphate Release Rate

Phosphate release rate from the sediment was calculated by estimating the variation of Phosphate fractions and total Phosphate in the sediment and pore water. The release of Phosphate from the sediment is dependent on the environmental factors and different mechanisms occurring in the reservoir. The formula derived by Nurnberg (1994) was used to calculate the release rate for in situ conditions from the reservoir sediments. The regression equation given by Nurnberg (1994) was derived by studying eight North American lakes and 63 literature data taken from lakes worldwide.
The release rate was calculated by the following equation;

\[
\text{Log RR} = 0.8 + 0.76 \log \text{TP}_{\text{sed}}
\]  \hspace{1cm} (4.1)

Where,

RR = Release rate

TP_{sed} = Total Phosphate in sediment

4.6.3 **Internal Phosphate Load**

Internal Phosphate loading in the Krishnagiri reservoir was also calculated using the formula outlined by Nurnberg (1994) for *in situ* study. Internal Phosphate loading was calculated as follows:

\[
\text{IPL} = \text{Phosphate release rate} \times \text{Anoxic factor}
\]

Where,

Anoxic factor = (Anoxic area \times anoxic period) / reservoir area

Dissolved oxygen depth profile of the Reservoir was measured monthly during 2012 by *YSI Professional plus* field probe in selected sampling locations in the reservoir. The anoxic area was calculated by interpolation of DO values in ArcGIS 9.3 environment. A value less than 1 mg/L was considered as absence of oxygen.

4.7 **SOIL EROSION ASSESSMENT**

4.7.1 **Revised Universal Soil Loss Equation (RUSLE)**

Soil erosion by water is a complex dynamic process by which productive surface soils are detached, transported and accumulated in a distant place resulting in exposure of subsurface soil while sediments deposit in reservoirs (Tirkey et al 2013). Many models were developed to predict the potential zones of soil erosion in watersheds. Revised Universal Soil Loss Equation (Renard et al 1997) is one of the robust and most widely used model
to predict soil erosion and thereby sediment yield. Many authors have used this model successfully in temperate watersheds (Angima et al 2003, Fu et al 2005, Yue-Qing et al 2008, Wang et al 2009) as well as tropical (Singh et al 1992, Dabral et al 2008, Jain & Das 2010, Tirkey et al 2013). The use of remote sensing and geographical information system (GIS) techniques later made soil erosion estimation and its spatial distribution in watershed possible (Jasmine & Ravichandran 2008, Bahadur 2009) with reasonable costs and better accuracy (Chen et al 2010). The RUSLE model (Renard et al 1997) structure is expressed as

$$A = R \times K \times LS \times C \times P$$  \hspace{1cm} (4.2)$$

where A is the average soil loss per unit area by erosion (t/ha/yr), R is the rainfall erosivity factor (MJ.mm / ha.h.year), K is the soil erodibility factor (t ha h/MJ ha mm), L is the slope length factor (dimensionless), S is the steepness factor (dimensionless), C is the cover factor (dimensionless) and P is the conservation support practice factor (dimensionless).

Rainfall Erosivity (R factor) is the term used in RUSLE to denote the potential capacity of the raindrops to cause detachment of the soil particles from its location. Wischmeier & Smith (1978) have recommended that at least 20 years of rainfall intensity data at short time intervals shall be used to accommodate natural climatic variations in estimation of R factor. R factor is seen highly correlated to soil loss at watersheds investigated in many parts of the world (Wischmeier & Smith 1978, Renard & Freimund 1994, Diodato et al 2008, Diodato & Bellocchi 2009) however, to obtain the long term rainfall erosivity of a region, high resolution automatic rainfall measurement and estimations based on such data are necessary. High resolution rainfall data, such as Pluviograph (Diodato 2005, Bonilla & Vidal 2011) which is essential to compute the storm intensity may not be available readily, especially in developing countries. For example, in the present study, automatic rain gauge
stations that record rainfall automatically are available only at Melumalai and KRP dam, whereas rain gauge stations that only record daily total rainfall depth are available in 12 locations in the Krishnagiri reservoir catchment area (Table 4.2). Several attempts have been made in the past (Yu & Rosewell 1996, Ferro et al 1999, Lu & Yu 2002, Grauso et al 2004, Diodato et al 2008) to manage this situation. Some of the researchers (Renard & Freimund 1994, Yu & Rosewell 1996, Lee & Heo 2011, Mello et al 2013) have used mean annual precipitation and modified Fournier Index to study relations between rainfall depth and erosivity. However, it would be desirable, instead of using mean annual rainfall, if daily rainfall depth can be related to the EI$_{30}$ of the area, then rainfall data available from most of the simple rain gauge stations can be reliably used to assess the R factor more accurately for a given watershed. Such attempts have been made later in some of the data scarce watersheds (Yin et al 2007, Men et al 2008) and statistical relationships have been derived with available data. These site specific empirical relationships made better estimates of erosivity (Diodato 2004, Grauso et al 2004, Angulo-Martinez & Begueria 2009) and therefore a similar procedure was followed in this study.

