POCRA Report on description of water balance framework
Oct 3, 2017
CTARA, IITB

1. Objective of the framework

The objective of this document is to describe the hydrological assessment framework which is being developed by CTARA IITB as part of its MoU with POCRA PMU. The requirement is to design a series of tools to help answer core questions of water availability assessment and water balance using both supply side analysis (surface water, soil moisture and ground water) as well as demand side analysis. The output of the framework will feed into the micro watershed-level climate resilient plans development for the targeted 500 micro watersheds of POCRA.

This document describes the selected model and provides the rationale and justification for the selected model vis-à-vis other alternatives and the model validation process that is being followed in the pilot watersheds.

2. The hydrological cycle and its components

Figure 1 shows the different components of water balance that are considered in the framework. The mini-watershed (POCRA cluster) is the unit of analysis for this water balance. The output is at the village level since village is the unit for microplanning. An important aspect of the water balance is that it considers both spatial and temporal differences. In other words, the framework takes cognizance of different land use pattern in the village (forest land, waste land, agricultural land etc.), different slopes and soil types, and accounts for each zone instead of an aggregated balance for the entire village. Additionally, it conducts a seasonal water balance, separating Kharif season balance from Rabi/summer balance.

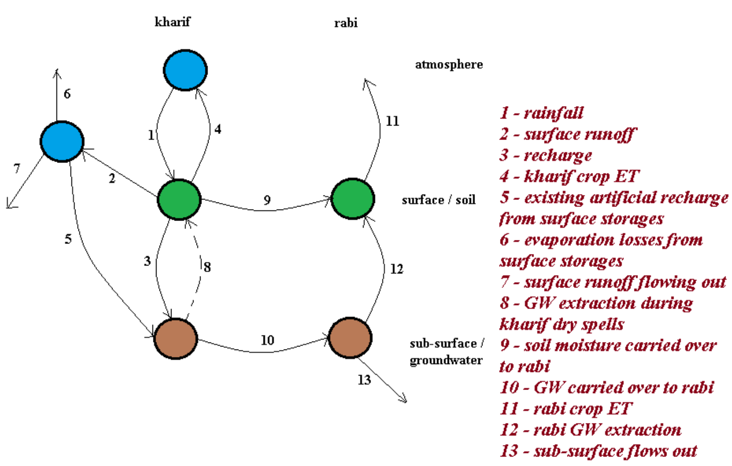


Figure 1: Various stocks and flows of the water balance

3. Key outputs

The two key outputs of the framework are (i) identifying Kharif vulnerable zones and stress mitigation and (ii) computing Rabi GW balance, i.e., estimating net ground water availability

A) Kharif vulnerability analysis:

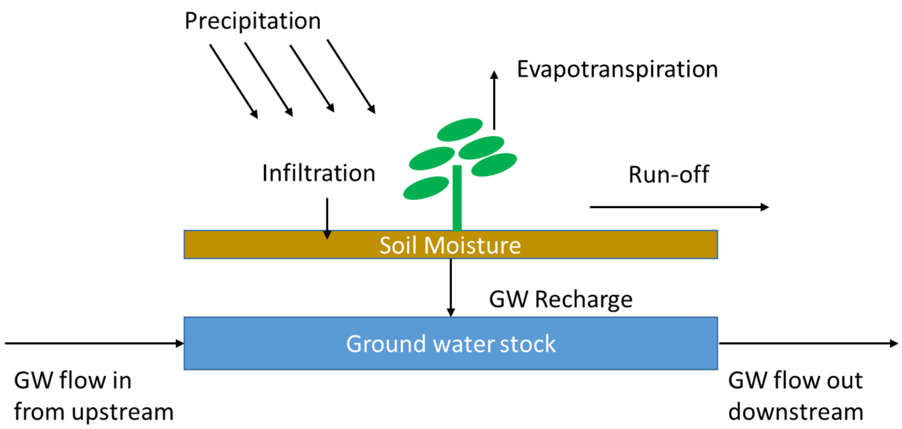


Figure 2: Components of Kharif balance

As Figure 2 shows, the main components of the water balance for Kharif season are: Precipitation, run-off, soil moisture content, crop evapotranspiration and ground water percolation. Based on the inputs of daily rainfall, LULC for the watershed, cropping pattern, soil texture, soil thickness and slope, this tool identifies Kharif stress zones within the agricultural farmland and computes the extent of crop stress as defined by the difference (in mm/day) between its potential evapotranspiration load and the actual evapotranspiration (PET minus AET). The Kharif stress zones are identified assuming a default cropping pattern that is standard for the region and not based on actual Kharif cropping pattern since that would reinforce existing conditions (social or material) in Kharif demand. This exercise will help identify which zone within the village are most impacted during Kharif dry spells and the estimated extent of protective irrigation that may be required depending on the rainfall pattern.

