Surface and groundwater accounting framework

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The current water accounting framework computes the water budget components at the point level and then those components are aggregated over micro watershed (200-500 ha) which is part of the village (1000 ha). This framework does not take into account the amount of water flowing into the village boundary from micro watersheds outside the village boundary. It also does not take into account the water leaving the village boundary from micro watershed inside the village boundary. Moreover, it does not account for losses during stream flows which add to the regional groundwater resource. Improving upon the existing framework will help in the correct assessment of various stocks and flows, especially the considerable amount of runoff made available to the downstream villages from the upstream villages. This can be used to tackle the crop water deficit more effectively and to plan infrastructure around the streams. In this initial proof-of-concept, we improve on the accounting of groundwater by incorporation of stream simulation process. Water from different farms is routed into the stream. Within the streams water is routed using the variable storage method. Rate and velocity component in a stream is computed using the Manning's equation.

Objective

1. Given a DEM and village boundary, dividing the village into micro watersheds such that either each watershed represents the whole or part of the watershed for the drain point in the village or it represents a part of village boundary where water is flowing IN or OUT of the village.
2. Using dem and identified drain points, to identify the stream segments and their respective contributing areas which will contribute water to the stream segments.
3. Simulate the water through these stream segments using routing methods and account for losses.

Input for differential watershed creation

- DEM (Digital Elevation Model)
  - Used for generating Stream Network
- Points of interest
  - Initially intersection of Administrative Boundary & Stream Network called drain points and location of key interventions such as CNBs.

Output:

- Micro-watersheds
    - Division of Administrative boundary into regions based on a watershed basis
- Differential Watershed for each point
- IN or OUT notion representing the flow of the administrative boundary
    - Represents Water Flow within or OUT of the administrative boundary
    - IN and OUT notion of water flow is also applicable to points taken in input which represented as a label in the output decomposition table

Concept of Differential Watershed:

A watershed of a point *p* describes an area of land that contains a common set of streams and rivers that drain into *p, which may be* a single larger body of water, such as a larger river, a lake or an ocean. It is any surface area from which runoff resulting from rainfall is collected and drained through a common point *p.* The differential watershed is computed for two points p and *q*, where *p* is downstream of *q.* It is that part of the watershed which contributes to p but not to q. This is usually a subset of the actual watershed of the point *p*.

This gives us an idea of how much new water has arrived at that particular point from different areas of watershed which can be used to conceptualize a water accounting framework representing how much of water is coming IN the village and how much of water is going OUT of the village. The concept of differential water helps us to identify the amount of water which will be surely available even if no water is allowed to transcend from the surrounding points either through runoff or groundwater, etc.

Example of Differential Watershed:

Let’s understand the concept of the differential watershed through an example. Consider the below cluster boundary as administrative boundary and the respective stream segments generated from watershed which is a natural boundary. The points on the stream network represent the drain points and the potential water storage structure points. Below is the watershed for point 9 and 10 respectively.

