Phase II Delivery PoCRA Dated
Technical Documentation of Model and Datasets
CTARA, IITB

Plugin Delivered on 19th Dec 2017.

1. Objective of the document

The objective of this document is to describe the plugin developed for water balance model which will run on desktop PC and eventually be freely available for wider use. The interface is easy to use and can be operated by the technically skilled but non specialist user. The document also describes the pre-processing of database to be done before being fed into the model. It describes the various tabular outputs as wells as maps being generated by the plugin to be utilized for cluster water balance exercise during microplanning of cluster.

2 Computer Requirements

You must have a computer with latest windows operating system, QGIS is known to run on just about any machine with Windows XP+, Any modern Linux (Ubuntu/Debian, Fedora/Red Hat, OpenSuse, Arch, Gentoo, etc), and Mac OS X. If you can run those OS you can run QGIS. The following programs must be installed for running the plugin.

1 QGIS Desktop version 2.18.12
2 Plugin

3 Description of plugin

The figure 1 gives the brief summary regarding the plugin. The inputs are divided into two parts. One which needs to be input by the user and second which are hard coded at the backend and generated from the inputs layer fed by the user in the plugin. User are provided with selecting the sowing threshold which means sowing will only happen after the mentioned amount of rainfall. User can also select the crop for which it wants to run the

Front End Inputs Need to Given by User

1 Cluster Boundary with zones
2 Land Use Land Cover
3 Soil
4 Slope
5 Cadastral
6 Rainfall

Back End Inputs used in the Plugin

1 Reference Evapotranspiration, ETo
2 Crop Coefficients - Kc,
3 Hydrologic soil Group, Curve Number
4 % Sand, % Silt, % Clay
5 Wilting Point, Field Capacity, Saturation
6 Ksat, Bulk Density, Available water content
7 Crop Root zone, Crop Depletion factor p

Plugin

Options
Colour Code Intervals
Crop Selection
Sowing Threshold

Output Generated by Plugin

1 Cadastral Vulnerability Map
2 Point wise Vulnerability Map
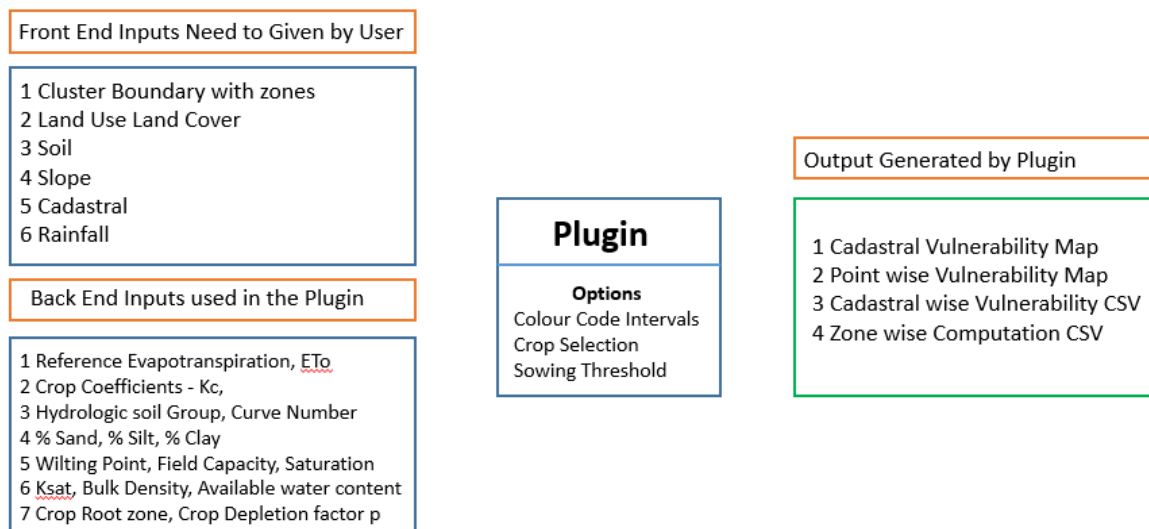3 Cadastral wise Vulnerability CSV
4 Zone wise Computation CSV

Figure 1 Description of Plugin

plugin. User can also categorize the intervals for the deficit water requirement. The process is described in fig 1. Data which is been used at the back end is given in the appendix.

4 Data Requirements and Pre-processing of Data

Table 1 gives the summary of the data requirements used in the plugin with its sources.

Table 1 Data requirement

Sr.No	Data	Source
1	Cluster Boundary	MRSAC
2	LULC	MRSAC
3	Soil	MRSAC
4	Cadastral Map	MRSAC
5	Cluster Boundary with zones	Processing
6	Slope	Processing
7	Rainfall	maharain.gov.in
8	DEM	SRTM, https://earthexplorer.usgs.gov/

Table 2 briefly describes the pre-processing needs to be done on the layers before being fed into the plugin. It also mentions the commands being used in the process.

Table 2 Pre-processing of Data

Sr.No	Input	Processing	Output	Commands Used
1	Cluster Boundary	Project the cluster boundary with number of villages in UTM projection.	Cluster Shapefile with required spatial extent.	Save command is used by selecting required villages
2	LULC	Using the cluster shapefile clip the LULC layer in UTM Projection	LULC layer with require spatial extent.	Qgis Clip Command
3	Soil	Using the cluster shapefile clip the soil layer in UTM Projection	Soil layer with required spatial extent.	Qgis Clip Command
4	Cadastral Map	Using the cluster shapefile clip the Cadastral layer in UTM Projection	Cadastral layer with required spatial extent.	Qgis Clip Command
5	DEM	Extraction of sub watersheds or zones from Dem	Zone layer with required spatial extent.	"r.watershed" , "r.to.vect"

6	Cluster Boundary with zones	Intersection of cluster boundary and zone layer and naming of zones	Cluster boundary with number of zones	Qgis Intersection Command
7	Slope	Extraction of slope layer from Dem	Slope layer with required spatial extent.	"r.slope"
8	Rainfall	Full year rainfall data in CSV format in two columns days and Rainfall	Rainfall CSV file	Excel

(a) LULC

The Land Use Land Cover file obtained from MRSAC by PMU unit contains the 35 types of land use and Land cover given in the table 3. This file has been obtained in the form of shapefile. The user needs to make sure that the file does not contain any other LULC type apart from the types given below in table 3. An example of LULC map has given in Figure 2.This is the first file which is required as input for plugin to run. The file needs to be projected in the UTM projection before being fed into the plugin. User also needs to make sure that the spatial extent of this file should be at least equal to the cluster boundary file. Failing any of the above mentioned requirements will not allow the plugin to run successfully.
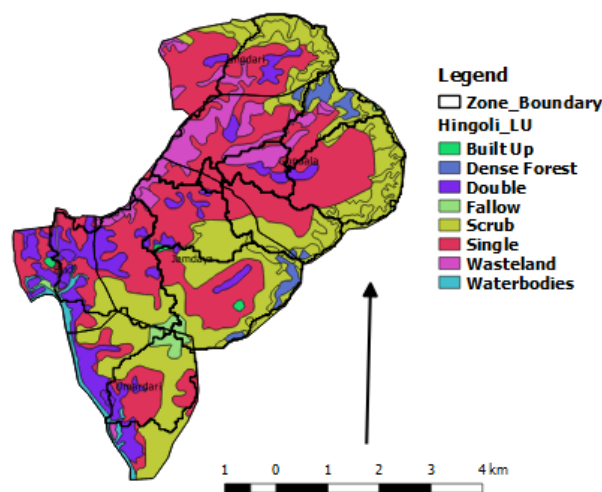

Figure2 LULC Map

(b) Soil

The Soil map obtained from MRSAC by PMU unit contains the 14 types of soil and depth of the soil has been categorized into 7 types given in the table 4. This file has been obtained in the form of shapefile. The user needs to make sure that the file does not contain any other soil type and depth apart from the types given below in table 4. This is the second file which is required as input to plugin to run. The file needs to be projected in the UTM projection before being fed into the plugin. User also needs to make sure that the spatial extent of this

file should be at least equal to the cluster boundary file. Failing any of the above mentioned requirements will not allow the plugin to run successfully. In figure 3 we can see the soil shapefile does not completely overlay or matches with the cluster boundary in such cases the plugin will not run.