To compute the baseline Kharif water balance, actual spatial cropping pattern is used which is done using a spatial land use input file that differentiates between single cropped, double cropped and perennial cropped areas as separate zones.

B) Runoff analysis and Kharif deficit mitigation

The second aspect of Kharif balance is to compute the cumulative run-off in different zones (supply side) and compare it with the Kharif deficit (demand side) to see which zones may be able to meet the Kharif protective irrigation demand by impounding run-off through existing or new structures. This analysis will be done by computing the cumulative run-off at key points in the cluster and in each Kharif deficit zone and comparing with the Kharif deficit.

This may be matched against impounded run-off in existing structures and in the design of potential intervention locations and key points in streams. The cumulative run-off passing through these points will be compared with the amount of Kharif protective irrigation required in that zone. This will help the field team identify zones which are most likely to benefit from line treatment with respect to Kharif dry spell mitigation and to propose suitable structures.

C) Rabi groundwater balance by zone

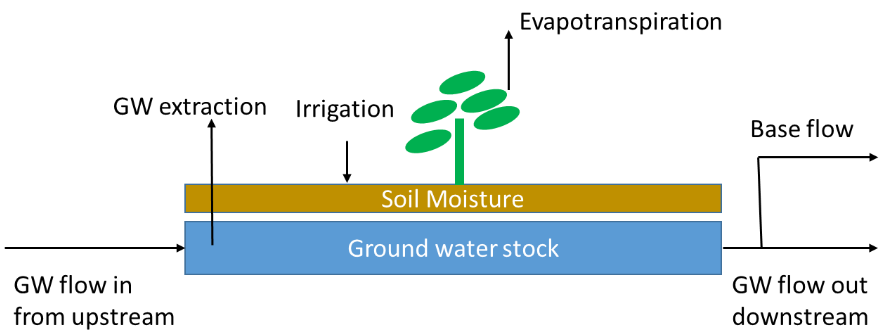


Figure 3: Components of Rabi water balance

Figure 3 shows the components of the Rabi water balance. Groundwater (GW) stock, which is built through recharge during the monsoon, plays a major role in Rabi. This stock varies depending on the geo-morphology and aquifer characteristics and the soil cover. Moreover, there is a base-flow, i.e., seepage of GW into streams (baseflow), GW flow in from upstream villages and flow out to downstream villages. Farmers extract groundwater during Rabi season and use it to irrigate their fields. The efficiency of application may vary based on the mode of application (flood, drip etc.). Hence, the correct estimation of groundwater stock available for Rabi is an important input to farmer and community decision-making.

This module will be used to compute the total groundwater stock available in different regions (a) at the end of Kharif season and (b) possibly, on a monthly basis thereafter. This, when compared with the evapotranspiration load of the cropping pattern will determine zones where there is over-extraction and zones which are net positive in terms of contribution to ground water. The inputs to this (in addition to those required Kharif balance) are spatial groundwater recharge during rainfall (to be computed in the Kharif balance), ground-water zones as defined by groundwater prospect and recharge priority map (Ref: GSDA), specific yield of aquifer, Rabi cropping pattern and the corresponding PET load. Note that extraction is accounted for indirectly by comparing available GW stock to crop ET load and assuming that the difference would be met by GW extraction where possible.

In summary, the key outputs of the hydrological framework are (A) Kharif dry spell vulnerable zones, (B) available run-off for stress mitigation and preferred zones for creation of new structures (C) Rabi groundwater availability with irrigation requirement for different zones within the village.

