METHODOLOGICAL APPROACH AND TUTORIAL

WEP: WEAP Erosion Plugin manual

WEAP version 2023.0

REPORT 251

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Methodological Approach and Tutorial (version 2023.0)

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1 Introduction

Estimating erosion plays a critical role in soil and water resource conservation, sediment load assessment, conservation planning, design for sediment control, and prioritisation of nature-based solutions, amongst others. Average global soil erosion has been assessed at 2.8 tons ha^{-1} y^{-1} (Borrelli et al., 2017). However, large spatial variation exists, and hotspots where erosion rates above 20 ton ha^{-1} y^{-1} are found as well. Results from this global assessment were based on an analysis of grids of 250x250 m but at smaller scales (fields, plots) much higher values have been reported in many places.

The two primary types of erosion models are (i) process-based models and (ii) empirically based ones. Full process-based model implementations are very demanding in terms of data requirements and computational resources when implemented at river basin scale (Eekhout et al., 2018). For this reason, typically a mix of physical and empirical approaches are included in erosion simulation models (e.g. Hunink et al., 2015; Willemen et al., 2019). It is recommended that erosion model concepts need to be chosen based on data availability and project requirements (Alewell et al., 2019).

It is well known that rainfall variability plays a dominant role in erosion processes and therefore most erosion models are based on dynamic hydrological models which allow simulations under different weather conditions. The WEAP[1] model (Water Evaluation And Planning Tool), as developed by the Stockholm Environment Institute (SEI), is one of the more frequently used models for water resources planning and scenario analysis. Up to now, WEAP did not include a module for the estimation of erosion rates. However, for many scenario assessments, erosion is an important topic to be accounted for, as it influences the lifetime and performance of grey infrastructure, and for evaluating the effectiveness of green infrastructure solutions (Hunink and Droogers, 2015; Simons et al., 2017; Simons and Hunink, 2018). FutureWater and SEI therefore have developed a plugin for WEAP (referred to as WEP: WEAP Erosion Plugin) to undertake erosion assessment studies.

The objective of this report is to introduce the methodological approach behind the erosion plugin and to provide a hands-on tutorial on using the WEAP Erosion Plugin (WEP).

[1] https://www.weap21.org/

2 Erosion

2.1 Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) was developed based on empirical studies in erosion plots and rainfall simulator experiments. The USLE is composed of six factors to predict the long-term average annual soil loss (A). The empirical equation includes the rainfall erosivity factor (R), the soil erodibility factor (K), the topographic factors (L and S), and the cropping management factors (C and P). The equation takes a simple product form:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

where: A (Mg ha^{-1} yr^{-1}) is the annual average soil erosion, R (MJ mm h^{-1} ha^{-1} yr^{-1}) is the rainfall-runoff erosivity factor, K (Mg h MJ^{-1} mm^{-1}) is the soil erodibility factor, L (dimensionless) is the slope length factor, S (dimensionless) is the slope steepness factor, C (dimensionless) is the land cover and management factor, P (dimensionless) is the soil conservation or prevention practices factor.

The original USLE method is based on the experimental unit plot concept. The unit plot is defined as the standard plot condition to determine the soil's erodibility (K). These conditions are when the LS factor = 1 (slope = 9% and length = 22.1 m), the plot is fallow, tillage is up and down the slope, and no conservation practices are applied (C and P are both 1). USLE and its parameters are based upon an 80-year history of erosion modelling and applications in over 100 countries. The origin of the USLE model was in the US to provide a management decision support tool and was based upon thousands of controlled studies on field plots and small watersheds since 1930.

An implementation of the USLE where the rainfall erosivity is replaced by runoff volume (Modified USLE, MUSLE) resulted in a satisfying prediction of measured sediment yield already in the mid-seventies and early eighties (Smith, Williams, Menzel, & Coleman, 1984; Williams, 1975). The latter allows the equation to be applied to individual storm events. Several variants of the MUSLE equation exist and MUSLE was even integrated in GIS (e.g. in ArcMUSLE; (Zhang, Degroote, Wolter, & Sugumaran, 2009).