4.7.1.1 Rain gauges

Rainfall in the Krishnagiri Reservoir watershed area is measured using both non-recording and recording type rain gauges (Table 4.2). The rainfall stations located within the watershed were selected from the India Meteorological Department managed rain gauge network (www.imd.gov.in) at Pune, India. Sixteen stations were identified which are located in and around the watershed boundary. Among these, fourteen are non recording type (daily rainfall depth) and two are self recording type. In addition, a float type (recording) rain gauge was set up in two locations namely Veppanapalli and Sulagiri within the watershed. They recorded rainfall at intervals of 15 min from August 2008 to December 2011 for a period of 40 months.
Table 4.2 Details of the rain gauges with periods of available data

<table>
<thead>
<tr>
<th>S. No</th>
<th>Rainguage Station</th>
<th>Type</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (m)</th>
<th>Years of Record</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Veppanapalli</td>
<td>Recording</td>
<td>78.1935</td>
<td>12.6953</td>
<td>580</td>
<td>2008-2011</td>
</tr>
<tr>
<td>2</td>
<td>Melumalai</td>
<td>Recording</td>
<td>78.0992</td>
<td>12.6079</td>
<td>636</td>
<td>1998-2011</td>
</tr>
<tr>
<td>3</td>
<td>Sulagiri</td>
<td>Recording</td>
<td>78.0093</td>
<td>12.6670</td>
<td>706</td>
<td>2008-2011</td>
</tr>
<tr>
<td>4</td>
<td>Hosur</td>
<td>Non-recording</td>
<td>77.8235</td>
<td>12.7439</td>
<td>862</td>
<td>1998-2011</td>
</tr>
<tr>
<td>5</td>
<td>Marandahalli</td>
<td>Non-recording</td>
<td>78.0039</td>
<td>12.3888</td>
<td>582</td>
<td>1998-2011</td>
</tr>
<tr>
<td>6</td>
<td>Panchapalli</td>
<td>Non-recording</td>
<td>77.9169</td>
<td>12.4652</td>
<td>980</td>
<td>1998-2011</td>
</tr>
<tr>
<td>7</td>
<td>KRP dam</td>
<td>Recording</td>
<td>78.1995</td>
<td>12.4707</td>
<td>715</td>
<td>2004-2011</td>
</tr>
<tr>
<td>8</td>
<td>Rayakottai</td>
<td>Non-recording</td>
<td>78.0370</td>
<td>12.5106</td>
<td>700</td>
<td>1998-2011</td>
</tr>
<tr>
<td>9</td>
<td>Malur</td>
<td>Non-recording</td>
<td>77.9398</td>
<td>12.9948</td>
<td>900</td>
<td>1998-2011</td>
</tr>
<tr>
<td>10</td>
<td>Masti</td>
<td>Non-recording</td>
<td>77.9974</td>
<td>12.8679</td>
<td>836</td>
<td>1998-2011</td>
</tr>
<tr>
<td>11</td>
<td>Bangarpet</td>
<td>Non-recording</td>
<td>78.1667</td>
<td>12.9833</td>
<td>817</td>
<td>1998-2011</td>
</tr>
<tr>
<td>12</td>
<td>Varathur</td>
<td>Non-recording</td>
<td>77.7500</td>
<td>12.9167</td>
<td>870</td>
<td>1998-2011</td>
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<td>13</td>
<td>Attibele</td>
<td>Non-recording</td>
<td>77.7704</td>
<td>12.7756</td>
<td>880</td>
<td>1998-2011</td>
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<td>14</td>
<td>KGF</td>
<td>Non-recording</td>
<td>78.2641</td>
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<td>1998-2011</td>
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<td>15</td>
<td>Krishnagiri</td>
<td>Non-recording</td>
<td>78.2185</td>
<td>12.5284</td>
<td>590</td>
<td>1998-2011</td>
</tr>
<tr>
<td>16</td>
<td>Bangalore</td>
<td>Non-recording</td>
<td>77.6327</td>
<td>12.7878</td>
<td>860</td>
<td>1998-2011</td>
</tr>
</tbody>
</table>