4. Recommended methodology

[A] The Kharif vulnerable zone model:

The Kharif vulnerable zone model consists of two steps:
[A1] to estimate various flows and crop water requirement at a given point on a daily basis during the Kharif growing season.
[A2] to compute and display stressed zones by aggregating the outputs of A1

The Kharif point model A1 is the core of the framework. Its role is to conduct a daily water balance for a point location with given soil properties and land use input. Given daily rainfall data, this tool models run-off, soil moisture level, actual crop evapotranspiration (AET) and groundwater percolation on a daily time-step. There are two classes of models which may be used for such a model. The first option is a ***step-wise model*** where first run-off is calculated, and then evapo-transpiration and then finally, groundwater infiltration. The second is a composite model where all are calculated at once with dependence on one-another. Most models differ in their input requirements and their focus on either of the flows. We have adopted a daily-composite model which is implemented as a spreadsheet and which is an adaptation of SWAT 2009 [Ref. Soil and Water Assessment Tool Theoretical Documentation 2009].

Some important differences with SWAT are as follows. First, unlike SWAT this is a simplified spreadsheet based model that can be run with data that is usually available (or can be collected) in the Indian context. Secondly, for the sake of simplicity the entire soil layer is considered as a single layer with homogenous properties [Ref: Downer 2007, Eilers et al 2007]. These properties are obtained from the MRSAC soil maps which are being validated against field samples in the pilot locations. Thirdly, the computation of the crop AET is limited to the root zone layer which is defined for each crop. It is assumed that moisture below the root zone is not accessible to the crop and water rise due to capillary action is ignored in the model. Also, lateral flows within the soil layer are also considered negligible and ignored in the proposed model.

Following is a description of how various flows are computed in the model A1 and comparison with some of the other approaches.

<u>Run-off calculation</u>
The Kharif model works at a daily time step. Daily rainfall input is given. A daily curve number

and retention factor is computed based on fixed parameters (soil HSG, slope and land-use type) and a variable parameter (soil moisture at the start of the day) [Ref: USDA TR-55, SWAT theoretical documentation 2009]. This is used to compute daily surface run-off. The methodology being used for run-off calculation is the SCS curve number method where in a daily curve number is computed based on the daily soil moisture levels. The methodology used is the same as that used by SWAT. The methodology also incorporates slope. There are many alternate approaches currently in use of which the Strange's table or the modified Strange's table ((dry-damp-wet method) are the simplest and widely used models in practice [Ref: Kudoli 2015]. The limitations of these methods is that they broadly consider three types of catchment area (good, medium, bad) and do not take specific parameters such as soil type, land use, slope profile etc. into account. The SCS Curve number methodology based on calculation of daily curve number is the preferred method used by standard softwares such as SWAT. They are applicable to Indian condition when we customise the input values for parameters such as soil profile (clay content, sand content, organic matter etc.), crop PET requirement etc. [Wagner 2011, MingXing 2010]

Crop evapotranspiration calculation

Once the run-off is calculated, the remaining water content infiltrates the soil. The actual crop evapotranspiration (AET) for the day is computed based on the available soil moisture at the start of the day and the crop's potential evapotranspiration (PET) requirement.

PET is the potential evapotranspiration load of the crop. There are many methods experimental as well as theoretical that are used to estimate the crop PET for a given crop and climate conditions. The Pan evaporation method is an experimental method used to calculate the evapotranspiration load of a reference crop (grass) under monitored climatic conditions. The Penman-Monteith equation uses daily temperature, humidity, radiation, wind speed etc [FAO paper No. 56]. The modified Penman method is one of the most commonly used theoretical methods. However, it is complicated to use because of the amount of data needed [FAO paper No. 56]. Instead, Blaney-Criddle is a simplified method which used only temperature and sunshine hours as input. However, this method too has its limitations and may not be too accurate. None of these methods appear to be a good approximation for the POCRA target districts. This is because the total crop ET load appears to be in excess of the crop ET load published by WALMI [Ref: WALMI 2009, WALMI 2005] for crops sown in Maharashtra.

Hence, our model is based on modified Blaney-Criddle method (altered to match WALMI crop ET load) which may be updated with experimental data when obtained through SAUs.

To calculate the AET, it is first assessed whether the crop is under water stressed conditions or not. A crop stress factor is calculated on a daily basis which is dependent on the soil moisture levels at the start of the day and soil properties of field capacity, wilting point and crop factors such as root zone depth and depletion factor. The standard methodology as described in the FAO crop evapotranspiration report is used to calculate AET [Ref: FAO Paper No. 56].