In the SWAT model, erosion caused by rainfall and runoff is computed with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). MUSLE is a modified version of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965, 1978). USLE predicts average annual gross erosion as a function of rainfall energy. In MUSLE, the rainfall energy factor (R) is replaced by a runoff factor. This improves the erosion prediction, eliminates the need for delivery ratios, and allows the equation to be applied to individual storm events.

This modified universal soil loss equation as used in SWAT is (Williams, 1995):

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

where

sed is the sediment yield on a given day (metric tons),

Qsurf is the surface runoff volume (mm H20/ha),
q_{peak} is the peak runoff rate (m^3/s),
$area_{hru}$ is the area of the hydrological response unit (HRU) (ha),
K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3 ·metric ton cm)),
C_{USLE} is the USLE cover and management factor,
P_{USLE} is the USLE support practice factor,
LS_{USLE} is the USLE topographic factor.

The two coefficients 11.8 and 0.56 were obtained during the original development of MUSLE and might be adjusted by calibration. In practice, most research assumes those coefficients as constants.

2.2 Implementation of MUSLE in WEAP Erosion Plugin (WEP)

The WEAP Erosion Plugin (WEP) is based on the MUSLE approach as described above. WEP has been designed to derive the following MUSLE parameters in a simplified way:

- R_USLE (rainfall-runoff erosivity factor)
  - Based on surface runoff as calculated by WEAP and the intensity of the rainfall expressed as hours in the day it rains (1-24)
- K_USLE (soil erodibility factor):
  - Derived from the geometric mean weight diameter of soil particles
- C_USLE (land cover and management factor)
  - User input between 0 (e.g. forest) and 1(degraded land)
- P_USLE (soil conservation and prevention practices factor)
  - User input between 0 (e.g. full erosion control measures) and 1(no erosion control measures)
- LS_USLE (slope and steepness factor)
  - Derived from the average slope in an area

2.3 Input data for the WEAP Erosion Plugin (WEP)

WEP requires the user to enter the following four input variables (see section below for details):

- Soil Particle Diameter
  - Geometric mean weight diameter of soil particles (mm). Values range from 0.0001 (clay) to 2 (sand). Is used to assess the K_USLE.
- Rain Intensity
  - Hours per day that rainfall occurs. 1 = daily rainfall falls in 1 hour (high intensity); 24 = daily rainfall fall during entire day (low intensity)
- C_USLE
  - Land cover and management factor. Values can range from 1 (fallow/bare land) to 0.001 (forest).
- P_USLE
  - Supporting conservation practice. Values range from 0 (very good manmade erosion resistance facility) to 1 (no manmade erosion resistance facility).

Since WEP version 2023. The following inputs are automatically estimated using Catchment Delineation Mode:

- Catchment area (area of the catchment in hectares)
  - Used to upscale erosion amounts.
- Slope (average slope in the catchment in degrees)
  - Used to assess the LS_USLE.

The WEAP implementation of the MUSLE parameters are more thoroughly described in Chapter 2.5.

2.4 WEAP Erosion Plugin (WEP) results

WEP provides the following <u>results</u>:

- **Erosion per Hectare [tons/ha]**
  - The amount of erosion in tons per hectare

$$11.8 * (\text{Surface Runoff [mm]} * \text{Peak Runoff [mm]})^{0.56} * K_{USLE} \bullet C_{USLE} \bullet P_{USLE} \bullet LS_{USLE}$$

where *Surface Runoff [mm]* is simulated by WEAP, *Peak Runoff [mm]* = Surface Runoff[mm] / Rain Intensity[hr]. MUSLE parameters as described in 2.5.

- **Erosion Total [tons]**
  - The total amount of erosion for the specific catchment in ton

*Erosion per Hectare [t/ha] * Area Calculated [ha]*

where *Erosion per Hectare [t/ha]* is estimated by the formula above, and *Area Calculated [ha]* is estimated automatically via Catchment Delineation Mode or added manually.