Table 3 Land Use Land Cover

Sr. No	Land Use Land Cover	Class
1	Cropped in more than two seasons	Agriculture
2	Cropped in two seasons	Agriculture
3	Rabi	Agriculture
4	Zaid	Agriculture
5	Kharif	Agriculture
6	Agricultural Plantation	Agriculture
7	Built up - Compact (Continuous)	Build Up
8	Built up - Sparse (Discontinuous)	Build Up
9	Industrial Area	Build Up
10	Rural	Build Up
11	Fallow Land	Fallow
12	Deciduous (Dry/ Moist/ Thorn) - Dense/ Closed	Forest
13	Evergreen/ Semi Evergreen - Dense/ Closed	Forest
14	Forest Plantation	Forest
15	Tree Clad Area - Dense/ Closed	Forest
16	Tree Clad Area - Open	Forest
17	Ash/ Cooling Pond/ Effluent and Other waste	Wastelands
18	Mining - Abandoned	Wastelands
19	Mining - Active	Wastelands
20	Quarry	Wastelands
21	Deciduous (Dry/ Moist/ Thorn) - Open	Scrub Forest
22	Evergreen/ Semi Evergreen - Open	Scrub Forest
23	Scrub Forest	Scrub Forest
24	Barren Rocky	Wastelands
25	Gullied/ Ravinous Land - Gullied	Wastelands
26	Scrub Land - Dense/ Closed	Wastelands
27	Scrub Land - Open	Wastelands
28	Vegetated/ Open Area	Wastelands
29	Reservoir/ Tanks - Permanent	Waterbodies
30	Reservoir/ Tanks - Seasonal	Waterbodies
31	River - Non Perennial	Waterbodies
32	River - Perennial	Waterbodies
33	Canal/ Drain	Waterbodies
34	Lakes/ Ponds - Permanent	Waterbodies
35	Lakes/ Ponds - Seasonal	Waterbodies

Table 4 Soil Type and Depth

Sr. No	TEXTURE	Sr.No	DEPTH
1	Clay loam	1	Very shallow (< 10 cm)
2	Clayey	2	Shallow (10 to 25 cm)
3	Gravelly clay	3	Shallow to very shallow (< 25 cm)
4	Gravelly clay loam	4	Moderately deep (25 to 50 cm)
5	Gravelly loam	5	Deep to very deep (> 50 cm)
6	Gravelly sandy clay loam	6	Deep (50 to 100 cm)
7	Gravelly sandy loam	7	Very deep (> 100 cm)
8	Habitation Mask	8	Habitation Mask
9	Loamy	9	Waterbody Mask
10	Loamy sand		
11	Sandy clay		
12	Sandy clay loam		
13	Sandy loam		
14	Silty clay		
15	Silty loam		
16	Waterbody Mask		
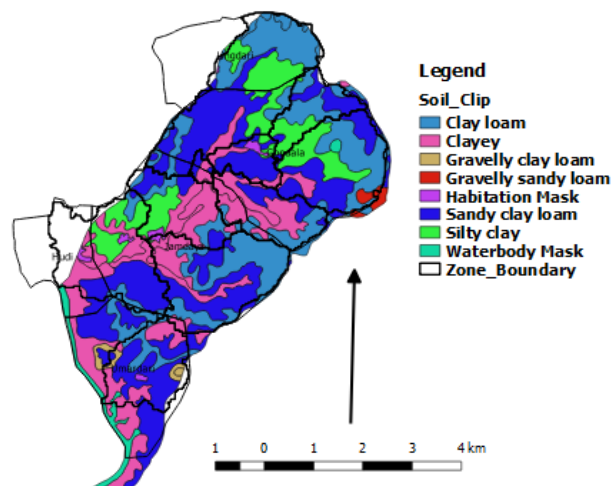
Figure 3 soil type

(C) Zones Map of cluster based upon sub watersheds

"r.watershed" is used to extract sub watersheds from the DEM. Minimum size of exterior watershed basin is selected as 1500 in this case. The threshold basin size (Minimum exterior basin) is the minimum area considered to be a basin. At DEM resolution of 30x30, each cell has area equal to 900 sq.m. So a threshold of 1500 means a minimum basin of 1350,000 sq.m or 135 hectares. Areas that drain off the map, or into the sea, and are smaller than that are not considered to be a basin.

"r.to.vect" is used to convert the sub watersheds raster file into vector file. Sometimes while automatically generating sub watersheds smaller polygons do form. Such polygons need to be merged with other sub watersheds. This is the third file which needs to be fed into the plugin. The file needs to be projected in the UTM projection before being fed into the plugin. User also needs to make sure that the spatial extent of this file should be equal to the cluster boundary file. For easy pre-processing or to reduce the work zone file should be intersected with the cluster boundary file and all the geometries or features falling outside the cluster boundary should be removed. The images of the same have been given in the figure 4.
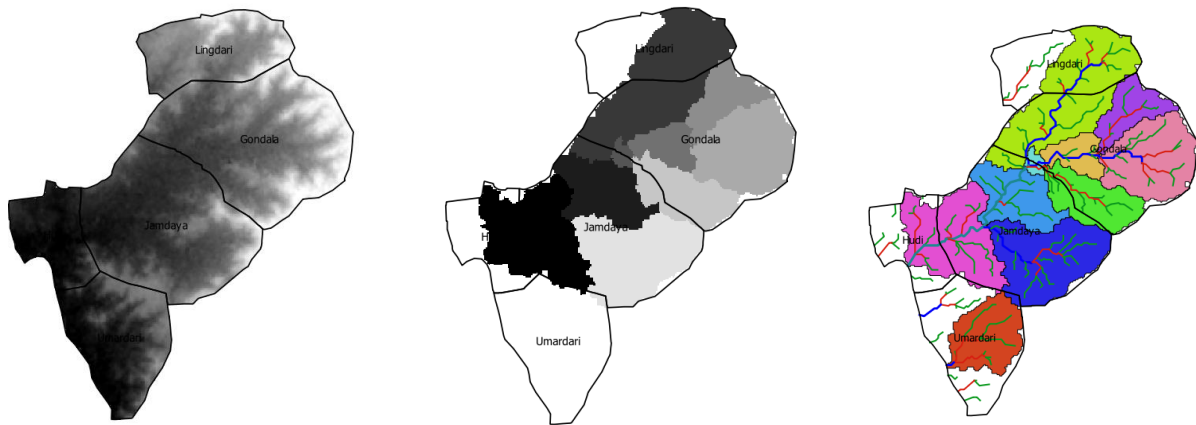

Figure 4 Zone Map

(d) Cadastral Map

The fourth file which user needs to input is cadastral shapefile. The file needs to be projected in the UTM projection before being fed into the plugin. User also needs to make sure that the spatial extent of this file should be at least equal to the cluster boundary file. An example of cadastral map has been given in figure 5.