Percolation to ground water

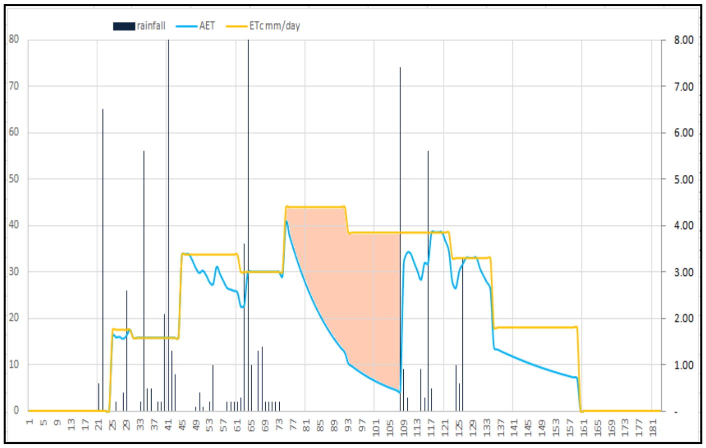
Percolation from the soil layer to the vadose zone is calculated at the end of each day based on the soil moisture level. There is no percolation if the soil moisture is below field capacity. If the soil moisture exceeds field capacity, then the amount of percolation depends on the water available for percolation (soil moisture – field capacity) and a percolation factor that is a function of soil conductivity. The method being used is as used by SWAT [SWAT theoretical documentation 2009]. The vadose zone is the unsaturated zone between the soil profile and the aquifer. For simplicity, this zone is not modelled. A time delay factor is used to estimate the change in ground water levels due to the water percolated from the soil layer.

The final soil moisture levels for the end of the day is calculated after accounting for increase due to any rainfall and decrease due to crop AET and percolation. The end-of-day soil moisture level is then considered as the start-of-day soil moisture for the following day. This exercise is repeated for the entire Kharif season. The output is daily soil moisture levels, crop AET and percolation to groundwater for the Kharif season.

Demarcation of stress zones by aggregation of output from A1

Once both PET and AET are available on a daily basis, the total daily stress is merely PET-AET, i.e., the daily *Kharif deficit*. This model is implemented both as a stand-alone spreadsheet as a python script in QGIS, a GIS system. In the QGIS version, various inputs to the model, such as soil texture, LULC etc., are assumed as available as suitable layers in the system. For A2, the Kharif deficit is aggregated for the whole monsoon season to compute the total excess water required (in mm) at the given field. These numbers are now computed at a regular sampling of the agricultural lands in the cluster and vulnerability zones are marked on a map. These are currently (i) <30mm,, (ii) 30-60mm, (iii)>60mm. These maps may be overlaid on revenue maps to identify the vulnerable farms and farmers which should be prioritised for any watershed intervention to ensure maximum impact.

Figure 4 shows a sample output. The graph shows circle rainfall (black bars), PET (yellow envelope) and calculated AET (blue). The gap between the yellow envelope and the blue envelope is the Kharif stress which is indicated by the solid colour. The second picture shows the spread of Kharif stress zones within Gondala cluster for year 2016. The darker the pixel, the higher is the vulnerability of the farms in the area (Note: Area not covered by pixels is non-agricultural land which is not evaluated for Kharif stress). The vulnerable zone map overlaid with farm survey numbers will be a key output of the hydrological framework.



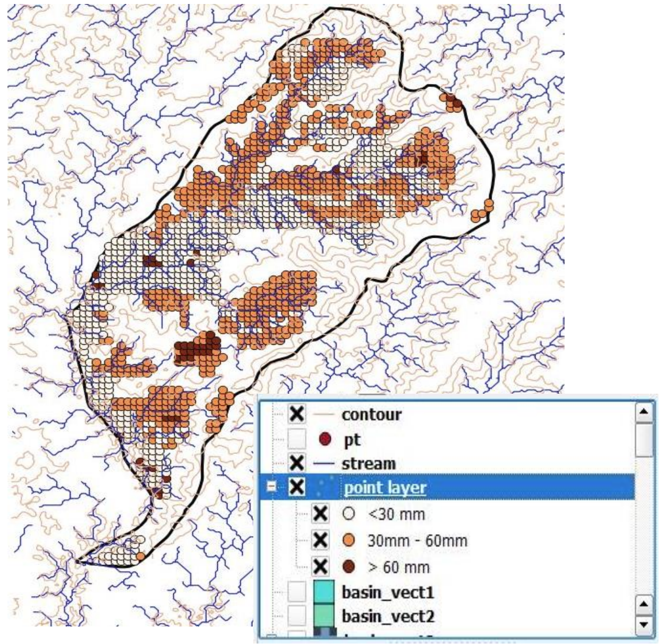


Figure 4: Daily PET, AET for a location and Gondala cluster vulnerability map

[B] The aggregated Kharif model:

The aggregated Kharif model for the watershed builds upon the point model described in previous section and has two steps
[B1] to develop an API to compute run-off at any point *p*
[B2] to select key locations and use B1 to compute run-off.