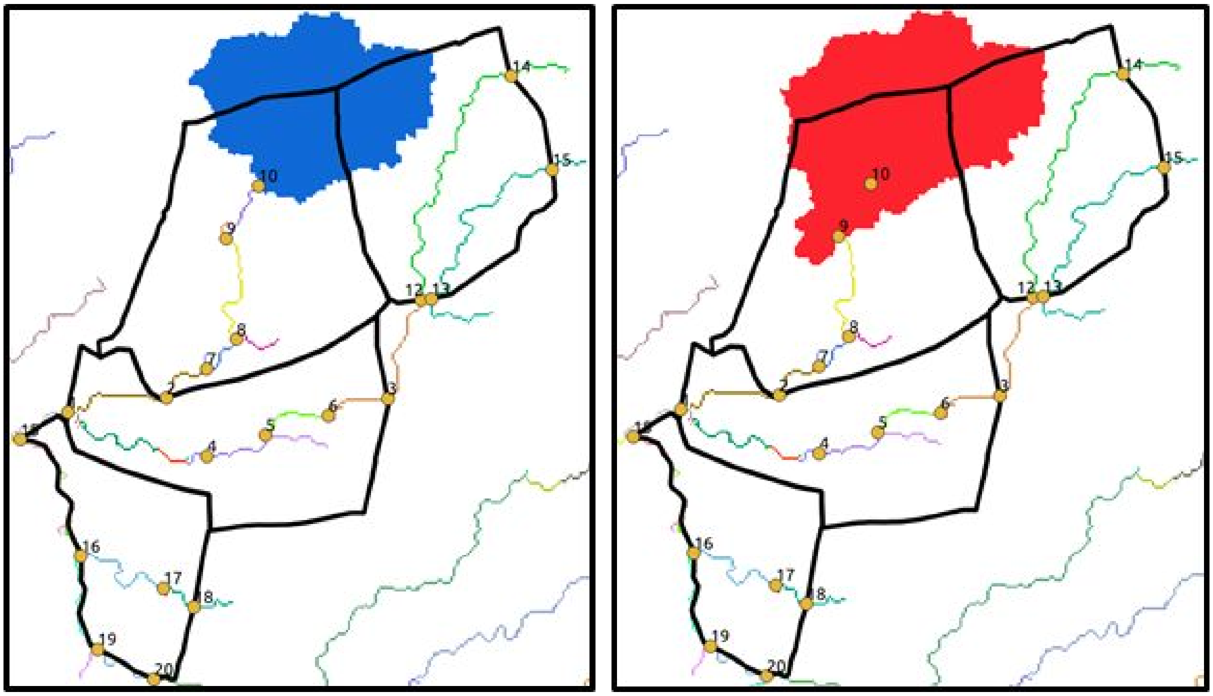


Figure 1 Watershed for point 9 and 10

Now, the differential watershed for point 9 is the amount of water accumulating at point 9 and is not part of the watershed for point 10. The below area marked in green represents the differential watershed for point 9. Say “X” amount of water is available in the watershed for point 10 and “Y” amount of water is available in the watershed for point 9, then the differential watershed for point 9 will comprise of “Y-X” amount of water.

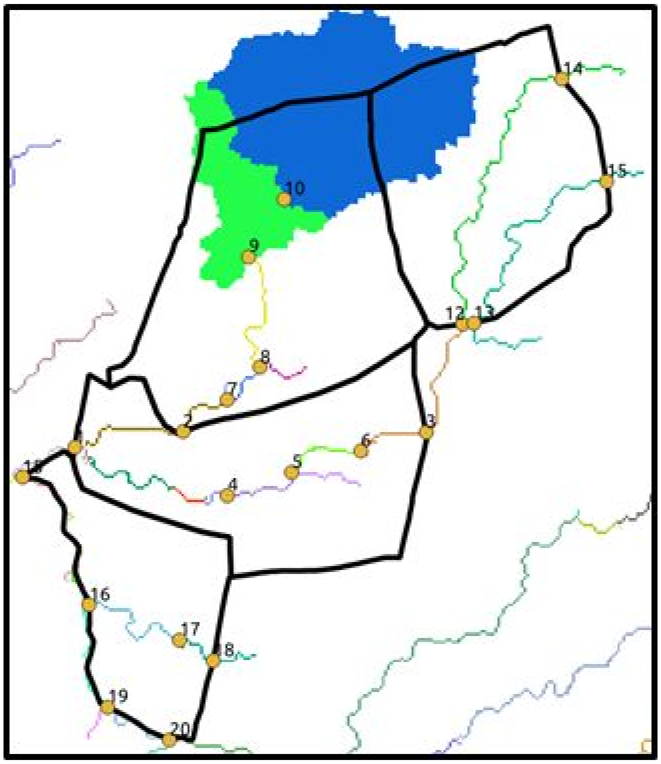


Figure 2 Differential watershed for point 9, 10

After delineating the differential watershed, the next step is to compute runoff in watershed using pocra water balance model and route that runoff through stream or channel network. Process for computing the channel water balance has been described below by taking an example of two micro watersheds. This can be easily extended to the whole village and cluster.

Channel water balance

We now outline a procedure of modeling the flow through this stream by a time-step simulation. This will help us in estimating various processes between farm-runoff and stream flows which leave the region, and also transmission losses which contribute to the groundwater regime. To achieve this, water budgets for the differential watersheds to be generated through PoCRA water balance process, i.e., through a geographical integration of pointwise water balance computations. Runoff generated will be routed through the identified stream of the differential watershed.

We shall now describe the simulation of a single stream segment or channel. Stream attributes/inputs required for routing are given below.