(e) Slope Map

This is the fifth file which user needs to give as input. The slope map has been generated by using the "r.slope" command. Slope map is generated by using the SRTM digital elevation model from USGS website. It has 30m*30m resolution. Any other DEM of same resolution or high resolution can also be used to generate the slope Map. Output of this command gives the slope map in raster format which needs to be fed into the plugin. The file needs to be projected in the UTM projection before being fed into the plugin. User also needs to make sure that the spatial extent of this file should be at least equal to the cluster boundary file. An example of slope Map has been given in figure 5.
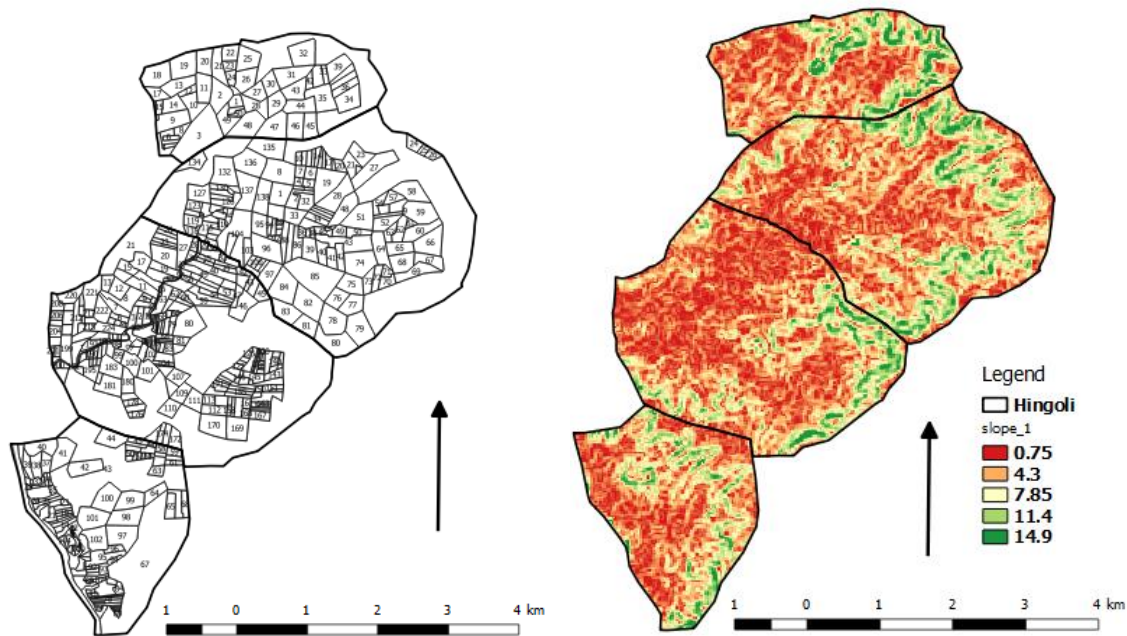
Figure 5 Cadastral and Slope Map

(f) Rainfall Data

Daily rainfall data for the whole cluster needs to be fed into the plugin. Currently the rainfall data has been downloaded from "maharain.gov.in". It gives the daily circle wise data in the form of month wise excel. The user needs to find out the nearby circle to the cluster or circle whose rainfall represents the rainfall pattern of cluster. Rainfall data of this cluster should be fed into the plugin. The rainfall data should be for the complete year.

(g) Stream Buffer Map

"r.watershed" is used to extract drainage Map from the Dem and later using *"r.to.vect"* it is converted into the vector shapefile. We need to run *"r.watershed"* two different times with different size of exterior watershed basin. First during extraction of sub watershed, second time during extraction of drainage. In this case it was run with the size of exterior watershed basin as 200. Later using "*r.buffer"* buffer area of around 200m is created around 3rd order and more than 3rd order streams. Similarly Buffer area of around 100m is created around 1st and 2nd order streams. Drainage network provided by PMU can also be used to extract buffer zone around it. This process is automated in the Plugin. An example of the stream buffer is given in figure 6.

The module *r.stream.order* calculates Strahler's and other stream hierarchy methods. It is a basic module for topological analysis of drainage networks. For current ordering Strahler's method has been used. The size of exterior watershed selected is equal to 200*30*30 = 180000 or 18 ha on 30*30 Dem with 200 as number of cells that needs to be drained from a cell.

Currently this has been kept optional. Based upon the need to find gat numbers nearer to the streams or under the zone of influence such maps of stream buffer can also be generated.
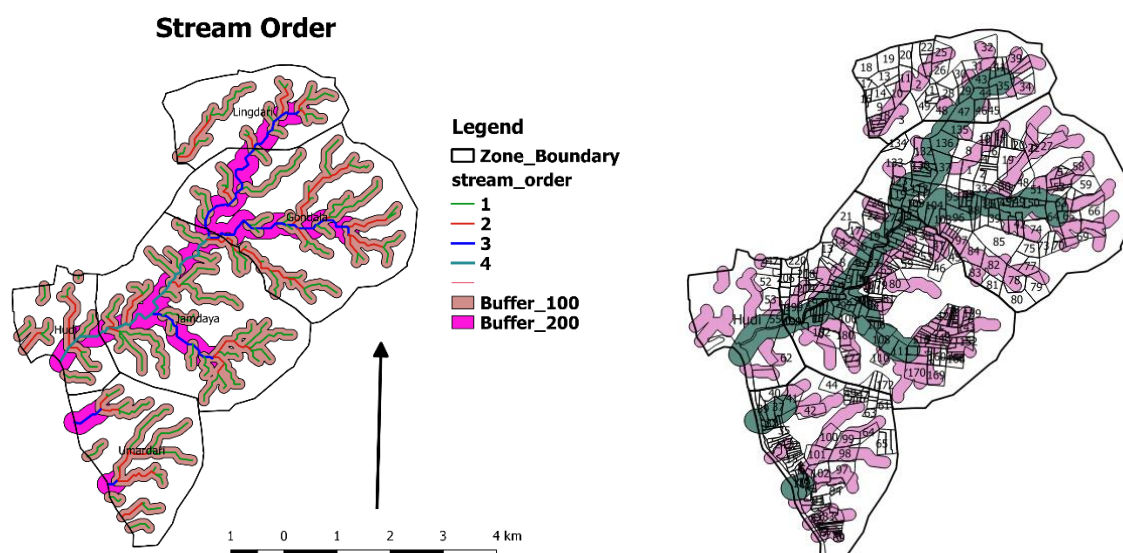
Figure 6 Stream Buffer

5 Description of Plugin

After the pre-processing the user needs to keep all the files in the same folder or directory which must be selected as Data set folder shown in fig 7. User can select the individual files or can give default names to the files. By giving the default names to files they will be automatically selected while selecting the data set folder. On the plugin the user needs to select the crop or multiple crops for which user wants to generate the computational water balance data. User can split the output into number of ET-Deficit intervals he wants. Sowing threshold will allow the user to define the amount of initial moisture required before sowing. Plugin display is shown in figure 7.