The GIS based watershed level model calculates the run-off generated from the Kharif point model for a regular grid of point locations within the watershed. Towards B1, the run-off calculation for a point *p* in the drain line is made by computing the watershed of *p*, and then aggregating the run-offs for the grid points lying in the watershed.

Towards B2 the points being selected for computing the available run-offs are (i) transit points of major streams across village boundaries, and (ii) transit points of minor streams across vulnerability zones. The scientific validity of the run-off model is based on the point-wise composite model A1 and elementary watershed ideas.

Figure 5 shows a sample output for the Gondala cluster. The graph shows the daily circle level rainfall. The map shows run-off calculations for two points of interest on the drainage line in Jamdaya. These points are on two important streams that meet in Jamdaya. The map shows the watershed (or catchment area) of each of the two points and computes the total run-off as well as peak run-off that will pass through these points for a given rainfall. This is an important output of the hydrological model which will be useful to estimate the potential to impound water beyond existing structures in different streams especially at points that may be close to Kharif stress zones.

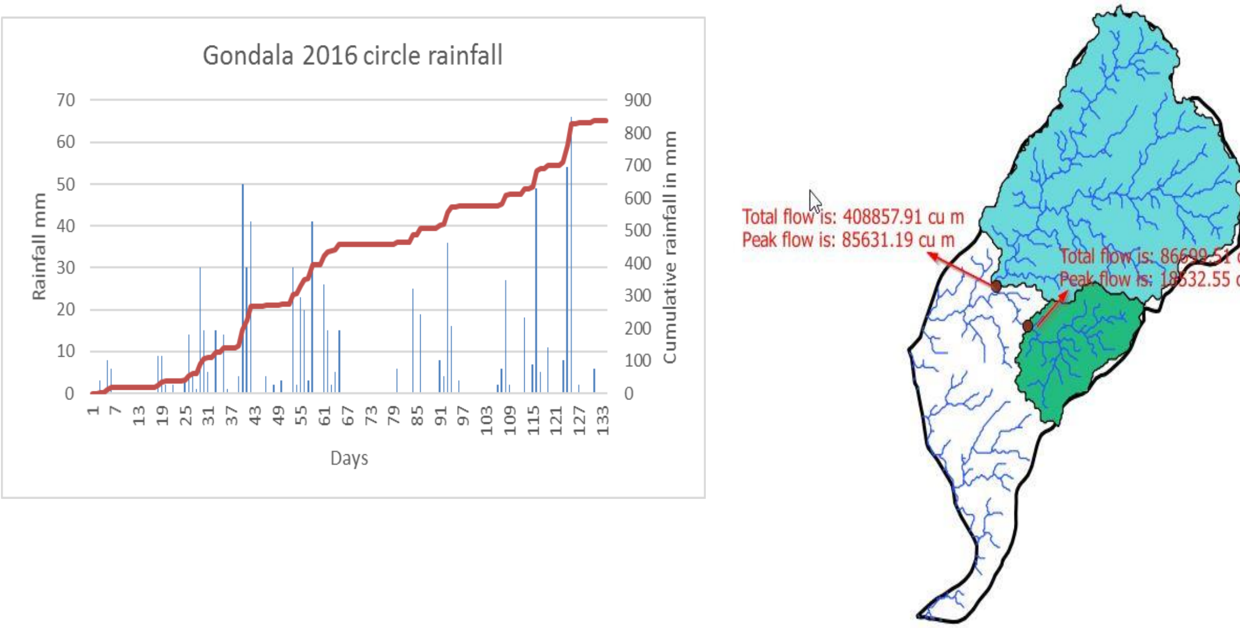


Figure 5: Daily Rainfall, cumulative run-off and Total and Maximum daily run-off and key locations.

[C] Rabi Groundwater model:

The objective of the groundwater model is to provide estimates of groundwater stocks and flows in a tabular form for various regions in the cluster and for different scenarios, e.g., of Rabi cropping intensity.