1. Channel length Lch.
2. Channel Top width when full ($W_{bnkfull}$)
3. Channel bottom width (W_{btm})

4. Channel depth when channel is full ($depth_{bnkfull}$)
5. Channel slope (Slpch)
6. Channel side slope(Z_{ch}:1, run to rise)
7. Effective hydraulic conductivity (Kch)
8. Manning's roughness coefficient (n)
9. $Coef_{ev}$ is the evaporation coefficient
10. fr_{trns} is the fraction of transmission losses
11. □bnk Bank flow recession constant

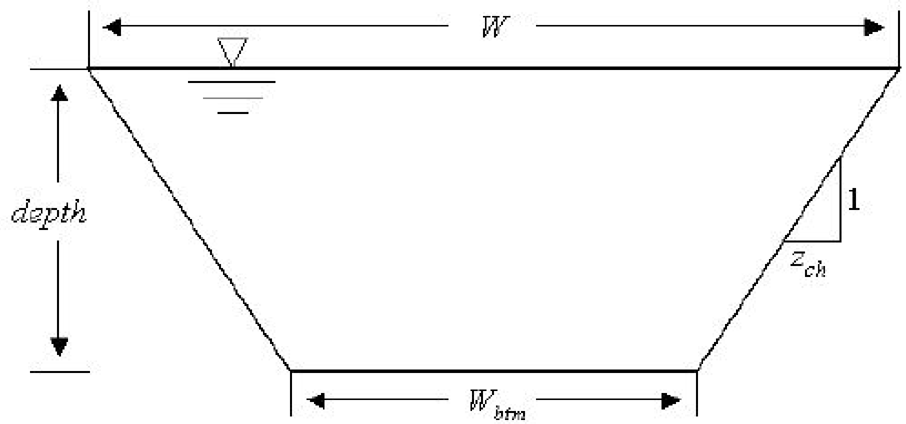


Figure 3 Channel cross section (swat theory, 2009)

Let us start with a differential watersheds for Lingdari micro watershed given in figure 5 below. Flow of equations, assumptions and process is described below and given in figure 4.

1. Certain channel parameters like channel lengths Lch, channel Top width when full ($W_{bnkfull}$) and channel depth when channel is full ($depth_{bnkfull}$) are extracted using Qgis. if user is aware of these parameters it can be used as input as well.
2. Initially, it is assumed that the side slope (run to rise ratio) is 2:1 or Z_{ch} =2.
3. From above bottom width of channel is computed.
4. For Lingdari watershed, at the beginning of first time step amount of water stored ($V_{stored,1}$) is set equal to the amount of runoff generated for that differential watershed + existing storage if any which is generally zero.
5. There is no inflow from the upstream, as no watershed upstream of Lingdari, Vin will be set equal to zero.
6. This water is routed into the channel and depth of water in the channel is calculated.
7. Once depth is known cross section area at water level, wetted perimeter and hydraulic radius are calculated.
8. Using manning's equation flow in the channel is computed.
9. $V_{out,2}$ at the end of time step will computed using the storage coefficient.

10. Various losses are computed and subtracted from the existing storage to get the net $V_{stored,2}$ storage in the channel at the end of time step.
11. $V_{stored,2}$ will act as $V_{stored,1}$ for the next time step and runoff generated from the watershed for the next time step will be added in to this to compute the Total $V_{stored,1}$
12. This total $V_{stored,1}$ will be used as volume to compute the new area of depth, hydraulic radius, wetted perimeter velocity etc.
13. $V_{out,2}$ will act as $V_{in,1}$ for the next stream segment.

In case of Gondala watershed same process will be followed with only difference being continuous inflow from Lingadari watershed. This means Vout of lingdari watershed will act as Vin of the Gondala watershed and will be added to channel existing storage to compute final storage for computing depth of water level.

Bottom width (m) is calculated using the equation given below when channel is full.

$W_{btm} = W_{bnkfull} - 2 * Z_{ch} * depth_{bnkfull}$

There is possibility that W_{btm} can be negative or zero when $Z_{ch} = 2$, during such scenario it is assumed that $W_{btm} = 0.5 * W_{full}$ and new value for the channel slope is calculated using the equation given below.