Figure 7 Plugin Display

Output

1 Cadastral Wise Vulnerability Map

After pre-processing the LULC layer shapefile, Soil shapefile, Rainfall data, Slope Map extracted from Dem using ("*r.slope.*"), zone boundary shapefile, cadastral shapefile all are fed into the plugin. UTM projections should be used while building this model. Cadastral wise vulnerability Map is generated when we fed all the shapefiles. This map will help us decide which survey numbers are more vulnerable and which are less vulnerable. Based upon this Map farmers from different gat numbers can be interviewed by cluster assistants. This will also help us decide which gat numbers required more watering's compared to other gat numbers. An example of the same has given in figure 8.
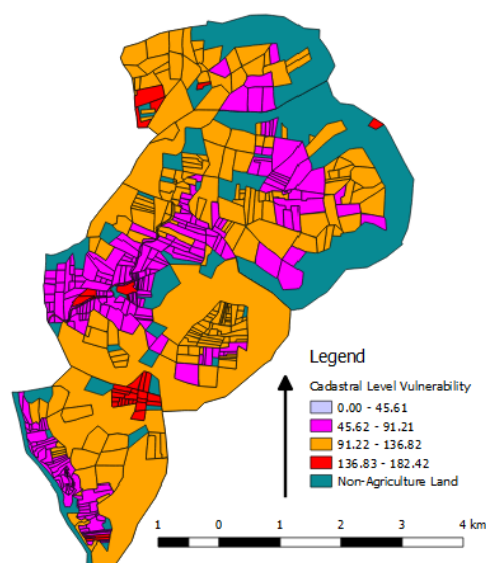

Figure 8 Cadastral Vulnerability Map

2 Vulnerability Map

Point wise vulnerability Maps are other outputs generated by plugin. The output will generate the Maps shown in the Following figure 9. It is an example of Gondala clusters. The map is made for single crop i.e. soybean crop for two years. In 2016 the area under vulnerability is less and in 2017 area under vulnerability has increased. The complete area is divide in 12 sub watersheds. The rainfall in both the years is almost the same. But in the year 2017 the rainfall is more erratic.
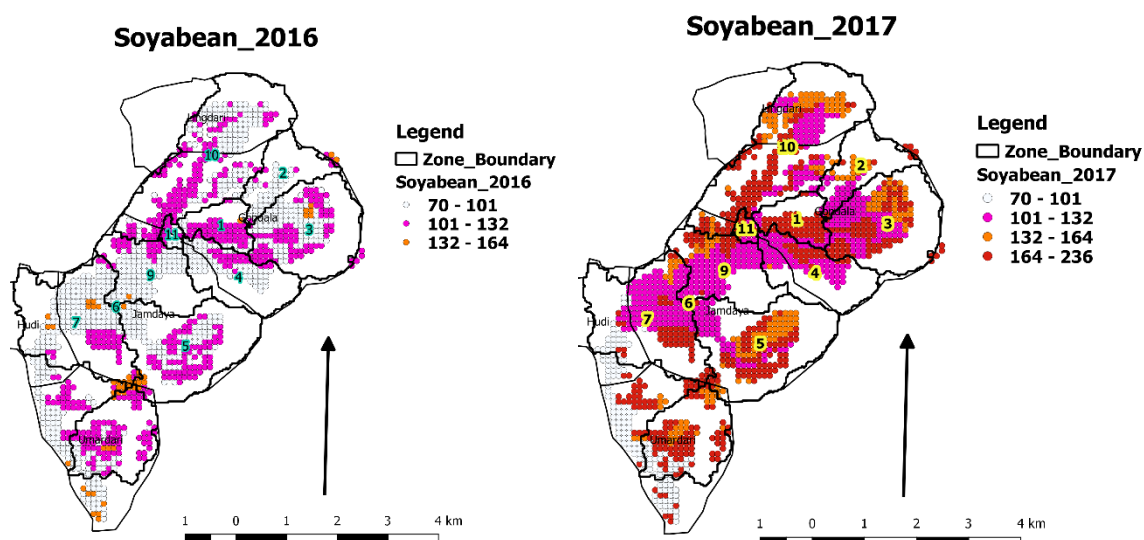
Figure 9 Vulnerability Map

3 Zone wise table for each Sub watershed

In most of the cases our watershed is divided into more than one soil type and land use. In such cases it is not wise to have one common computational table for complete watershed or village. To ease that process the watershed is divided into sub watersheds. But Within sub watershed there can be more than two types of soil and land use. Due to this weighted average of computational data is taken based upon the area under each soil type. For each crop there will be one table for zone.

Zone wise table The sub watershed 3 from figure 9 has been taken as an example. Values calculated from the LULC map are shown as an example in the following table. Values for the area under scrub forest, dense forest, Gao than and Fallow land has to be filled by the field team. The agriculture area is divided into number of crops grown in that region which will be filled by cluster assistant.

Table 5 Land Use

AREA (HA)	AREA LULC Map (ha)	Field Readings (ha)
Revenue Area	235	Crop 1
		Crop 2
		Crop 3
Scrub Forest	124	
Built up	10	
Dense Forest	0	
Fallow Land	0	

The table 6 will be generated for each zone based upon the type of crops in the cluster. Once the layers are fed into the plugin, based upon the number of zones in the zone shapefile computational data will be generated in form of csv in the data folder directory.

Table 6 Computational Data

Data	Soyabean	Bajra	Cotton	Tur	Wasteland	Scrub forest	Dense Forest
Rainfall	837	837	837	837	837	837	837
Runoff in Monsoon	360	479	355	374	432	406	346
Infilitration in Monsoon	477	358	482	463	405	431	491
Soil Moisture Crop end	72	78	1	16	23	1	1
GW Recharge in Monsoon	59	84	31	35	69	60	62
AET Crop End	346	184	449	411	312	370	427
PET Crop End	454	289	754	601	518	634	779
AET Monsoon End	346	184	449	411	305	356	427
PET Monsoon End	454	289	721	601	518	634	779
Monsoon Deficit(PET-AET)	108	105	272	190	86	77	226
Crop duration Deficit(PET-AET)	108	105	305	190	206	264	352

Vulnerable Survey Numbers with in Sub watersheds

Performing Spatial Joins Spatial Join is a classic GIS problem - transferring attributes from one layer to another based on their spatial relationship. In QGIS, this functionality is available through the Join Attributes by location tool. The tool can be found in following tab

Go to Vector ‣ Data Management Tools ‣ Join attributes by location.

Each gat number has been allotted a point and for that point computations has been done. From the computation data Gat number wise deficit has been shown in the CSV file. Number of watering required for each gat number is also added in the CSV file. An example of Gat wise vulnerability has been shown in table 7.
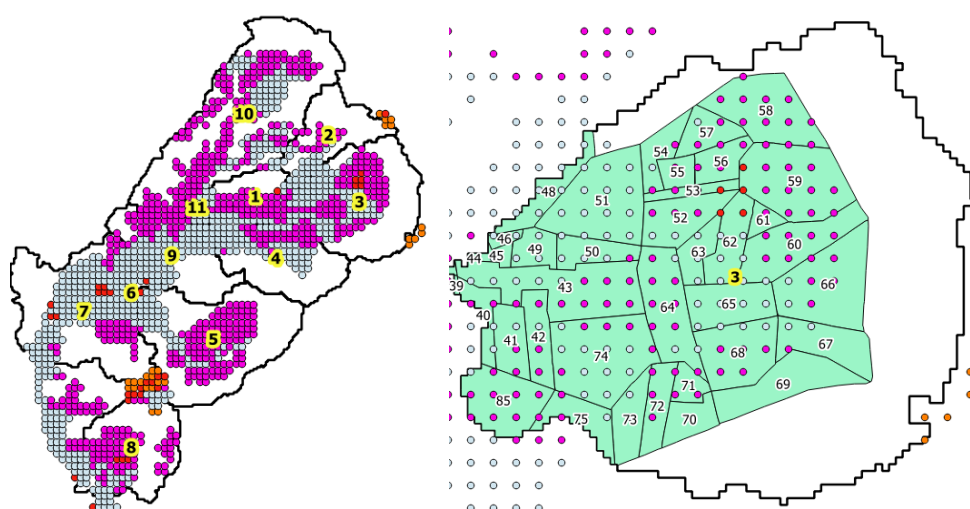
Figure 10: Gat wise vulnerability