Each flow/stock or water level is estimated for the *region as a whole.* This has special implication in the water levels, which are assumed as representative in the region. The inputs to the estimation process are:
(i) Net infiltration to GW in Kharif season. This arises from model A1 and A2.
(ii) Planned Rabi cropping evapotranspiration load in mm. This may be computed by deciding the crop-mix to be taken and computing the net ET load.
(iii) Soil moisture available at the start of Rabi. This too is obtained from Part A.

The two outputs of the model are
(i) Estimated 1st October groundwater levels.
(ii) Estimated fall in groundwater level from 1st October to 1st June of subsequent year, assuming that is sustainable

An illustration is provided in Appendix A for Gondala cluster.

The Model

The stock/flow numbers will be calculated from GIS-coupled lumped model of interacting zones represented as cells (see e.g., [Wang]. Each cells will have certain key (i) scientific attributes such as mean elevation, aquifer thickness, specific yield, and (ii) transient values such as water table. Moreover, there will be adjacency relationships between cell *Ci* and *Cj*, to allow the computation of flows between them.

The methodology will be validated against MODFLOW [2017] a standard tool for simulating saturated flows. The cluster will be modelled as a single domain with a single aquifer layer with homogenous specific yield and hydraulic conductivity. These values will be sourced from state agencies such as GSDA or WALMI or from literature. The aquifer depth will be used from field data. The model will be simulated as two stress periods, the Kharif and the post-Kharif (i.e., Rabi). The cluster is assumed to be a watershed and the boundary conditions will be posed accordingly, i.e., a no-flow condition for all points except at the exit, which would be modeled as a known-head. Drains will match the specified drainage layer obtained from MRSAC and the base-flows will be computed as water which exits through the drains. Rabi cropping will be assumed as uniform throughout the region and modeled as a known discharge for that region.

The validation of the model requires two GIS layers which are awaited. These are (i) detailed LULC, with Kharif, Long-Kharif, Rabi and Summer, as well as Fallow, Scrub, Open Forest and Dense Forest, and for good and bad year rainfall to estimate cropping zones, and (ii) Groundwater recharge priority and prospect spatial maps, to validate the output and the use of groundwater for Rabi.

4. Operational procedure

This section details out the recommended process on how the proposed water budget may be made operational in the field and feed into the micro watershed planning.

No	Activity	Agency	Input	Outcome
1	Organising library of all secondary data for the cluster (various spatial files, rainfall data etc.)	PMU-IT	Checklist of datasets and maps and years to be selected	A ready-to-use library of required files for each cluster
2	Generation of basic maps for all villages in the cluster and handover of maps to field agency	PMU-IT	Secondary data and spatial files	a. Basic maps with layers such as: Cluster boundary, Village boundary,

				Streams, Contour lines/ slope b. Kharif vulnerable zones (tentative) based on a default PET c. Demarcation of zones from where data needs to be collected during field visit
3	Microplanning exercise in the field: data collection using templates provided (two types of data will be collected: one required as data input and the other required as reference for validation of model output)	Field agency	a. Templates for data collection(e.g. cropping pattern, existing watershed structures etc) b. Demarcation of zones from where data needs to be collected during field visit and sampling methodology	Field survey data and measurements. Actual and potential Kharif, Long Kharif, Rabi and Summer zones.
4	Plugging in primary data as input into the model and executing the models. Hand off model output to field agency	PMU-IT	Field data from field agency (preferably in electronic format)	Model outputs for the cluster: a. Kharif vulnerable zone maps b. available run-off at key points c. GW stock for Rabi
5	Validation of model output	Field agency	Model output such as Kharif vulnerable zones, peak run-off, GW levels at the start of Rabi	Validated model output and/or corrections.
6	Participatory Micro watershed development	Field agency	Validated model output	Microwatershed plans which

			a. Kharif vulnerable zones and farms b. Run-off in various streams esp. interaction with neighbouring villages c. Rabi sustainable cropping pattern scenario options	propose interventions that address vulnerable zones within village and estimate of run-off potential for each zone
7	Approval of plans	PMU	Microwatershed plans for each cluster	Approved plans
8	Model support and continuous fine-tuning	CTARA	Feedback from PMU-IT and field level staff	

5. Next steps and Improvements

The following are the immediate next steps:

a. Refinement of GW model (Part C)

Incorporation of long Kharif and separating rabi with summer. Better coupling of part-A with infiltration and soil moisture specification in ground water model. Simplifying MODFLOW into standardized thumbnail simulation and there implementation scripts.

b. Refinements of Soil moisture, Infiltration and Run-off modules.