$Z_{ch} = (W_{bnkfull} - W_{btm})/(2*depth_{bnkfull})$

Once the side slope and bottom width are known we can compute the depth of the water level in the channel from volume of water (aggregated runoff) computed for the differential watershed. First we compute the area of cross section (m2) using the channel length (km) using below equation.

Ach = Volume in channel / Lch*1000

Volume in the channel (m3) is calculated by adding the runoff generated for the differential watershed to the volume stored at the end of time step of that channel. For the first time step volume stored will be equal to zero.

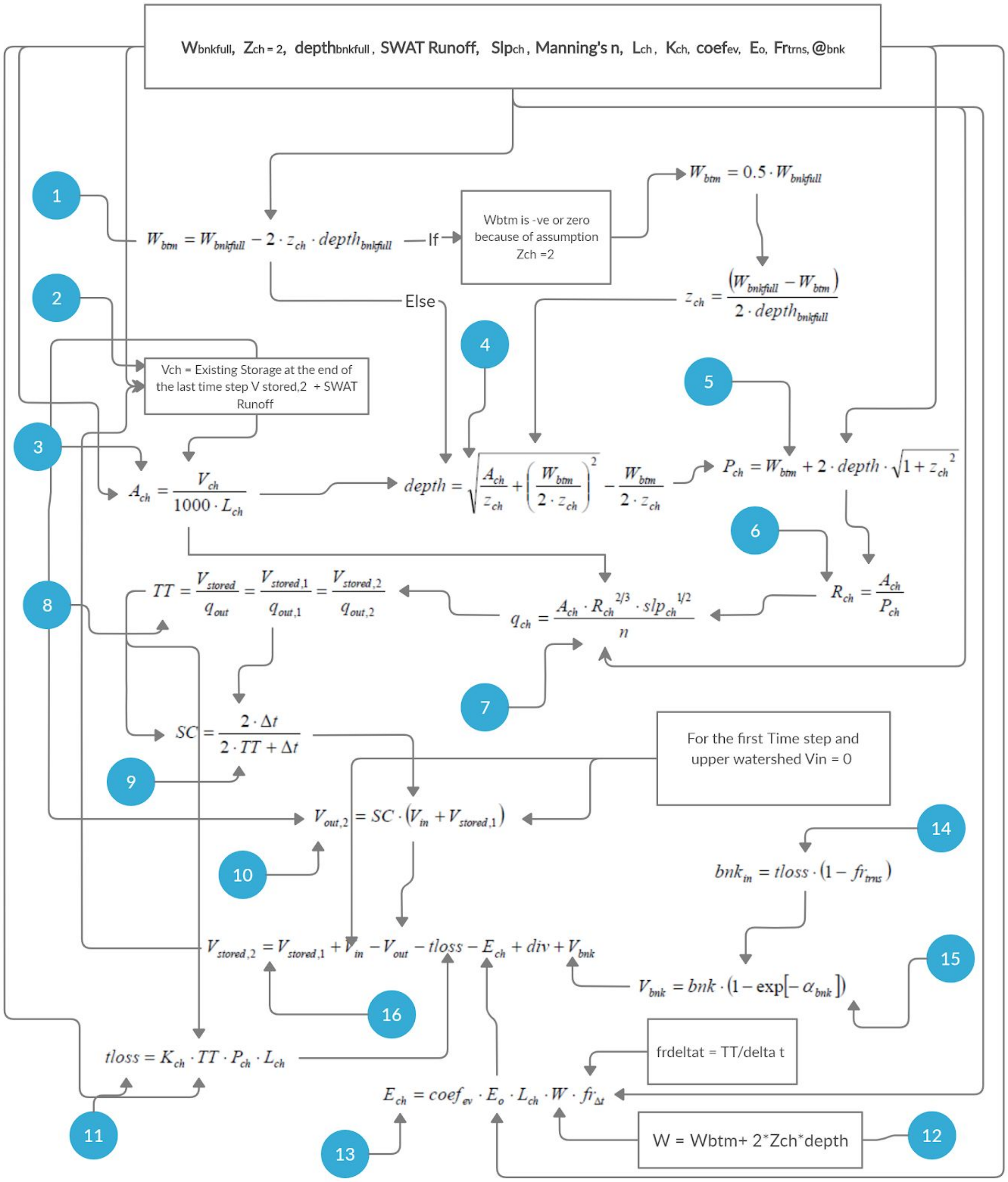


Figure 4 Channel water balance computing process

After computation of the cross section area depth (m) of the water in the channel, depth of water level can be computed using the equation given below.

$$depth = \sqrt{\frac{A_{ch}}{z_{ch}} + \left(\frac{W_{btm}}{2 \cdot z_{ch}}\right)^2} - \frac{W_{btm}}{2 \cdot z_{ch}}$$

Width of water level at computed depth in the channel can be computed using the equation given below.