Table 7 Gat wise vulnerability

Zone	AREA m2	Gat Number	Deficit mm	Mean Soil M mm	Watering's Req
3	20186.6	55	300.6	51.7	6
3	43807.3	41	302.9	113	6
3	44932.4	42	305.2	113	6
3	35156.9	56	305.6	51.7	6
3	14577.5	61	306.6	51.7	6
3	109521	58	308.7	51.7	6
3	88572.8	75	310.6	109.8	6
3	294478	85	316.7	79	6
3	591.6	44	321.2	45	6
3	134575.8	59	325.5	48.5	6
3	40883.6	72	331.6	45	6
3	21333.8	71	332.3	45	6
3	18392.5	53	340.3	44.1	6
3	67894.1	67	265.7	195.8	5
3	53228.4	62	268.1	227.3	5
3	147266.7	74	268.7	224.2	5
3	64644.3	52	274.2	140.3	5
3	32742.7	63	277.5	213.3	5
3	91136.3	60	279.3	126.5	5
3	36062.2	54	279.4	128	5
3	38596.6	57	285.2	124.1	5
3	144678.5	43	287.6	134.8	5
3	128271.6	66	289.3	114.2	5
3	88826.1	68	289.5	132.2	5
3	97179.5	64	299.6	106.3	5
3	6889	46	229.1	280.5	4
3	25120.2	45	229.1	280.5	4
3	30278	49	229.6	279.5	4
3	137214.3	51	230.5	277.8	4
3	69217.1	65	231.4	276.1	4
3	98775.4	48	231.5	276	4
3	48181.9	40	243.1	310.5	4
3	45536.7	73	247.1	304.2	4
3	39155.5	50	247.5	233.4	4

Appendix 1 Terminologies Explained

The runoff curve number (also called a curve number or simply CN) is an empirical parameter used in hydrology for predicting direct runoff or infiltration from rainfall excess. The runoff curve number is based on the area's hydrologic soil group, land use, treatment and hydrologic condition. To account for different soils' ability to infiltrate, they have been divided into four hydrologic soil groups (HSGs).

- **HSG Group A** (low runoff potential): Soils with high infiltration rates even when thoroughly wetted. These consist chiefly of deep, well-drained sands and gravels. These soils have a high rate of water transmission (final infiltration rate greater than 0.3 in./h).
- **HSG Group B** Soils with moderate infiltration rates when thoroughly wetted. These consist chiefly of soils that are moderately deep to deep, moderately well drained to well drained with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (final infiltration rate of 0.15 to 0.30 in./h).
- **HSG Group C:** Soils with slow infiltration rates when thoroughly wetted. These consist chiefly of soils with a layer that impedes downward movement of water or soils with moderately fine to fine textures. These soils have a slow rate of water transmission (final infiltration rate 0.05 to 0.15 in./h).
- **HSG Group D** (high runoff potential): Soils with very slow infiltration rates when thoroughly wetted. These consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission (final infiltration rate less than 0.05 in./h).

Evapotranspiration or ET

The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapotranspiration (ET). Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes.

Reference evapotranspiration or ET_o

The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ET_o. The reference surface is a hypothetical grass reference crop with specific characteristics. FAO Penman-Monteith method is now recommended as the sole standard method for the definition and computation of the reference evapotranspiration.

Reference evapotranspiration surface

The reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The fixed surface resistance of 70 s m^{-1} implies a moderately dry soil surface resulting from about a weekly irrigation frequency.

Crop evapotranspiration (ET_c)

The crop evapotranspiration differs distinctly from the reference evapotranspiration (ET_o) as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. The

effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient (K_c). In the crop coefficient approach, crop evapotranspiration is calculated by multiplying ET_o by K_c.

$$ET_c = K_c \, ET_o$$

Single crop coefficient approach (K_c)

The K_c predicts ET_c under standard conditions. This represents the upper envelope of crop evapotranspiration and represents conditions where no limitations are placed on crop growth or evapotranspiration due to water shortage, crop density, or disease, weed, insect or salinity pressures. The ET_c predicted by K_c is adjusted if necessary to non-standard conditions, $ET_{c\ adj}$, where any environmental condition or characteristic is known to have an impact on or to limit ET_c.

ET_c under soil water stress conditions

Where the conditions encountered in the field differ from the standard conditions, a correction on ET_c is required. Low soil fertility, salt toxicity, soil waterlogging, pests, diseases and the presence of hard or impenetrable soil horizons in the root zone may result in scanty plant growth and lower evapotranspiration. Soil water shortage and soil salinity may reduce soil water uptake and limit crop evapotranspiration. The effects of soil water stress are described by multiplying the basal crop coefficient by the water stress coefficient, Ks.

Saturation

During a rain shower or irrigation application, the soil pores will fill with water. If all soil pores are filled with water the soil is said to be saturated. There is no air left in the soil. It is easy to determine in the field if a soil is saturated. After the rain or the irrigation has stopped, part of the water present in the larger pores will move downward. This process is called drainage or percolation.

Field capacity

Field Capacity is the amount of soil moisture or water content held in the soil after excess water has drained away and the rate of downward movement has decreased. This usually takes place 2–3 days after rain or irrigation in pervious soils of uniform structure and texture. After the drainage has stopped, the large soil pores are filled with both air and water while the smaller pores are still full of water. At this stage, the soil is said to be at field capacity. At field capacity, the water and air contents of the soil are considered to be ideal for crop growth.

Permanent wilting point

Little by little, the water stored in the soil is taken up by the plant roots or evaporated from the topsoil into the atmosphere. If no additional water is supplied to the soil, it gradually dries out. The dryer the soil becomes, the more tightly the remaining water is retained and the more difficult it is for the plant roots to extract it. At a certain stage, the uptake of water is not sufficient to meet the plant's needs. The plant loses freshness and wilts; the leaves change colour from green to yellow. Finally the plant dies. The soil water content at the stage where the plant dies, is called permanent wilting point. The soil still contains some water, but it is too difficult for the roots to suck it from the soil.

Total Available water

As the water content above field capacity cannot be held against the forces of gravity and will drain and as the water content below wilting point cannot be extracted by plant roots, the total available water in the root zone is the difference between the water content at field capacity and wilting point.

$$TAW = 1000(q_{FC} - q_{WP}) Z_r$$

Readily Available Water

Although water is theoretically available until wilting point, crop water uptake is reduced well before wilting point is reached. Where the soil is sufficiently wet, the soil supplies water fast enough to meet the atmospheric demand of the crop, and water uptake equals ETc. As the soil water content decreases, water becomes more strongly bound to the soil matrix and is more difficult to extract. When the soil water content drops below a threshold value, soil water can no longer be transported quickly enough towards the roots to respond to the transpiration demand and the crop begins to experience stress. The fraction of TAW that a crop can extract from the root zone without suffering water stress is the readily available soil water.