2.5 WEAP Erosion Plugin (WEP) parameters

2.5.1 K_USLE (soil erodibility factor)

K_USLE factor is the soil erodibility factor which represents the susceptibility of soil to erosion as measured under the standard unit plot condition:

- Clay soils are resistant to detachment and have low K values
- Sandy soils have low runoff rates and have low K values
- Silt loam soils are moderately susceptible to detachment produce moderate runoff and, have moderate K values
- Silty soils are the most erodible of all soils. They are easily detached; tend to crust and produce high rates of runoff. K values are between 0.02 and 0.04

In WEP the K factor is calculated based on (Renard et al., 1997) using the geometric mean weight diameter of soil particles (mm):

K_USLE = 0.0437 • exp(-(log(Dg) + 1.6680)^2 / (2 • 0.7661^2)) where:

Dg is the geometric mean weight diameter of soil particles (mm)
note that the *log* is the log for base 10

Typical values of Dg (and the associated K_USLE) are:

Sand: 0.2 – 2.0 mm (0.0197 - 0.0016)
Loam: 0.06 – 0.2 mm (0.0369 - 0.0197)
Silt: 0.002 - 0.06 mm (0.0177 - 0.0369)
Clay: 0 - 0.002 mm (0.0000 - 0.0177)

2.5.2 C_USLE is the cropping management Factor (C)

C_USLE is a reduction factor to soil erosion vulnerability and is related to land use. C_USLE is the vegetation cover percentage and is defined as the ratio of soil loss from specific crops to the equivalent loss from tilled, bare test plots. The value of C_USLE depends on vegetation type, stage of growth, and cover percentage. Lots of literature exists on proposed C_USLE values. Some methods derive the C factor from satellite-based remote sensing data (Hunink et al., 2015) which allows accounting for spatial and temporal variability. Table 1 provides one reference that can be used in the WEAP model, but this can be adapted as desired.

Table 1. Cropping management factor C_USLE. Source: (Park et al., 2007)

Land Use	Vegetation cover	C_USLE
Follow/Bare land		1.0
Paddy field		0.34
Upland		0.31
Grassland	(95 ~ 100% cover) Grass	0.003
	Weeds	0.01
	(80% cover) Grass	0.01
	Weeds	0.04
	(80% cover) Grass	0.04
	Weeds	0.09
Forest	(75 ~100% cover)	0.001
	(40 ~ 75% cover)	0.002 ~ 0.004
	(20 ~ 40% cover)	0.003 ~ 0.01

2.5.3 P_USLE is the supporting conservation practice factor

P_USLE is the reduction factor that represents the effects of practices such as contouring, strip cropping, and terracing, that help prevent soil from eroding by reducing the rate of water runoff. Table 2 shows the value of the support practice factor according to the cultivating methods and slope. The P value ranges from 0 to 1 where 0 represents a very good manmade erosion resistance facility and 1 represents no manmade erosion resistance facility. Table 2 provides reference values for the P factor, but other sources can be used as desired.

Table 2. Support practice factor P according to the types of cultivation and slope. Source: (Parveen and Kumar, 2012)

Slope (%)	Contouring	Strip Cropping	Terracing
0.0 - 7.0	0.55	0.27	0.10
7.0 - 11.3	0.60	0.30	0.12

11.3 - 17.6	0.80	0.40	0.16
17.6 - 26.8	0.90	0.45	0.18
>26.8	1.00	0.50	0.20

2.5.4 Topographic Factor (LS)

LS_USLE is the topographic factor that accounts for the effect of topography on erosion. The two parameters that constitute the topographic factor are slope gradient and slope length factor. The slope- and slope length factors are estimated in WEP using the equations of (Van der Knijff et al., 1999):

$$LS = 44.6 * (\sin \beta) ^ 1.3$$

where:

β is the average slope (degrees)

3 Tutorial

> Note:
> For this module, you will need to have completed the WEAP Tutorial modules ("WEAP in One Hour, Basic Tools, Scenarios, and Hydrology) or have a fair knowledge of WEAP (data structure, key assumptions, expression builder, creating scenarios). To begin this tutorial on WEAP Erosion Plugin (WEP), go to the Main Menu of WEAP, select "Revert to Version" and choose the version named "Answer key for 'Hydrology' module."