Width of water (m) in the channel at computed depth = W_{btm} + 2 * Z_{ch} * depth

Pch is the wetted perimeter (m) at computed depth in a channel. Pch can be computed using the equation given below

$$P_{ch} = W_{btm} + 2 \cdot depth \cdot \sqrt{1 + z_{ch}^{2}}$$

Hydraulic radius Rch (m) for computed depth of flow can be computed using wetted area divided by wetted perimeter

Rch = Ach/Pch

Manning's equation for the uniform flow in the channel is used to compute the rate and velocity of flow in a reach segment for a given time step.

$$q_{ch} = \frac{A_{ch} \cdot R_{ch}^{2/3} \cdot slp_{ch}^{1/2}}{n}$$

$$v_{c} = \frac{R_{ch}^{2/3} \cdot slp_{ch}^{1/2}}{n}$$

q_{ch} is the flow rate (m3/s) in the channel and Vc is the flow velocity (m/s). n is the manning’s coefficient slpch is the channel slope (m/m).

For the given stream segment the storage routing is based upon the continuity equation

Vin -Vout = change in storage

Vin (m3) is the volume of the inflow during the time step and Vout is the volume of outflow during the time step or average of volume at the beginning and at the end of time step..

TT Travel time (s) is computed by dividing the volume of water in the channel by flow rate.

$$TT = \frac{V_{stored}}{q_{out}} = \frac{V_{stored,1}}{q_{out,1}} = \frac{V_{stored,2}}{q_{out,2}}$$

Where V stored,1 and V stored,2 are the storage volume at the beginning of time step and at end of time step. qout,1 and qout,2 are the flow rate at the beginning of time step and at the end of time step.

$$SC = \frac{2 \cdot \Delta t}{2 \cdot TT + \Delta t}$$

SC is the storage coefficient dependent upon travel time (s) and time step (s).

$$V_{out,2} = SC \cdot \left(V_{in} + V_{stored,1}\right)$$

Vout,2 (m3) is the amount of water going out of the stream channel at the end of time step. Vout,1 for the first time step is equal to the Vch which is volume stored in the channel.

Transmission Losses

It is possible for the stream to lose water from the side and bottom of the channel. This is known as transmission loss and can be calculated using.

$$tloss = K_{ch} \cdot TT \cdot P_{ch} \cdot L_{ch}$$

Tloss (m3) are the channel transmission losses and Kch (mm/hr)is the effective hydraulic conductivity (Lch km).

Evaporation Losses

$$E_{ch} = coef_{ev} \cdot E_o \cdot L_{ch} \cdot W \cdot fr_{\Delta t}$$

Where Ech (m3) is the evaporation from the stream, coefev is the evaporation coefficient, Eo is the potential evaporation (mm) Fr**Δ**t is the fraction of time step in which water is flowing and is calculated by dividing the travel time by length of time step.

Bank Storage

Amount of water entering the bank storage on a given day can be calculated using

$$bnk_{in} = tloss \cdot \left(1 - fr_{trns}\right)$$

Bnkin (m3) is the amount of water entering the bank storage. fr_{trns} is the fraction of transmission losses entering the deep aquifers.

Amount of water entering the stream from the bank storage is given by Vbnk (m3.

$$V_{bnk} = bnk \cdot \left(1 - \exp\left[-\alpha_{bnk}\right]\right)$$

Bnk is the total amount of water in the bank storage and α_{bnk} is the bank flow recession constant.