RAW = p TAW

RAW the readily available soil water in the root zone [mm], p average fraction of Total Available Soil Water (TAW) that can be depleted from the root zone before moisture stress (reduction in ET) occurs [0-1]. The factor p differs from one crop to another. The factor p normally varies from 0.30 for shallow rooted plants at high rates of ET_c (> 8 mm d^{-1}) to 0.70 for deep rooted plants at low rates of ET_c (< 3 mm d^{-1}). A value of 0.50 for p is commonly used for many crops.

Appendix 2 Database used at the back end

Currently the values of Evapotranspiration for different regions are taken from the WALMI which are given in appendix 1. WALMI data also provides the total crop duration and total crop water requirement. But the current model requires the value of daily crop water requirement. As seasonal crop water requirement will not help us calculate the actual water taken by the crop and hence the impact of dry spells. FAO provides the different crop stages duration data and monthly crop coefficients Kc values. Monthly kc values can be used on daily basis. FAO values have been scaled up or scaled down to match the WALMI total crop water requirement and crop duration. The modified crop duration and Kc values have been given in appendix 2. Initial curve number to start the calculation process has been assigned based upon the soil hydrologic group, land use and soil type. The values of the curve number has been given in appendix 3.

Table 1 Montly ETo Values Region wise for POCRA Districts

Monthly ET0	Parbhani	Aurangabad	Amravati	Nanded	Yavatmal	Wardha
Jan	3.95	4.36	4.74	4.29	4.77	3.93
Feb	5.17	5.6	5.89	5.42	5.93	6.05
March	5.29	6.5	7.03	6.39	7.05	0.71
April	7.03	7.55	8.13	7.33	7.96	5.8
May	8.25	8.86	9.09	8.22	9.26	9
June	7.51	6.32	8.2	7.03	7.96	7.17
July	4.77	4.64	4.61	5.26	4.55	4.63
Aug	4.55	3.98	4.45	4.77	3.93	4.06
Sept	4.78	4.39	4.7	5.03	4.5	4.83
Oct	4.8	5.02	5.32	5.01	4.84	4.42
Nov	3.9	4.52	4.76	5.57	4.23	4.3
Dec	3.48	4.16	4.36	4.57	4.22	3.55
Agro climatic zone	7	7	7	7&8	8	8
Mapped Districts	parbhani, latur, osmanabad, beed	Aurangabad, jalna, jalgaon	buldhana, Amravati, Akola	Washim, Nanded, Hingoli	Yavatmal	Wardha

Table 2 Adjusted Kc and Crop duration values

Adjusted Kc and duration values					
Crop		Stage I	Stage II	Stage III	Stage IV
Orange	Duration	60	90	120	95
	Kc	0.42	0.42	0.42	1.57
Sorgum	Duration	16	28	36	24
	Kc	0.32	0.5	0.75	0.52
Cotton	Duration	39	78	39	39
	Kc	0.47	0.79	1.21	0.79
Tur	Duration	34	51	60	25
	Kc	0.36	0.68	0.92	0.84
Banana	Duration	120	60	180	5
	kc	0.75	0.83	1.1	0.6
Bajra	Duration	13	21	34	22
	kc	0.5	0.7	0.2	1.05
Sugarcane	Duration	35	60	190	80
	kc	0.4	1.25	0.75	0.7
Udid	Duration	15	22	26	11
	kc	0.36	0.82	0.79	0.36
Moong	Duration	15	22	26	11
	kc	0.36	0.82	0.79	0.36
Soyabean	Duration	20	25	45	20
	kc	0.3	0.7	1.15	0.7

Table 3 Hydrologic soil groups and Curve numbers

Lookup table (don't move)			Lookup used				
Soil type	HSG						
Clay Loam	D		LU	HSG A	HSG B	HSG C	HSG D
Clayey	D		Agriculture	67	78	85	89
Gravelly Clay	D		Deciduous - Dense	30	55	70	77
Gravelly Clay Loan	D		Deciduous open	36	60	73	79
Gravelly Loam	B		Fallow land	77	86	91	94
Gravelly Sandy Cla	B		habitation	77	85	90	92
Gravelly Sandy Loa	B		Scrub dense	49	69	79	84
Gravelly Silty Clay	C		Scrub Forest	57	73	82	86
Gravelly Silty Loan	C		Scrub open	68	79	86	89
Loamy	B						
Loamy sand	A						
Sandy	A						
Sandy Clay	D						
Sandy Clay loam	C						
Sandy loam	A						
Silty clay	D						
Silty clay loam	D						
Silty loam	B						

Table 4 Soil Depth

S.No	Soil Depth from Map	Soil Depth used m
1	deep (50 to 100 cm)	1
2	habitation mask	0.1
3	shallow (10 to 25 cm)	0.25
4	very deep (> 100 cm)	1.5
5	waterbody mask	0.1
6	moderately deep (25 to 50 cm)	0.5
7	shallow to very shallow (< 25 cm)	0.25
8	very shallow (< 10 cm)	0.1

Table 5 Crop Root Depth

Sr.No	Crops and LU	Root Depth
1	Soyabean	0.9
2	Bajra	1.5
3	Moong	0.75
4	Sorghum	1.5
5	Cotton	1.35
6	Udid	0.75
7	Banana	0.75
8	Sugarcane	0.75
9	Orange	1.1
10	Rice	0.75
11	Sunflower	1.15
12	Tur	0.75
13	Grapes	0.9
14	Maize	1.35
15	Deciduous - dense crop	3
16	Deciduous open crop	1.5
17	Scrub dense crop	1.5
18	Scrub forest crop	1.5
19	Scrub open crop	0.5

Table 6 Soil Parameters

SN No	Soil Type	HSG	Sand %	Clay %	Gravel %	WP	FC	Saturation	Ksat mm/hr	Bulk Density	AWC
1	Clay loam	D	32	34	0	0.206	0.341	0.442	2.7	1.48	0.14
2	Clayey	D	28	51	0	0.303	0.427	0.487	0.52	1.36	0.12
3	Gravelly clay	D	23	48	10	0.285	0.415	0.488	0.83	1.36	0.12
4	Gravelly clay loam	D	31	34	10	0.206	0.343	0.444	2.32	1.47	0.12
5	Gravelly loam	B	41	17	10	0.109	0.024	0.408	10.83	1.57	0.12
6	Gravelly sandy clay loam	B	49	26	10	0.16	0.273	0.412	5.83	1.56	0.1
7	Gravelly sandy loam	B	63	10	10	0.065	0.158	0.402	33.29	1.58	0.08
8	Gravelly silty clay	C	7	47	10	0.277	0.42	0.512	1.7	1.29	0.13
9	Gravelly silty loam	C	21	15	10	0.099	0.282	0.415	6.8	1.55	0.16
10	Loamy	B	42	20	0	0.126	0.256	0.411	10.2	1.56	0.13
11	Loamy sand	A	82	8	0	0.05	0.106	0.41	69.09	1.56	0.06
12	Sandy	A	91	5	0	0.03	0.071	0.424	108.06	1.53	0.04
13	Sandy clay	D	51	42	0	0.254	0.364	0.43	0.73	1.51	0.11
14	Sandy clay loam	C	57	28	0	0.172	0.271	0.406	6.09	1.57	0.1
15	Sandy loam	A	65	11	0	0.172	0.258	0.399	6.67	1.59	0.09
16	Silty clay	D	9	46	0	0.272	0.415	0.506	1.9	1.31	0.14
17	Silty clay loam	D	11	34	0	0.206	0.371	0.47	2.65	1.41	0.17
18	Silty loam	B	19	16	0	0.105	0.291	0.418	6.97	1.54	0.19
19	Waterbody mask	D	28	51	0	0.303	0.427	0.487	0.52	1.36	0.12
20	Habitation mask	D	32	34	0	0.206	0.341	0.442	2.7	1.48	0.14