3.1 Open the WEAP tutorial and Revert to Version

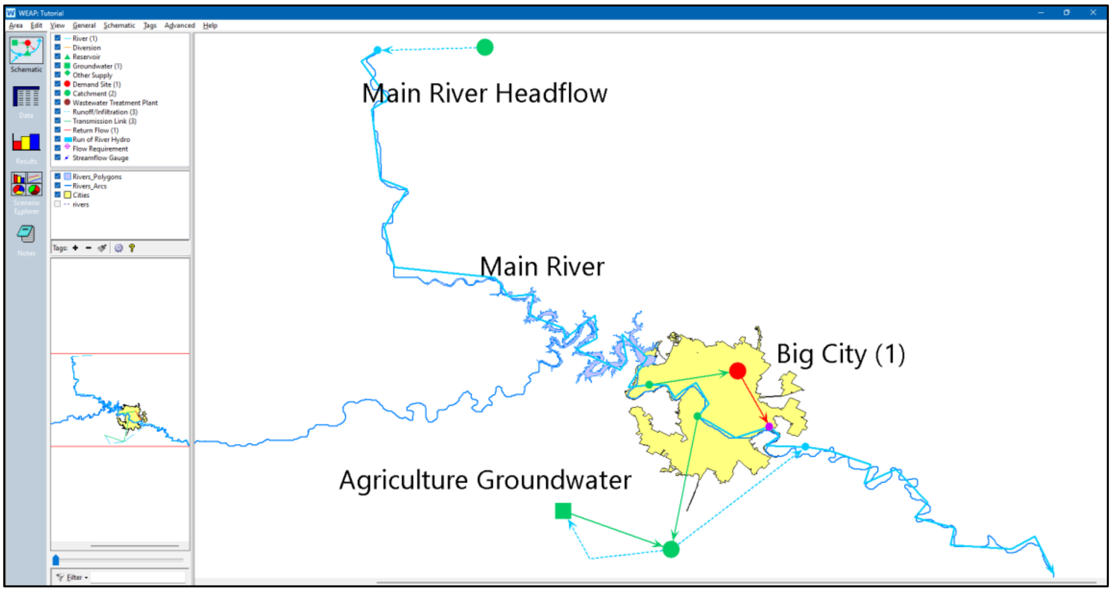
After opening WEAP select:

```
> Area > Open > ”Tutorial”
```

Revert to the version "Answer key for 'Hydrology' module":

```
> Area > Revert to Version > “Answer key for ‘Hydrology’
module”
```

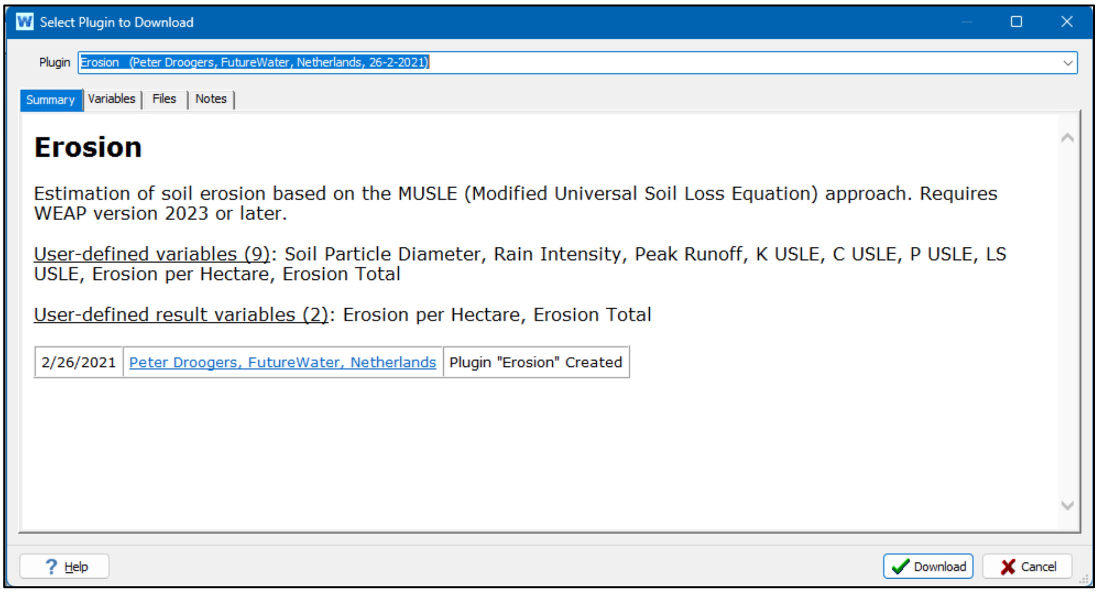
The Schematic View should look like below:



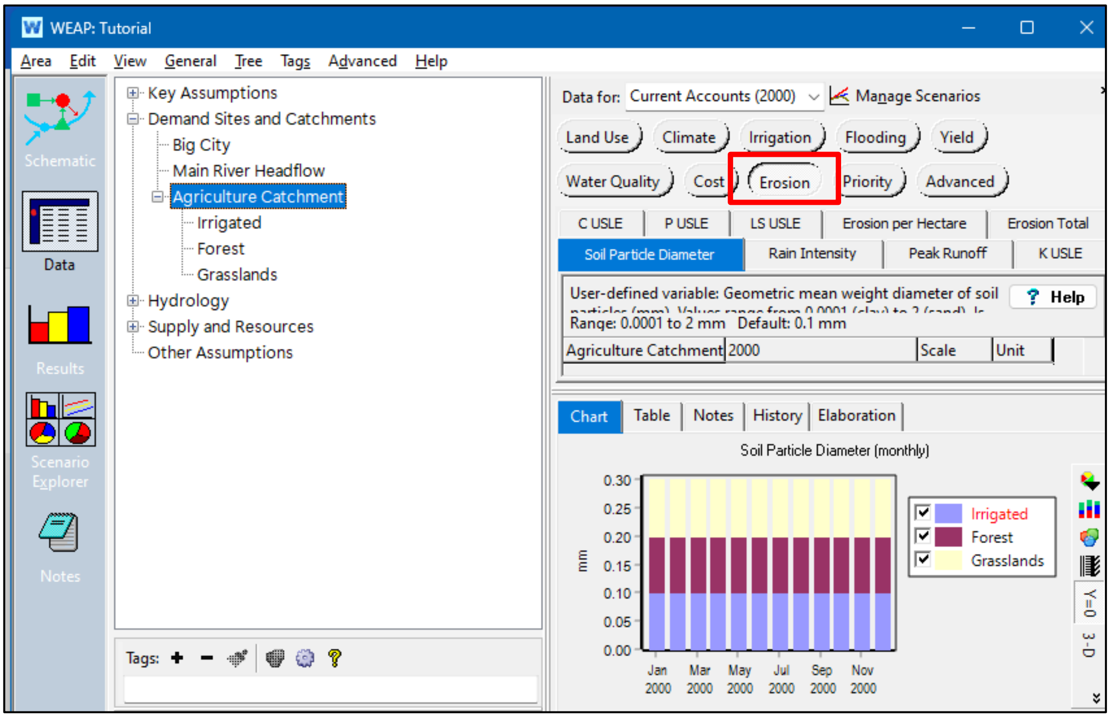
3.2 Import the Plugin

The WEAP Erosion Plugin (WEP) can be imported into the WEAP area. Note that for each new WEAP Area, the Plugin has to be imported if erosion should be calculated.