[Part A1] Validation of forests and non-agricultural lands into point wise estimation processes.
[Part A2] Incorporation into regional and temporal aggregation modules. Preparing both modules in release forms.

c. Validation of models against field measurements and surveys. A validation process has been designed and partly executed during field trip to Hingoli and Jalna cluster in mid-September. Validation with other three clusters is to be initiated.

d. Creation of templates for microplanning and data collection and discussion with Yashada to finalize theses templates. This will involve understanding their crop and intervention planning modules and customizing water balance outputs.

e. Procurement of LULC and other Maps. Preparing secondary data validation report on maps data as well as agriculture data.

f. Creation of User Manuals for the models.

Appendix A: Rabi groundwater balance illustration

The Rabi groundwater model is best explained in the following table for the Gondala cluster. Here we assume conductivity K=1.2 m/d and specific yield =0 (which will be validated with support from GSDA). Note that Lingadari sits above Gondala which sits above Jamdaya.

Conventions

The hydrological year is divided into two periods - the Kharif period of 123 days starting on 1st June and the post-Kharif or Rabi season of 242 days, starting on 1st October. All numbers are in mm except water levels, which are in mbgl (meters below ground level). The stock and flow levels are the net changes in the given period. Thus, for example, TD-K is the amount of water lost (in mm) to downstream zones via groundwater flows throughout the Kharif period.

Symbol	Zone	Lingdari Village (262 Ha.)	Gondala Village (1037 Ha.)	Jamdaya village (958 Ha.)
	Elevation (msl)	486	461	437
Assumptions. Sy=0.03, K=1.2, starting average Rabi soil moisture =120mm.				
Kharif				
I-K*	**Infiltration to GW**	**180**	**182**	**179**
FU-K	GW From Upstream	0	12	14
GW-K	Change in GW stock	116	112	114
TD-K	GW To Downstream	35	13	3
TBF-K	GW To Baseflows	28	68	50
TBDRY-K	GW To Boundary	0	0	25
EWL-KE#	**Estimated increase in WL (m)**	**3.86**	**3.73**	**3.8**
Rabi				
GW-R	Change in GW stock	-116	-112	-114
FU-R	GW From Upstream	0	20	25
C-R	***Rabi Crop****	**34**	**64**	**67**
TD-R	GW To Downstream	62	24	6
TBF-R	GW To Baseflows	20	45	29
TBDRY-R	GW To Boundary	0	0	40
WL-KE#	**Estimated Rabi Ending GW level**			
EWL-KE	Actual Year-Ending level	*x*	*y*	*z*

Table 1: Sample GW Model Output for Gondala Cluster

Interpreting the Table.

(i) It is clear that I-K > G-K > C-R which states that (a) the Rabi utilization must be less than the rise in groundwater stock in Kharif and (b) this in turn, must be less than the total infiltration.

(ii) We call the fraction (C-R)/(I-K + FU-K - TD-K – TBF-K – TBDRY-K) as the ***Rabi Utilization Fraction RUF***. This is essentially the fraction of available GW stock that is extracted by farmers for irrigating their Rabi crop. The RUF determines peak groundwater stocks, operating groundwater levels and stream flows and is a critical parameter of the system. As RUF rises and approaches 1, one or more of the following conditions arise. See Figure 6 below.

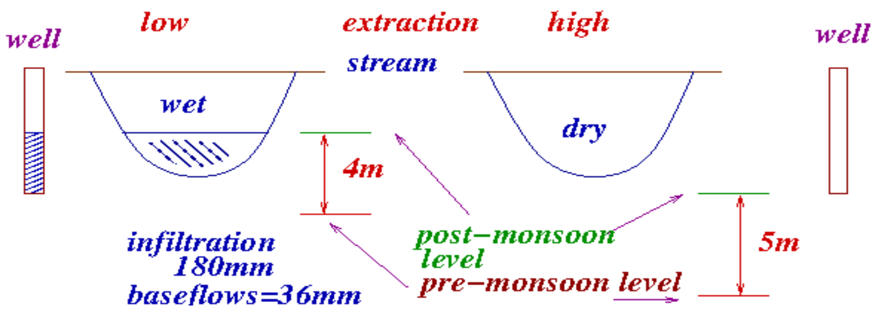


Figure 6: Comparison of low and high extraction regimes .