4.7.1.2 Float type rain gauges

This type of rain gauge is very popular in India. Rain entering the gauge is led to a float chamber through a funnel. With increase in rainwater in the chamber, the float rises. A pen mounted on the float through a lever system touches a graph chart wrapped around the circumference of the drum is driven for 24 hrs after which the graph has to be replaced. By the time the
pen reaches the top of the graph the float also reached top of the chamber. At this point syphonic action takes place in the chamber and all the water in the chamber below the float empties. The pen comes back to its original position. If there is no rainfall the pen moves horizontally over the graph at that level. One syphonic action means 10 mm of rainfall and the time taken to collect the depth of rain can be noted from the horizontal axis of the graph.

4.7.1.3 Rainfall Data

The basic data used in this study include the daily depth of rainfall from non-recording rain gauges and the rainfall charts (records depth at every 15 min for 24 hrs) from recording rain gauges of the watershed. Daily Rainfall data from 2004 to 2011 were collected from the State Ground and Surface Water Resources Data Centre, Tharamani, Government of Tamil Nadu (for the stations located in Tamil Nadu) and (for stations in Karnataka state). Copy of the rainfall charts for the period 2004-2011 from float type rain gauges in Krishnagiri Dam, Sulagiri, Veppanapalli and Melumali were obtained from the respective stations.

In total, the rainfall dataset of daily rainfall depths for 12 stations and another data set of rainfall charts for 4 stations (depth for every 15 min for 24 hrs) for the period 2004 to 2011 were available for the analysis of erosivity. Rainfall charts were analysed for amount of rainfall (mm), duration of rainfall (h), maximum 30-minute intensity \( I_{30} \) in mm/h and average intensity for the period of study.

4.7.2 Rainfall Erosivity Factor (R)

Rainfall Erosivity \( R = EI_{30} \) is the product of a rainfall’s total energy \( E \) and its maximum 30-minute intensity \( I_{30} \) (Foster et al 1981, Renard et al 1997). Rainfall total energy is related to the total amount of rainfall in a
storm. It is also partially related to intensity because the energy content per unit rainfall (unit energy) is related to rainfall intensity. Rainfall intensity also has a direct effect on erosion besides its effect on storm energy. The maximum 30-minute intensity is a better measure of the intensity effect than either average intensity or peak intensity (Renard et al 1997). Hence, rainfall amount and rainfall intensity are the two most important variables that determine erosivity. The computation of total energy for a storm is given by Equation (4.3).

\[
E = \sum_{k=1}^{m} e_k \Delta V_k
\]  

(4.3)

Where: \( e \) is unit energy (energy per unit of rainfall), \( \Delta V \) is the rainfall amount for the \( k^{th} \) period \( k \) is an index for periods during a rain storm where intensity can be considered to be constant, \( m \) is number of periods. Unit energy is computed from:

\[
e = 0.29[1-0.72 \exp (-0.082i)]
\]

(4.4)

in which \( i \) is the rainfall intensity (mm/h).

Regression analysis for the rainfall depth and erosivity was done using linear, logarithmic, exponential, power, polynomial and quadratic methods to arrive at the best relationship which was then validated.

The performance was assessed by the difference between the estimated erosivity and the measured actual erosivity which is the experimental error and the Mean Absolute Error and Root Mean Square Errors was computed as given in Equation (4.5) and Equation (4.6) respectively.
Mean Absolute Error

\[
\text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |\varepsilon_i| \quad (4.5)
\]

Root Mean Square Error

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \varepsilon_i^2} \quad (4.6)
\]

The relationship that developed better coefficient of determination and least error was chosen for estimating erosivity for the remaining stations which record only the rainfall depth.