`> Advanced > Plugins > Download`



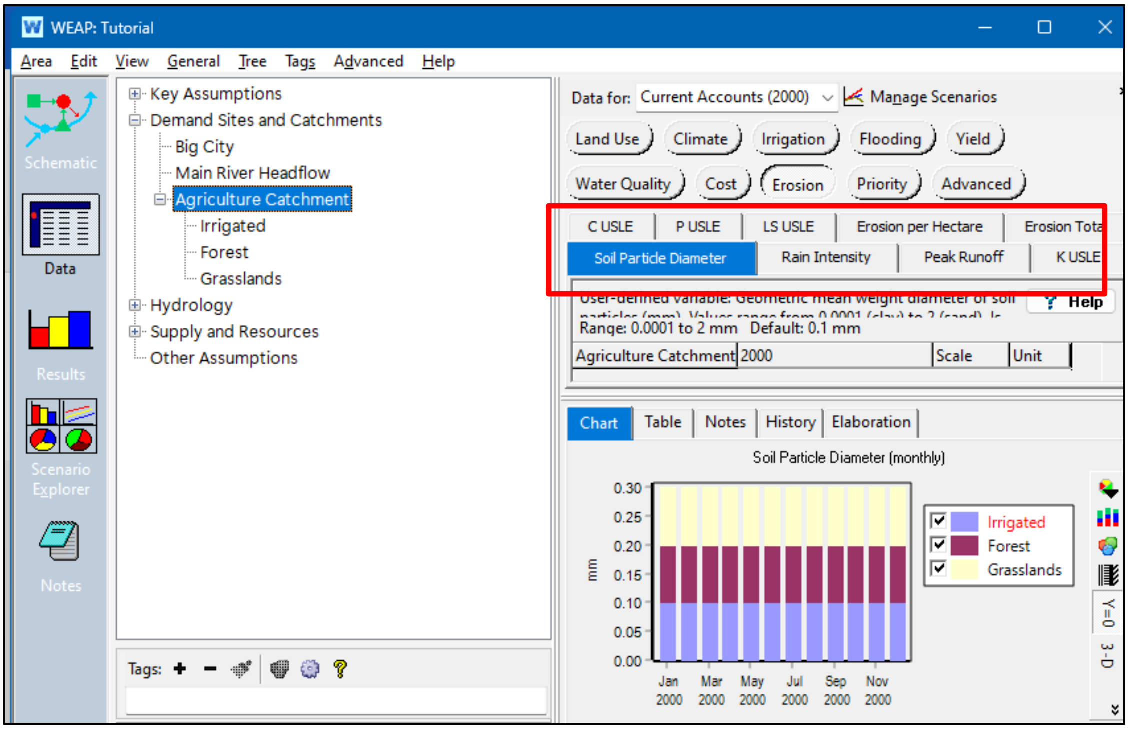
To check whether importing has been successful the new tab `Erosion` under `Data > Catchment` should appear:



3.3 Add the appropriate erosion data

The specific soil and land data to calculate the erosion rate should be entered in WEAP. In this tutorial, the erosion of the three land covers in the Agriculture Catchment will be assessed:

```
> Data View > Agriculture Catchment > Erosion > Soil Particle
Diameter
```



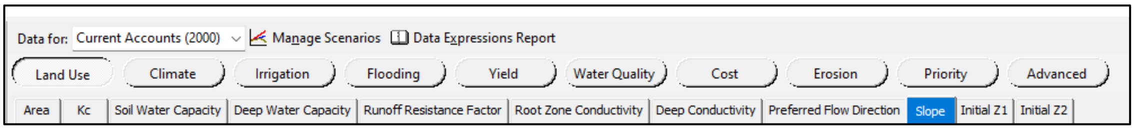
Enter the following data for the three land covers in the Agriculture Catchment:

	Soil Particle Diameter (mm)	*Slope (degrees)*	*Rain Intensity (hr per day)*	*C USLE (-)*	*P USLE (-)*
Irrigated	*0.002*	*2*	*4*	*0.34*	*0.8*
Forest	*0.002*	*5*	*4*	*0.01*	*0.8*
Grasslands	*0.002*	*10*	*4*	*0.04*	*0.8*

Data as shown above are derived using guidelines as presented in the previous Chapter. It is assumed that soils (clay) and climate are similar for the three land covers. Differences are:

- **Irrigated** areas are located on flat land (slope 2 degrees), sensitive to erosion (C_USLE) and conservation practice is low (P_USLE).
- **Forest** areas are located on reasonable flat land (slope of 5 degrees), have high vegetation coverage (C_USLE) and conservation practice is low (P_USLE).
- **Grass** areas are located on undulating land (slope of 10 degrees), reasonably covered (C_USLE) and conservation practices are low (P_USLE).