Channel water balance

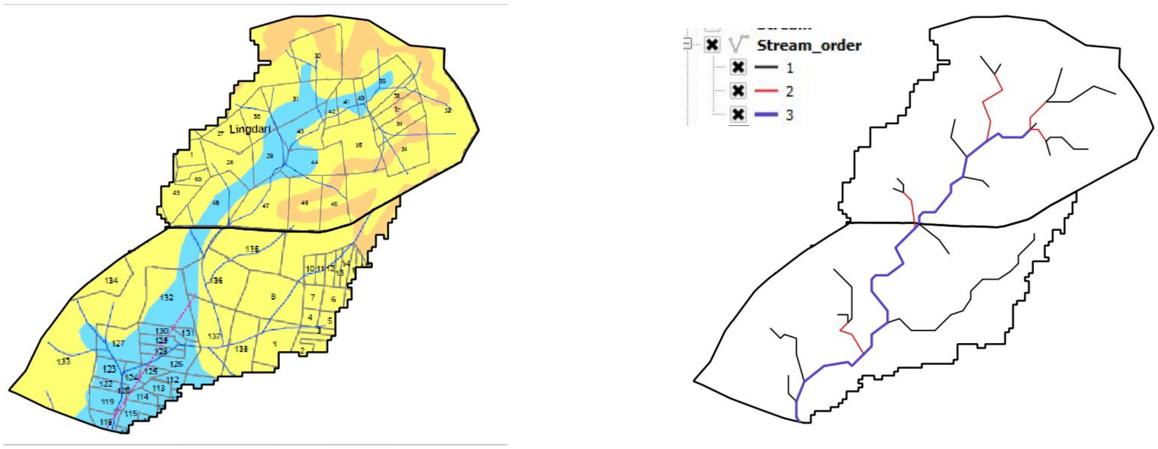
Water storage in the stream segment at the end of time step is computed using the

$$V_{stored,2} = V_{stored,1} + V_{in} - V_{out} - tloss - E_{ch} + div + V_{bnk}$$

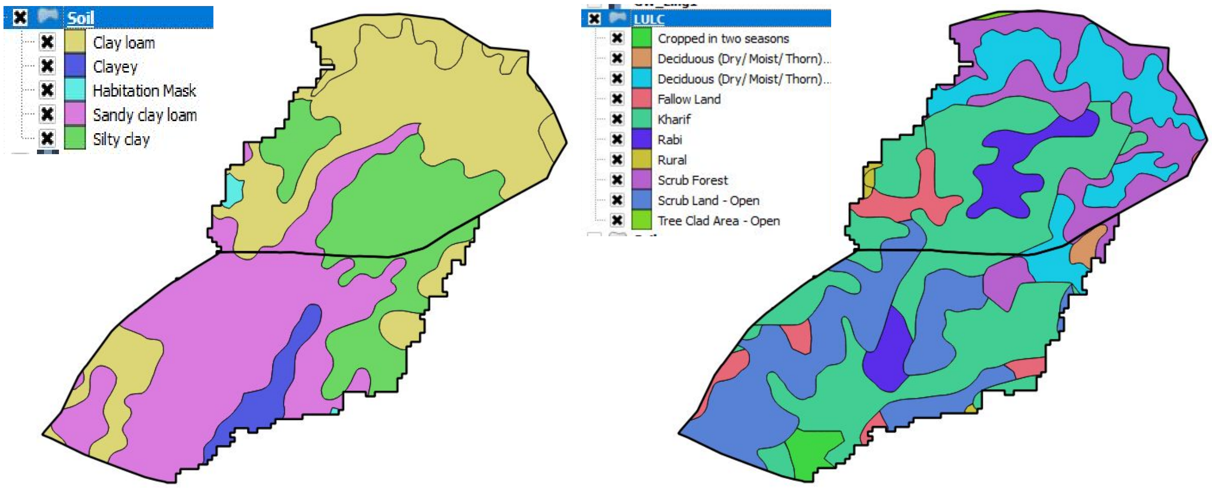
Where $V_{stored,2}$ (m3) is equal to the volume of water in the reach at the end of time step.

Case-Study - Lingadari - Gondala system.

Gondala cluster is located in Sengaon taluka of hingoli district. It falls in assured rainfall region with rainfall varying from 600mm - 800mm. The terrain of the of the cluster is highly undulating. Cluster has varying soil type dominated by sandy clay loam, silty loam, clay loam and depth varying from 0.1m to 1m deep. Main crops of the cluster are cotton, soyabean, tur and haldi.