4.7.2.1 Statistical analysis

There were 435 daily rainfall events recorded in the four stations during 2004 - 2011. A detailed analysis of rainfall charts of all events were done to identify rainfall event that exceeds a depth of 12.6 mm, as the energy for the droplet of water to cause erosion is available only when the depth exceeds 12.6mm (Renard et al 1997). Each event that exceeds 12.6 mm depth is considered for estimating the rainfall erosivity. The depth for every 30 min was tabulated and the intensity for every 30 min was calculated. Unit energy for the rainfall was estimated using the Equation (4.4). The product of energy and the maximum 30 minute intensity gives the rainfall erosivity (R factor) for the day considered. Of the 435 events, only 178 rainfall events exceeded the 12.6 mm intensity and were used in the regression analysis.

The power function gave the highest coefficient of determination of all the combinations than the other regression methods. The regression equation has a 0.736 coefficient of determination and hence used to estimate the rainfall erosivity with data from other meteorological stations. The simple
A power function developed (Figure 4.6) to estimate the rainfall erosivity \( (R) \) from the depth of rainfall \( (P) \) is given below (Equation 4.7).

\[
R = 0.199 \, P^{1.896}
\]  

(4.7)

![Figure 4.6 Regression relationship between rainfall erosivity and Rainfall depth](image)

4.7.3 Soil Erodibility Factor \( (K) \)

Soil erodibility factor \( (K) \) represents the physical property of the soils eroded and is based on its grain size distribution and the organic matter content. The most widely used and cited algebraic approximation for calculation of erodibility (Wischmeier & Smith 1978, Yue-Qing et al 2008, Kouli et al 2008) where the silt fraction does not exceed 70% is given in Equation (4.8).

\[
K = 2.8 \times 10^{-7} \, M^{1.14} \, (12-a) + 4.3 \times 10^{-3} \, (b-2) + 3.3 \times 10^{-3} \, (c-3)
\]  

(4.8)
Where K is the Soil erodibility factor (Mg – ha –hr/ha-MJ-mm), M is Particle size parameter (% silt + % very fine sand)*(100 - % clay), a is the Percentage of organic matter content in the soil, b is soil structure code (very fine granular (1), fine granular (2), medium to coarser (3), blocky platy or massive (4)) and c is the profile permeability class (rapid -1, moderate to rapid- 2, slow to moderate -3, slow- 4 and very slow- 5).

Soil erodibility factor was calculated based on the collection and analysis of soil samples from the watershed. The Krishnagiri Reservoir watershed has six major types of soil series. The soil series map for the Krishnagiri district prepared by the Soil Survey and Land Use organisation, Department of Agriculture, Coimbatore was collected and overlaid on the watershed. This soil map of the watershed was used as stratifier to group locations and select locations for collection of soil samples. Forty six soil samples were collected for analysis through a grid sampling approach with stratification of the watershed by the soil series from locations identified randomly within the selected grid.

4.7.3.1 Soil collection procedure

About 2-3 kg of soil sample was collected at a predetermined location within the watershed, by cutting the topsoil layer to a depth of 10 cm and an area of 100 cm² with the help of shovel and thorough mixing. The soil samples were shade dried in the laboratory and passed through 2 mm sieve and stored in polythene bags before further analysis. Samples were processed as per the procedure given by Loring & Rantala (1992) for the estimation of physical properties and organic matter content. The Particle size distribution of the soil samples have been established through Sieve Analysis.
4.7.3.2 Mechanical sieve analysis

1000 gram of soil was taken and sieved through the IS sieve 4.77mm, 2.8mm, 1.4mm, 1.0mm, 0.6mm, 0.425mm, 0.250mm, 0.180mm, 0.125mm and 0.075mm. The percentage of mass retained between 0.425mm and 0.075mm gives the percentage of fine sand, which is used in determining the K factor of the RUSLE.

4.7.3.3 Wet sieve analysis

The soil fraction passing through the 0.075mm sieve is taken for the hydrometer analysis to determine the percent of silt and percent of clay. The classification was based on the following:

- Very fine sand  -  0.10 – 0.50 mm
- Silt  -  0.05 – 0.002 mm
- Clay  -  0.002 mm

4.7.3.4 Organic matter content

The organic matter content in the soil was analyzed by Loss on Ignition method (550 °C, 3h). The weight difference gave the organic matter present in the sediment and expressed as percent of the sediment by weight.