Appendix 3 Excel Model

The current Excel model has been made as two soil layer model. First layer represents the crop root zone and second layer represents the remaining soil depth. Initially, we need to fix a land use, soil type, and slope and HSG group for our area to select a CN number which is known as **CN₂**. From this CN number **CN₃** and **CN₁** values are calculated. After the calculation of CN numbers Smax and S3 Soil retention parameters are calculated for **CN₁** and **CN₃**. Then S (retention parameter) is calculated for initial soil moisture content. After that value of S is varied daily with daily change in soil moisture content. With new soil retention parameter, value of CN number is revised to get new CN number every day. With daily change in CN number daily calculations for runoff is done. Initial Soil Moisture for day1 has been set equal to wilting point of soil. Initial soil moisture for Day2 is computed from the previous day soil moisture, infiltration, near surface storage values and the water taken by the crop. Initially, without any rainfall and If there is no infiltration the soil moisture is set equal to wilting point. If there is some infiltration happening then it is added to the first layer and the value is compared to the field capacity of the soil. If infiltration is more than field capacity the moisture is added to the second layer. Similarly the amount of water added to the second layer is compared against its field capacity and extra water is added to the ground.

Runoff Calculation

Initial CN₂ value is selected based upon the look up table given in the appendix 2 table 3. Based upon the soil texture, the soil has been classified into different hydrologic groups. Depending on the land use and HSG curve number value is selected.

Runoff is affected by the soil moisture before a precipitation event, or the *antecedent moisture condition* (AMC). A curve number, as selected above, may also be termed AMC II or **CN₂**, or average soil moisture. The other moisture conditions are dry or wilting point, AMC I or **CN₁**, and moist or field capacity, AMC III or **CN₃**. Based upon the amount of rainfall the moisture condition of the soil or AMC will change daily. The curve number can be adjusted based upon their AMC condition by using the following formulas. **Both CN₁ and CN₃** can be calculated using the following equations.

$$CN_1 = CN_2 - \frac{20 \cdot (100 - CN_2)}{(100 - CN_2 + \exp[2.533 - 0.0636 \cdot (100 - CN_2)])}$$

$$CN_3 = CN_2 \cdot \exp[0.00673 \cdot (100 - CN_2)]$$

Retention Parameter

Retention Parameter varies spatially due to change in Land use, management, and slope and temporally due to change in soil moisture content. Retention Parameter can be calculated using two methods. One method allows retention parameter to vary with plant ET. Traditional method allows it vary with soil water content. We are using traditional method for computation.

$$S = S_{max} \cdot \left(1 - \frac{SW}{[SW + \exp(w_1 - w_2 \cdot SW)]}\right)$$

S_{max} is the potential maximum soil moisture retention after runoff begins. SW is the soil moisture value excluding the wilting point. W_1 and W_2 are the shape coefficients. The value of S_{max} is calculated using the CN1 value and using the following equation.

$$S = 25.4\left(\frac{1000}{CN} - 10\right)$$

The value of W_1 and W_2 is calculated using the following equations. FC is the amount of water in soil profile at field capacity. S3 is the retention parameter for the moisture condition III or **CN₃** value. SAT is the amount of water in the soil profile when soil is completely saturated.

$$w_1 = \ln\left[\frac{FC}{1 - S_3 \cdot S_{max}^{-1}} - FC\right] + w_2 \cdot FC \qquad 2$$

$$w_2 = \frac{\left(\ln\left[\frac{FC}{1 - S_3 \cdot S_{max}^{-1}} - FC\right] - \ln\left[\frac{SAT}{1 - 2.54 \cdot S_{max}^{-1}} - SAT\right]\right)}{(SAT - FC)}$$

The daily retention parameter is adjusted by using the new soil moisture values every day. Then the Daily curve number value is calculated from the new value of the retention parameter based upon the new soil moisture value for that day.

$$CN = \frac{25400}{(S + 254)}$$

The initial curve number **CN₂** used as starting point for all the calculations is appropriate for slope 5%. To take into account the slope factor the value of **CN₂** is modified based upon the following equation where CN_{2s} is the modified curve number based upon the slope. Slp is the slope value corresponding to the point where calculation is being done. **CN₃** is curve number value corresponding to the AMC III.

$$CN_{2s} = \frac{(CN_3 - CN_2)}{3} \cdot [1 - 2 \cdot \exp(-13.86 \cdot slp)] + CN_2$$

Runoff

The model was built to provide the runoff for varying land use and soil types. The Runoff is calculated by using the following equation. R_{day} is the rainfall on any given day.

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

Ia is the initial abstraction, or the amount of water before runoff, such as infiltration, or rainfall interception by vegetation; historically, it has generally been assumed Ia =0.2S

If rainfall value is more than initial abstraction than the above equation is used to calculate the runoff for the given day otherwise the value of runoff for that day is set equal to 0.

CN has a range from 30 to 100; lower numbers indicate low runoff potential while larger numbers are for increasing runoff potential. The lower the curve number, the more permeable the soil is. As can be seen in the curve number equation, runoff cannot begin until the initial abstraction has been met. It is important to note that the curve number methodology is an event-based calculation, and should not be used for a single annual rainfall value, as this will incorrectly miss the effects of antecedent moisture and the necessity of an initial abstraction threshold.

Infiltration

It is the process by which water on the ground surface enters the soil. Daily infiltration is calculated by subtracting the runoff value from the rainfall value.

Infiltration = Rainfall – Runoff

Reference evapotranspiration ETo Values are taken from the data provided by the Walmi given in Table 1 Appendix 2.

Crop evapotranspiration (ET$_c$)

The crop evapotranspiration differs distinctly from the reference evapotranspiration (ET$_o$) as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. The effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient (K$_c$). In the crop coefficient approach, crop evapotranspiration is calculated by multiplying ET$_o$ by K$_c$.

$$ET_c = K_c\, ET_o$$

Single crop coefficient approach (K$_c$)

The K$_c$ predicts ET$_c$ under standard conditions. This represents the upper envelope of crop evapotranspiration and represents conditions where no limitations are placed on crop growth or evapotranspiration due to water shortage, crop density, or disease, weed, insect or salinity pressures. The ET$_c$ predicted by K$_c$is adjusted if necessary to non-standard conditions, ET$_{c\ adj}$, where any environmental condition or characteristic is known to have an impact on or to limit ET$_c$. Kc Values used in the model for crops is given in the **Table 2 Appendix 2.**

ET$_c$ under soil water stress conditions

Where the conditions encountered in the field differ from the standard conditions, a correction on ET$_c$ is required. Low soil fertility, salt toxicity, soil waterlogging, pests, diseases and the presence of hard or impenetrable soil horizons in the root zone may result in scanty plant growth and lower evapotranspiration. Soil water shortage and soil salinity may reduce soil water uptake and limit crop evapotranspiration.