(a) the system is unsustainable, i.e., does not maintain year-end groundwater levels,
(b) the overall variations in GW levels become large and the wells operate at a much lower levels. This may impact stream flows.
(c) This may impact the access to GW by all farmers during Rabi.
(d) Overall lower levels at the year-end will impact initial moisture content at start of Kharif and access to groundwater for Kharif protective irrigation.

The optimum value for RUF depends on the local geography and must ascertained by a survey of farmers who (i) have access to wells for Rabi, and (ii) the well depth at start of Rabi and (iii) if their wells are deeper than the predicted well levels at the end of Rabi.

Consider for example, when Jamdaya increases its Rabi average PET requirement from 64mm to 134 mm. We then obtain the diagram below with wells G1, G2 in Gondala and J1, J2 in Jamdaya, where G1 and J1 are close to streams and G2 and J2 are farther away. The well levels are obtained from MODFLOW are also shown below in Figure 7.

Upstream Gondala Village *Downstream Jamdaya Village*

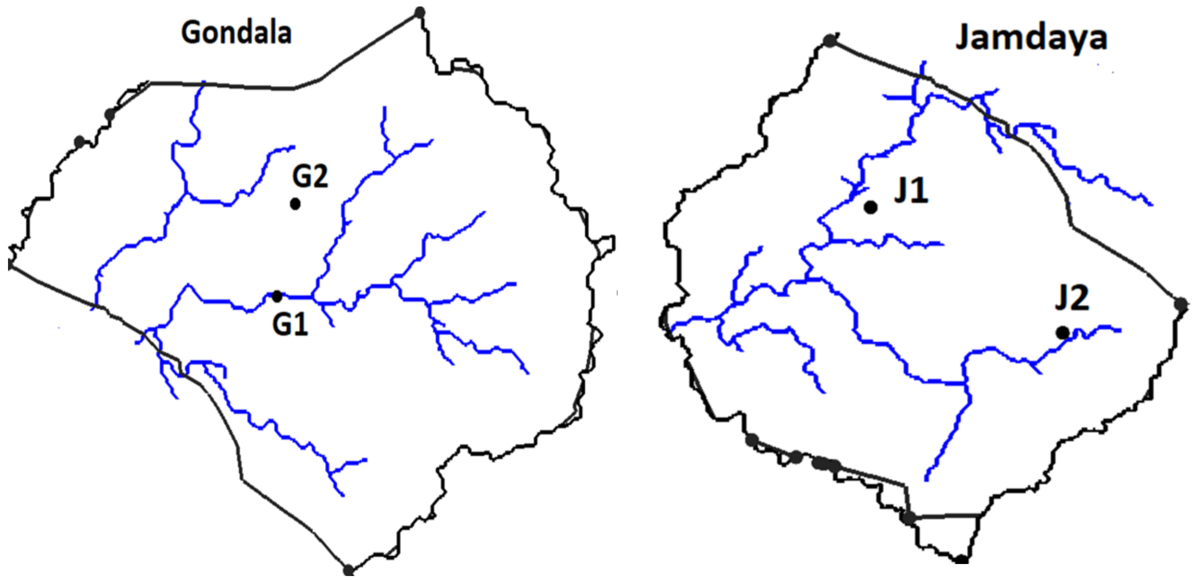


Figure 7: Well locations in Jamdaya and Gondala in the Gondala cluster.

		Scenario1 (low extraction)		Scenario2 (high extraction)	
Wells	**Elevation**	Pre-monsoon MBGL	Post-monsoon MBGL	Pre-monsoon MBGL	Post-monsoon MBGL
G1	**460.2**	3.6	2.2	3.9	2.4
G2	**472-484**	10	5.5	13	8.5
J1	**442**	2.9	1.2	4.6	1.2
J2	**462.5**	7	3.1	7.7	3.7

Table 2: Well levels obtained from MODFLOW for locations in Jamdaya and Gondala in the Gondala cluster.

Thus the use and interpretation of the model requires a field procedure which (i) marks existing and proposed Rabi areas, and (ii) well depths and well levels in the above areas. The validation must include actual measurements of well-depths and water levels at the start and the end of the monsoons. The exact field procedure is to be designed in consultation with the field agency

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