4.7.4 Slope Length and Slope Steepness Factor (LS)

The slope length and slope steepness factors account for the effect of topography on soil erosion. In this study the combined LS-factor was computed for the watershed in ArcGIS Spatial analyst extension using the DEM following the equation proposed by Moore & Burch (1986 a, b) and
used by several researchers (Hickey 2000, Bizuwerk et al 2008, Ozcan et al 2008, Csafordi et al 2012). The Equation is given below

\[ LS = \left( \frac{x}{22.1} \right)^m (0.065 + 0.045S + 0.0065S^2) \]  

(4.9)

where: \( X = (\text{Flow Accumulation} \times \text{Cell value}) \) i.e., slope length (m),

\( S = \) slope gradient (%),

\( m = \) slope contingent variable that depends on slope percentage.

In this study, these factors are estimated using the Digital Elevation Model. The slope length factor \( L \) is defined as the distance from the source of runoff to the point where deposition begins, or runoff becomes focused into a defined channel. The interaction of angle and length of slope has an effect on the magnitude of erosion. For example, soil losses from plots on irregular slopes may be dependent on the slope immediately above the point of measurement. As a result of this interaction, the effect of slope length and degree of slope should always be considered together. With the help of Digital Elevation Models (DEM) and GIS, the slope gradient (S) and slope length (L) may be determined accurately and combined to form a single factor known as the topographic factor, \( LS \).

The determination of \( LS \) factor can be done in GIS environment. This can be presented as a single index. The process of generating the slope angle, slope length and \( LS \) factor followed in the study is as follows:

- First the sinks in the SRTM DEM of 90 m x 90 m cells were identified and filled
- The filled DEM was used as input to determine the flow direction which is calculated for every central pixel in input
blocks of 3 by 3 pixels, each time comparing the value of the central pixel with the value of its 8 neighbouring pixels (D8 Pointer algorithm) using ArcGIS. The output map contains flow directions as N (to the North), NE (to the North East).

- The Flow Direction was used as an input grid to derive the Flow Accumulation. The operation performs a cumulative count of the number of pixels that naturally drain into outlets. The operation can be used to find the drainage pattern of a terrain.

- The flow accumulation was used as an input grid in the Drainage Network Extraction

- The Extracted Drainage Network was in turn used in Drainage Network Ordering

- The Drainage Network Ordering Map was used to derive the Overland Flow Length

- The slope was then derived from the DEM and the overland flow length and the slope were used as inputs in derivation of LS factor map.

4.7.5 Cover and Management Practice Factor (C)

C factor reflects the effect of cropping and management practices on soil erosion rates, and is the factor used most often to compare the relative impacts of management options on soil and water conservation plans. The C factor in the RUSLE can also be used to study the relative impact of management options available for a particular region on soil erosion by simulating different types of measures. The land use map of the study area (Figure 2) was used to determine the C factor values.
4.7.6 Conservation Practice Factor (P)

Conservation practice factor is the ratio of soil loss from a plot with a specific conservation practice to the corresponding loss from a plot with up and down cultivation under identical conditions (Ghanshyamdhas 2004). Several researchers have performed experiments to calculate the p factor for various conservation practices. In areas with more than one type of practice in use, a weighted value of P as per the area under each practice is considered. Based on Wischmeier & Smith (1965, 1978) and some reported values from literature (Renard et al 1997, Herweg & Ludi 1999, Angima et al 2003, Hessel & Tenge 2008) the values of P for different types of practices were selected.

4.7.7 Sediment Delivery Ratio (SDR)

Sediment yield from each subwatershed was calculated using Sediment Delivery Ratio (SDR). The amount of sediment transported effectively through runoff from its source can be estimated by Sediment Delivery Ratio (SDR). SDR can vary widely depending on parameters like area of the watershed, land use, length of the watershed, runoff, and relief length factor. Several methods for calculation of SDR are available in literature (Williams & Berndt 1972, Renfro 1975, Vanoni 1975, Williams 1977, Walling 1983, Lu et al 2006). In this study, the following expression is used to estimate the SDR (Williams 1977) which is comprehensive.

\[
SDR = 1.36 \times 10^{-11} (A)^{-0.0998} (Z/L)^{0.3629} CN^{5.444}
\]  
(4.10)

Where

A \( \text{ is the drainage area in km}^2 \),

\( Z/L \) \( \text{ is the relief-length factor in m/km, (ratio between difference in elevation in m, of the watershed and the mouth of the} \)
stream, versus length of watershed along main stream in km),

CN is the long term average SCS curve number.