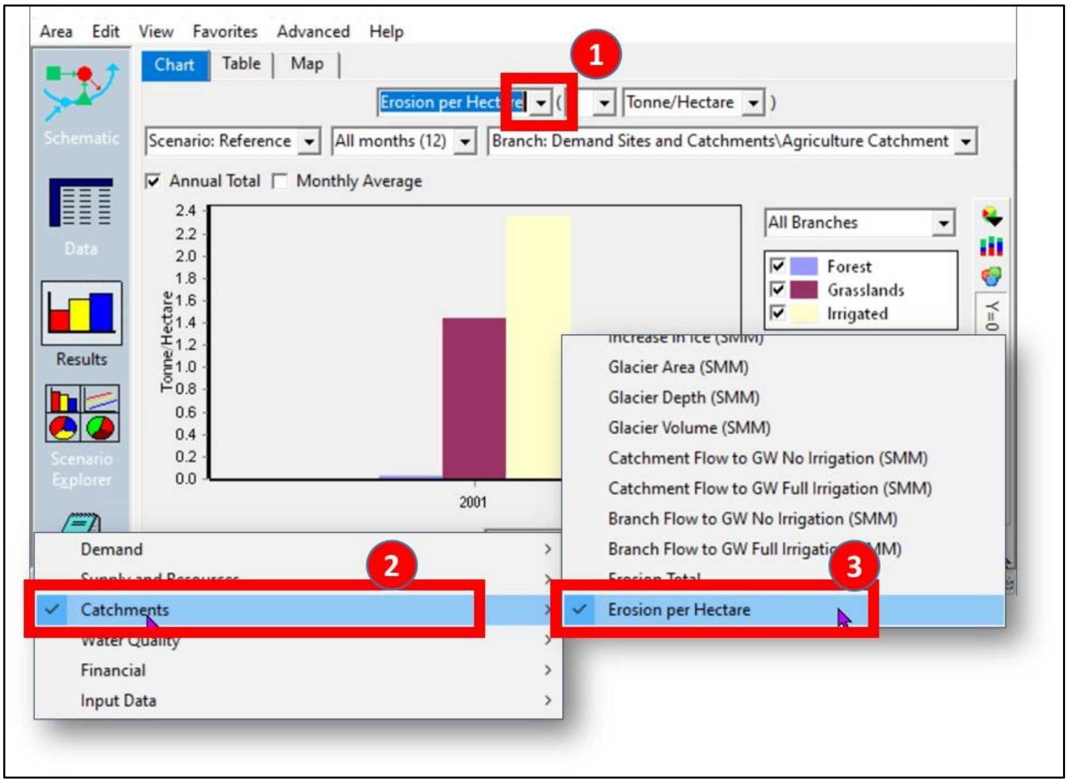
NOTE: Slope should be inserted under Land Use for Current Account (2000). When using Automatic Catchment Delineation mode slope is filled in automatically.



3.4 Look at the results

Results for Erosion are located in the “Catchment” category in the primary variable pull-down menu.

```
> Result View > Catchments > Erosion per Hectare
```