Forces acting on the soil water decrease its potential energy and make it less available for plant root extraction. When the soil is wet, the water has a high potential energy, is relatively free to move and is easily taken up by the plant roots. In dry soils, the water has a low potential energy and is strongly bound by capillary and absorptive forces to the soil matrix, and is less easily extracted by the crop. When the potential energy of the soil water drops below a threshold value, the crop is said to be water stressed. The effects of soil water stress are described by multiplying the basal crop coefficient by the water stress coefficient, Ks:

If Soil Moisture is > F.C – RAW than Ks = 1

For D$_r$ > RAW or Soil Moisture < F.C – RAW

$$K_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p)TAW}$$

Where, K_s is a dimensionless transpiration reduction factor dependent on available soil water, D_r root zone depletion [mm], TAW total available soil water in the root zone [mm], p fraction of TAW that a crop can extract from the root zone without suffering water stress

Ks = IF(Day 1 Soil Moisture <Wilting Point,0,(IF(Day 1 Soil Moisture >(Field Capacity*(1-depletion factor p)+depletion factor *wilting point),1,(Day 1 Soil Moisture – Wilting Point)/(Field Capacity-Wilting Point)/(1-depletion factor))))

After the computation of K_s, the adjusted evapotranspiration $ET_{c\,adj}$ is computed

Soil Moisture Calculations

Initially the soil moisture is set equal to wilting point. There are two terms being calculated soil moisture after infiltration and soil moisture. Soil moisture after infiltration means when current day infiltration and AET is taken into account and added to the last day soil moisture or previous day readings or end of the day soil moisture.

1. *SM after Recharge (Day 1) = Wilting Point*

2. *SM after Recharge (Day 2) = ((SM Layer 1 Day1*1*Soil Thickness Layer 1 + (Infilteration+NSS2-AET-NSS3)/1000)/ Soil Thickness Layer 1)*

3. *SM Day 1 = (SM after infiltration Day1 *Soil Thickness*1000-Recharge to Secondary Layer)/Soil Thickness Layer 1/1000*

From this value recharge to secondary layer is subtracted to arrive at the actual soil moisture at the end of the day.

4. *SM Day 2 =MIN(((SM after infiltration Day2 *Soil Thickness*1000-Recharge to Secondary Layer)/Soil Thickness Layer 1/1000),Saturation Point)*

The value of Soil Moisture after infiltration is compared with field capacity of layer 1, if the value is less than field capacity, recharge to secondary layer is set to 0. Now if value of soil moisture after infiltration is more than field capacity of layer 1 and If previous day soil moisture of layer 2 is less than saturation capacity of layer 2 then water to second layer is added. The amount of water that percolates from layer 1 to 2 depends upon the unsaturated conductivity of the soil layer, the remaining capacity of layer 2 to absorb the water and availability of water above the field capacity of first layer.

5. *Recharge to Secondary Layer=IF(Soil Moisture after infiltration layer 1<Field Capacity,0,IF(Layer 2 Soil Moisture Day1 <Saturation point, MIN((Saturation Point-Layer 2 Soil moisture day1)*Thickness of soil layer 2*1000,(SM after infiltration Layer 1 - Field Capacity)* Thickness of soil layer *1000* daily percolation factor),0))*

After accounting the recharge for secondary layer if the water entering the top layer is higher than its saturation point then that water is removed as secondary runoff.

6. *Secondary Runoff = IF(((SM Layer 1 Day 1*1*Soil Layer Thickness 1+(Infilteration+NSS2-AET-NSS-Recharge to secondary Layer)/1000)/Soil Thickness)>Saturation Point,(((SM Layer 1 Day*

1*1*Soil Layer Thickness 1+(Infilteration+NSS2-AET-NSS-Recharge to secondary Layer)/1000)/Soil Thickness)-Saturation)*Soil Layer Thickness*1000,0)

Similarly Soil Moisture after infiltration for layer 2 is computed. Infiltration for layer 2 is equal to the recharge to secondary layer.

7. $SM\ after\ infiltration\ layer\ 2 =$
$$\frac{[\ (soil\ moisture\ layer\ 2\ day\ 1*soil\ thickness*1000)+recharge\ to\ secondary\ layer\ or\ infiltration]}{(soil\ thickness/1000)}$$

If soil moisture for layer 2 is less than field capacity there will no percolation to GW. If it is more than field capacity then the difference between the two will be added as groundwater recharge.

Percolation to Groundwater=IF(SM after infiltration layer 2<Field Capacity, 0, (SM after infiltration layer 2-Field Capacity)*Soil Layer 2*1000* daily percolation factor)

8.
$$w_{perc,ly} = SW_{ly,excess} \cdot \left(1 - \exp\left[\frac{-\Delta t}{TT_{perc}} \right] \right)$$

9.
$$TT_{perc} = \frac{SAT_{ly} - FC_{ly}}{K_{sat}}$$

After filling the layer 2 till field capacity some water is removed from the layer as GW percolation. Maximum water that layer 2 can hold is till saturation point.

10. *Layer 2 Soil Moisture = MIN (((SM after infiltration layer 2*)/Soil Thickness *1000-Percolation to Gw)/Soil Thickness /1000), Saturation Point)*

Layer 2 can have maximum water till it is saturated. When layer 2 is above field capacity water is removed from layer 2 added as groundwater recharge.

Soil moisture for both the layers are added in the end to get the complete soil moisture. These calculations are done pointwise. At end of the model we get runoff, infiltration, soil moisture, groundwater PET and AET value for at given point or location and crop. Final output will be in the form of table 6 described above.

References

1 Downer (2007), "Development of a simple soil moisture model in the hydrologic simulator GSSHA", Oct 2007.

2 Eilers V.H.M., Carter R. C. , Rushton K.R. (2007), "A single layer soil water balance model for estimating deep drainage (potential recharge): An application to cropped land in semi-arid North East Nigeria", Geoderma 140 (2007) 119–131.

3 FAO, "FAO Irrigation and Drainage Paper No. 56 on Crop evapotranspiration – guidelines for computing crop water requirements", FAO Water Resources Development and Management service.

4 Kudoli A. B. and Oak R.A. (2015), "Runoff estimation by using GIS based technique and its comparison with different methods – a case study on Sangli watershed", IJERMT ISSN: 2278-9359 (Volume-4 Issue-5).

5 MingXing et al (2010), " Regional soil moisture simulation for Shaanxi province using SWAT model validation and trend analysis", Science China Earth Science, Vol 53 No. 4.

6 MODFLOW Hughes, J.D., Langevin, C.D., and Banta, E.R., 2017, Documentation for the MODFLOW 6 framework: U.S. Geological Survey Techniques and Methods, book 6, chap. A57, 40 p., https://doi.org/10.3133/tm6A57.

7 Soil and Water Assessment Tool Theoretical Documentation 2009 by TAMU: http://swat.tamu.edu/media/99192/swat2009-theory.pdf

8 USDA (1986), " Urban hydrology for small watersheds", USDA Technical Release 55

9 Wagner P.D. et al. (2011), "Hydrological modelling with SWAT in a monsoon-driven environment: Experience from the Western Ghats, India", ASABE Vol 54(5): 1783-1790.

10 WALMI (2009), "Kharif hangamateel Sinchan Vyavasthapan – Shetkaryansathi Mahiti Pustika kramank 16", Water and Land Management Institute Publication 16, Aurangabad, Maharashtra.

11 WALMI (2005), "Rabi va Unhali hangamateel Pik Niyojan va Sinchan Vyavasthapan – Shetkaryansathi Mahiti Pustika kramank 17", Water and Land Management Institute Publication 17, Aurangabad, Maharashtra.

12 Wang, Lei, and Christopher R. Jackson, Magdalena Pachocka, Andrew kingdom, "A seamlessly coupled GIS and disturbed groundwater flow model", Environmental Modeling and Software, vol.82,pp 1-6, (2016).