This equation considers the watershed land use and topography through CN and Z/L ratio and therefore can make reliable estimates (Williams 1977, Leone et al 2008).

4.8 SOIL AND WATER ASSESSMENT TOOL (SWAT)

The SWAT (release 2005) is a continuous physically-based distributed river basin model simulating water, sediment and pollutant yields (Gassman et al 2007). SWAT allows different physical processes to be simulated in a watershed. For modelling, the watershed is divided into sub-basins, each containing a main channel and a specific combination of land use, soil type and management practices, which will allow the definition of hydrological response units (HRU). These units are lumped land areas in the sub-basin that are comprised of unique land cover, soil and management combinations (Betrie et al 2010, Arnold et al 2012). In modelling the watershed, water balance is the driving force for all the processes that takes place in the watershed. Water balance computations are performed at this level of spatial discretization. Simulation of hydrology of a watershed can be separated in to two divisions. In the first division, the land phase of the hydrological cycle that controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin was modelled. In the second division, the water routing phase of the hydrological cycle that defines the movement of water, sediment through the channel network of the watershed to the outlet was modelled.
4.8.1 Land Phase of the Hydrological Cycle

The hydrological cycle simulated by SWAT is based on the following equation.

\[ SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \]  

(4.11)

Where \( SW_t \) is the final soil water content (mm H\(_2\)O), \( SW_0 \) is the initial soil water content on day \( i \) (mm H\(_2\)O), \( t \) is the time (days), \( R_{day} \) is amount of precipitation on day \( i \) (mm H\(_2\)O), \( Q_{surf} \) is the amount of surface runoff on day \( i \) (mm H\(_2\)O), \( E_a \) is the amount of evapotranspiration on day \( i \) (mm H\(_2\)O), \( w_{seep} \) is the amount of water entering the vadose zone from the soil profile on day \( i \) (mm H\(_2\)O) and \( Q_{gw} \) is the amount of groundwater flow on day \( i \) (mm H\(_2\)O).

The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases the accuracy and gives a much better physical description of the water balance. The various inputs and processes involved in this phase of the hydrological cycle are given below

4.8.1.1 Climate

The climate of the watershed provides the moisture and energy inputs that control the water balance and determine the relative importance of the different components of the hydrological cycle. The climate variables required for the model are daily precipitation, maximum/minimum temperature, solar radiation, wind speed and relative humidity.
4.8.1.2 Soil temperature

Soil temperature affects the movement of water and the decay rate of the residue in the soil. Daily average soil temperature is calculated at the soil surface and the centre of each soil layer which depends on the bulk density and the soil water content.

4.8.1.3 Hydrology

Precipitation may be intercepted and held in the vegetation canopy or fall directly to the soil surface. Water on soil surface will infiltrate into the soil profile or flow overland as runoff. Runoff moves quickly towards a stream channel and contributes to short-term stream response. Infiltrated water may be held in the soil and later evapo-transpired or it may slowly make its way to surfacewater system via underground flow paths.

The soil profile is subdivided into multiple layers including infiltration, evaporation, plant uptake, lateral flow, and percolation. SWAT offers various methods to estimate the potential evapotranspiration (PET), such as Hargreaves, Penman-Monteith, and Priestley (Neitsch et al. 2005). The Penman-Monteith method was used in this study because the PET evaluation is based on the basic data such as solar radiation, wind speed, air temperature and relative humidity, while wind speed is not considered by the Hargreaves and Priestley methods. The model computes evaporation from soil and plants separately. Potential soil water evaporation is predicted as a function of potential evapotranspiration and leaf area index, whereas actual soil water evaporation is predicted by using exponential functions of water content and soil depth. Plant transpiration is predicted as a linear function of potential evapotranspiration and leaf area index.
4.8.1.4 Erosion

Erosion and sediment yield were estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE). While the USLE uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield. The use of MUSLE results in a number of benefits

- The prediction accuracy of the model is increased
- The need for a delivery ratio is eliminated
- Single storm estimates of sediment yields can be calculated

The hydrology model estimates runoff volume and peak runoff rate within the sub basin area and used to calculate the runoff erosive energy variable. The crop management factor in the model is recalculated on the day when runoff occurs.