Groundwater recharge priority map and stream order



Soil and LULC of the region

Some of the channel characteristics like length, width, area of micro watershed and stream network etc have been computed using the digital elevation model in QGIS and google earth. Hydraulic conductivity is taken from canal seepage losses given in GEC methodology. Manning’s coefficient has been taken from the literature. Value of recession constant and partitioning of transmission loses to deep aquifer has been assumed for the purpose of this simulation.

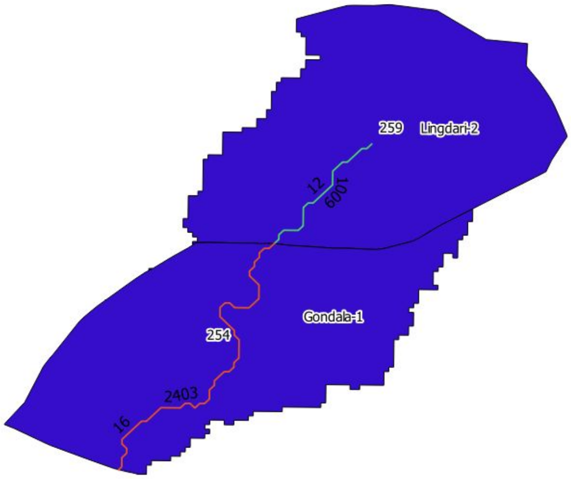


Figure 5 - Computing streamflow in microwatersteds of Lingdari and Gondala

Stream Characteristics

Sr No.	Constants	Lingdari stream	Gondala Stream
1	Full Depth (m) depthbnkfull	3	3
2	Full Width (m) Wbnkfull	14	18
3	Lenth (km) Lch	1	2.4
4	Zch	1	1
5	Slope Slpch	0.01	0.006
6	Bottom Width Wbtm	8	12
7	Watershed area (ha)	250	250
8	Hydraulic Conductivity Kch mm/hr	20	20
9	Manning's h	0.05	0.05
10	Evaporation Coefev	0.1	0.1
11	Bank flow recession αbnk	0.3	0.3
12	Fraction of transmission loses to deep aquifer Frtrns	0.7	0.7
13	time step sec DT	3600	3600
14	Eo (mm)	1	1

Result

Result of stream simulation shows that due to higher slope and narrow width in Lingdari micro watershed the farm runoff generated is quickly being removed from the streams and there are fewer transmission loses. Whereas, in case of Gondala micro watershed which is downstream of the lingdari, slope is less and there is inflow from the lingdari watershed, which leads to higher transmission loses. Transmission losses in Lingadari comes out to be 7 mm whereas in gondala it comes out to be 91mm. Due to this significant amount of water is available to farms in stream proximity areas and most of the wells are observed in the vicinity of streams only. Fraction of transmission loses to deep aquifer is 70% of the transmission loss and reaming is entering into the stream bank as storage. 30 % of this stream bank storage is returning back into the channel.

Table Results of stream flow

Sr No	Item	Lingdari (mm)	Gondala (mm)
1	Rainfall (2018)	674.5	674.5
2	Runoff	219	219
3	Transmission Loss	7	91
4	Bank In	2	28
5	return flow	0.5	7
6	V_out	212	348

Net groundwater availability in the Gondala micro-watershed has increased significantly from 40mm to 131mm after the incorporation of streamflow routing process into the existing water balance framework. The availability of runoff has increased after adding outflow from Lingadri micro watered Gondala micro watershed. This availability of extra runoff can be tapped to build storage structures as per the requirements of the farms and agriculture systems in the area while keeping in view the overall sustainability of the system.

Table Results of water balance after incorporation of streamflow (approximate)

Sr. No	Description	Lingdari before stream flow incorporation (mm)	Lingdari After (mm)	Gondala before stream flow incorporation(mm)	Gondala After (mm)
1	Rainfall (2018)	674.5	674.5	674.5	674.5
2	Runoff	219.0	219.0	219.0	431.0
3	Infiltration	455.0	462.0	455.0	546.0
4	SM	58.0	58.0	58.0	58.0
5	GW recharge	40.0	47.0	40.0	131.0
6	AET	357.0	357.0	357.0	357.0
7	PET (input)	450.0	450.0	450.0	450.0
8	Vout	0.0	212.0	0.0	348.0

References:

[1] Swapnil Patil, title “GIS based Tools for Watershed and Agriculture” , M.Tech thesis report, Computer Science and Engg., IIT Bombay, 2019.

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