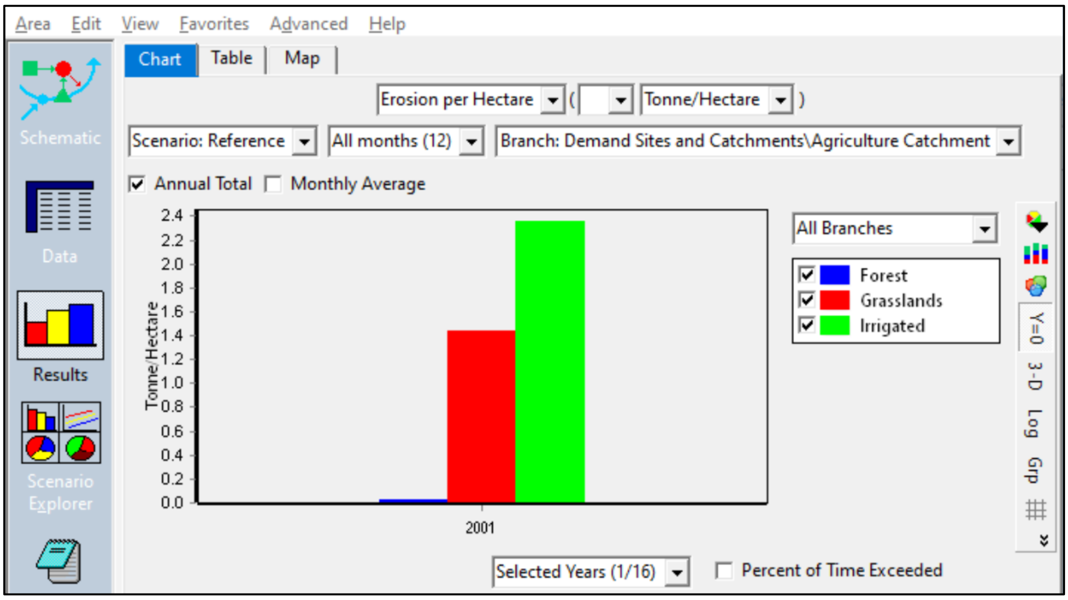


3.5 Exploring erosion reduction options

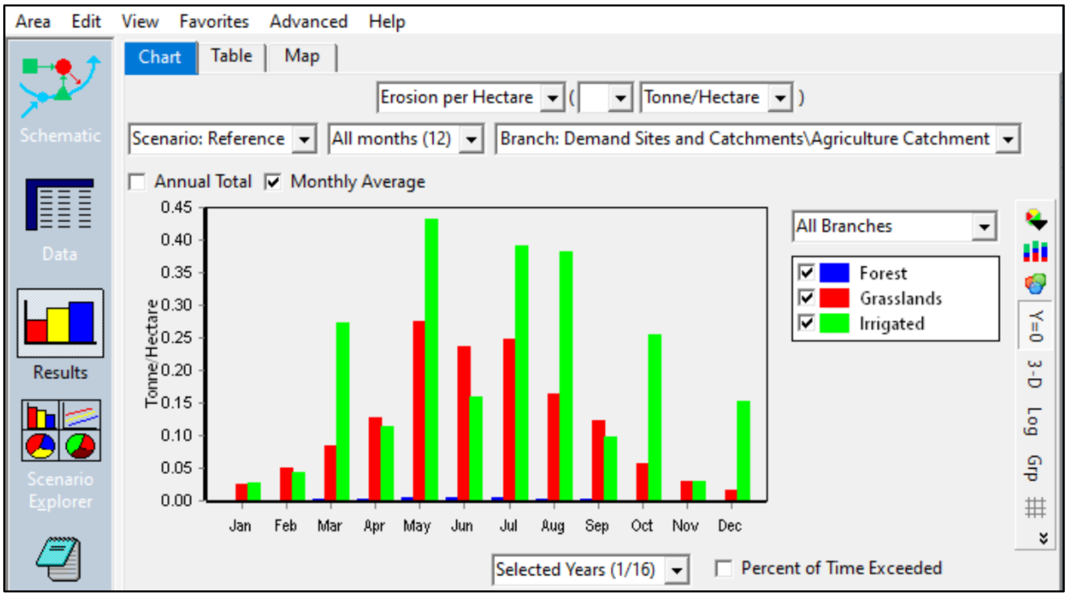
Results show that for this case erosion of the irrigated area is quite high with over 2 tons ha^{-1} y^{-1}. Also for the grassland erosion is quite high with about 1.4 ton ha^{-1} y^{-1}. Some options that might be interesting to explore further:

- At present, climate conditions are considered to be constant for each year. What would happen with erosion if more extreme rainfall is happening?
- Surface runoff is quite high. With different land management soil parameters (e.g. Runoff Resistance Factor and Root Zone Conductivity) might change. What is the impact on erosion?
- Introducing conservation practice methods (e.g. contouring, vegetation strips, terracing) can be entered by changing the P_USLE. What is the erosion reduction that can be achieved?
- Erosion in the forest area is relatively low (0.03 ton ha^{-1} y^{-1}). What would be the impact of forest degradation (C_USLE will increase) on erosion?

Annual erosion for the three land covers in tonnes per hectare:



Monthly erosion for the three land covers in tonnes per hectare:



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