4.8.2 Routing Phase of the Hydrological cycle

Land phase of the hydrological cycle determines the loadings of water, sediment, nutrients and pesticides to the main channel and then the loadings are routed through the stream network of the watershed using a command structure similar to that of HYMO (Neitsch et al 2005). In addition, SWAT models the transformation of chemicals in the stream and streambed.
4.8.2.1 Flood routing

As water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another potential loss is the removal of water from the channel for agricultural or human use. Flow may be supplemented by the direct rainfall on the channel and or addition of water from point source discharges. Flow is routed through the channel using a variable storage coefficient method developed by Williams or Muskinghum routing method (Neitsch et al 2005). Variable storage method was followed in this study. Figure 4.7 shows the stream processes as modelled in SWAT.

4.8.2.2 Sediment routing

The transport of sediment in the channel is controlled by two processes namely deposition and degradation. The maximum amount of sediment that can be transported from a reach segment is a function of the peak channel velocity. The available stream power is used to reentrain loose and deposited material until all the material is removed. Excess stream power causes bed degradation which is adjusted for stream bed erodibility and cover.
In the SWAT Runoff is estimated using SCS-CN method whereas the sediment yield is estimated using MUSLE equation. The procedures for the above methods are explained below.

### 4.8.3 Runoff and Sediment

#### 4.8.3.1 Runoff estimation

The Runoff will be estimated by using the Soil Conservation Service Curve Number (SCS-CN) method. This method is a simple, predictable, and stable conceptual method for estimating direct runoff depth based on storm rainfall depth.

The SCS-CN method is based on the water balance equation and two fundamental hypotheses. The first hypothesis equates the ratio of the actual amount of direct surface runoff (Q) to the maximum potential surface runoff (P) to the ratio of the actual infiltration (F) to the amount of potential maximum retention (S). The second hypothesis relates the initial abstraction (Iₐ) to the potential maximum retention (S). The mathematical expression of the water balance equation and the two hypotheses, respectively, are

\[
P = I_a + F + Q \tag{4.12}
\]

\[
\left[\frac{Q}{P - I_a}\right] = \frac{F}{S} \tag{4.13}
\]

\[
I_a = \lambda S
\]

Where,

- \(P\) = total precipitation
- \(I_a\) = initial abstraction
- \(Q\) = direct surface runoff
4.8.3.2 Curve number

In this curve number the parameter $S$ representing the potential maximum retention depends upon soil, vegetation and land use of the catchment and also the antecedent moisture condition in the catchment which is defined as the rainfall event just prior to the commencement of rainfall. For convenience in practical application the Soil Conservation Services (SCS) has expressed $S$ (in mm) in terms of a dimensionless parameter CN as

$$ S = [(25400/CN) - 254] \quad (4.14) $$

$$ CN = [(25400/S) + 254] \quad (4.15) $$

The constant 254 is used to express $S$ in mm.

A CN value of 100 represents highly impervious layer (zero potential retention) whereas the value of CN for water is zero.

4.8.3.3 Estimation of sediment yield

The sediment yield can be predicted by using the MUSLE (Modified Universal Soil Loss Equation). The major input to the MUSLE model is the Runoff factor. The runoff factor is calculated using the runoff and peak runoff rates measured at the outlet of the watershed. In general the mathematical expression used to express MUSLE is

$$ sed = 11.8(Q_{surf} \cdot q_{peak} \cdot area_{hr})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \quad (4.16) $$
Where,

\( sed \) is sediment yield on a given day in tones

\( Q_{surf} \) is the volume of runoff in mm H\(_2\)O/ha

\( q_{peak} \) is the peak flow rate in cubic meters per second

\( area_{hru} \) is the area of HRU in ha

\( K_{USLE} \) is the USLE soil erodibility factor

\( C_{USLE} \) is the USLE cover and management factor

\( P_{USLE} \) is the USLE support practice factor

\( LS_{USLE} \) is the USLE topographic factor

\( CFRG \) is the coarse fragment factor

4.8.4 SWAT Model Configuration

One of the first steps in model set-up consists of the identification of the calculation units (or HRUs) for the water balance. The river network for the Krishnagiri reservoir catchment area was extracted from the digital elevation model (DEM) from SRTM data, using standard analytical techniques contained in the ArcSWAT GIS interface. In total, 19 sub-basins were defined and 333 HRUs (unique land use/soil combinations within sub-basins) were generated by the model.

4.8.4.1 User weather database

A user weather database was created to bring the weather condition of the Krishnagiri watershed into the model. A pre-processor, pcpSTAT generated the precipitation statistics for the weather stations Melumalai and Bengaluru using daily precipitation depths from 1998 to 2011. Other statistical parameters estimated using pcpstat were average monthly precipitation, standard deviation, skew coefficient, probability of a wet day
following a dry day, probability of a wet day following a wet day and average number of days of precipitation in month. Similarly the average daily dewpoint per month, daily temperature and humidity data were used from Melumali and Bengaluru station. The results of the pre-processor were manually entered into the SWAT database to reflect the weather of the Krishnagiri Reservoir catchment area.

4.8.4.2 User soil database

A user defined soil database was included into the SWAT database to represent the soil conditions of the Krishnagiri watershed.

4.8.4.3 Simulation period

Discharge and sediment data from the period January 1, 1998 to December 31, 2011 were used as the simulation period for warm-up, calibration and validation.

4.8.4.4 Calibration and validation using Sequential Uncertainty Fitting algorithm (SUFI2) - SWATCUP

In Sequential Uncertainty Fitting (SUFI-2), parameter uncertainty accounts for all sources of uncertainties such as uncertainty in driving variables (e.g., rainfall), conceptual model, parameters, and measured data. The degree to which all uncertainties are accounted for is quantified by a measure referred to as the $P$-factor, which is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU). As all the processes and model inputs such as rainfall and temperature distributions are correctly manifested in the model output (which is measured with some error) - the degree to which we cannot account for the measurements - the model is in error; hence uncertain in its prediction. Therefore, the percentage of data captured (bracketed) by the prediction uncertainty is a good measure to assess
the strength of our uncertainty analysis. The 95PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling, disallowing 5% of the very bad simulations. The methodology followed in SWAT- CUP is given in Figure 4.8.

**Figure 4.8** The link between SWAT (orange), iSWAT (green), and SUFI2 (yellow). The entire algorithm is run by two batch files: `SUFI2_pre.bat` and `SUFI2_post.bat`
As all forms of uncertainties are reflected in the measured variables (e.g., discharge), the parameter uncertainties generating the 95PPU account for all uncertainties. The goodness of fit and the degree to which the calibrated model accounts for the uncertainties are assessed by the above two measures. Theoretically, the value for \( P \text{-factor} \) ranges between 0 and 100\%, while that of \( R \text{-factor} \) ranges between 0 and infinity. A \( P \text{-factor} \) of 1 and \( R \text{-factor} \) of zero is a simulation that exactly corresponds to measured data. The degree to which we are away from these numbers can be used to judge the strength of our calibration. A larger \( P \text{-factor} \) can be achieved at the expense of a larger \( R \text{-factor} \). Hence, often a balance must be reached between the two. When acceptable values of \( R \text{-factor} \) and \( P \text{-factor} \) are reached, then the parameter uncertainties are the desired parameter ranges.

4.8.5 Model Evaluation Statistics

4.8.5.1 Nash-Sutcliffe Efficiency (NSE)

Nash-Sutcliffe efficiency (NSE) is a normalized statistic (Nash and Sutcliffe, 1970) that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as shown in Equation 4.17.

\[
\text{NSE} = \left[ \frac{\sum_{i=1}^{n} (Y_{i}^{\text{obs}} - Y_{i}^{\text{sim}})^2}{\sum_{i=1}^{n} (Y_{i}^{\text{obs}} - Y_{i}^{\text{mean}})^2} \right]^{1/2}
\]  

(4.17)

where \( Y_{i}^{\text{obs}} \) is the \( i_{th} \) observation for the constituent being evaluated, \( Y_{i}^{\text{sim}} \) is the \( i_{th} \) simulated value for the constituent being evaluated, \( Y_{i}^{\text{mean}} \) is the mean of observed data for the constituent being evaluated, and \( n \) is the total number of observations. NSE ranges between \(-\infty \) and 1.0 (1 inclusive), with NSE=1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicates that the mean
observed value is a better predictor than the simulated value, which indicates unacceptable performance.

4.8.5.2 Percent bias (PBIAS)

Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias. PBIAS is calculated with Equation 4.18.

\[
PBIAS = \left[ \frac{\sum_{i=1}^{n} (y_{i}^{obs} - y_{i}^{sim}) \times 100}{\sum_{i=1}^{n} y_{i}^{obs}} \right]
\]

Equation 4.18

where PBIAS is the deviation of data being evaluated, expressed as a percentage.