Using Technology to Ensure Ground Water Safety and Security in Tribal Blocks of Maharashtra:

A tool kit for developing a decision support tool on planning drought mitigation measures

Groundwater Survey and Development Agency, Pune

&

Institute for Resource Analysis and Policy, Hyderabad

In Collaboration with

UNICEF, Mumbai

January 23, 2015

Contents

1. Introduction

In Maharashtra, ground water is the main source of drinking water in rural areas. The tribal population in the state depends on hand pumps or dug wells for meeting their domestic water needs and these sources dry up in peak summer. Situation is worse during droughts, when monsoon fails. When scarcity hits, the poor communities compromise their personal hygiene requirements to meet their productive water needs.

In Maharashtra, the Groundwater Survey and Development Agency (GSDA) undertakes the water level monitoring quarterly in 1531 watersheds to produce data on depth to water levels in wells and their seasonal fluctuations. Based on these data, the renewable groundwater resources available during the monsoon months in each one of the watershed is estimated. The existing monitoring system and the assessment methodology are not robust enough to capture all the real peak and troughs of the water levels in wells, and the dynamic situation with respect to water availability in drinking water sources across the seasons. At best, they show the aggregate recharge occurring in watersheds and depth to water levels.

In fact, the recharge assessment carried out periodically shows that very few watersheds in Maharashtra experience groundwater over-exploitation. But, in reality, hundreds of thousands of wells (agro wells and drinking water sources) have gone dry during the past 10-15 years in the state due to sharp seasonal drawdowns in water levels.

High monsoon rainfall or large quantum of recharge during monsoon does not ensure year round water availability in wells for domestic uses. In sum, there is no direct correlation between rainfall occurrence and groundwater availability and drought occurrence in a watershed. Therefore, drought forecasting cannot be made based on simplistic considerations of data on water level in wells and estimates of renewable groundwater availability in the watersheds, and instead should involve complex considerations.

There are many reasons for this. *First:* the ground water withdrawal for agriculture from aquifers is very high in semi-arid regions, as the demand for water in irrigated agriculture far exceeds water demand for domestic uses in every village and groundwater is the primary source of water to meet various needs in semi-arid areas. *Second*: the ground water withdrawal for agriculture can change remarkably between a wet year and a dry year, as both the seasonal water demands and water availability can change dynamically between such typical rainfall years. *Third*: there is natural outflow of groundwater from shallow aquifers, and this is significant in hilly areas with hard rock formations and this is altered by withdrawals, due to which water level trends in wells in such regions are quite dynamic and complex, and there are limits on utilizable recharge induced by the geo-hydrological setting of an area.

In order to integrate these complex considerations in assessing droughts and water scarcity, it is proposed to correlate the historical data for selected locations in a block of Chandrapur district on the following: rainfall magnitude and pattern; runoff/stream flows, including lean season flows; depth to water levels in wells during different seasons; pre-post monsoon fluctuation in water levels in wells; the cropping pattern & cropped areas (in different seasons); and occurrence of droughts in terms of intensity and extent. The outcomes of this analysis can be applied to the data obtained from real time monitoring of precipitation and water levels in observation wells to improve the predictability of ‘drought occurrence’ and ‘emergence of drinking water shortage’.

The innovation seeks to improve the predictability of quantity and quality of water in drinking water supply wells and droughts, using data on rainfall, groundwater levels and cropping patterns. As a result, it will provide real time information on the condition of groundwater in the villages.

2. The Decision Support Tool

The decision support tool is based on a series of mathematical models (relationships) established between: the rainfall characteristics (amount of annual rainfall, number of rainy days, and onset of monsoon): rainfall and other hydrological processes and outcomes (runoff, monsoon recharge, total infiltration and utilizable groundwater recharge in the aquifer); and annual rainfall and condition of groundwater in terms of summer water levels, socio-economic outcomes such as cropping intensity and irrigation intensity and drought occurrence in terms of villages affected by water scarcity.

The models can predict the following: the probability of occurrence of meteorological droughts in a particular year, based on date of arrival of monsoon. Further, based on data of rainfall and water level fluctuations in wells during monsoon, it can estimate: the quantity of groundwater in the aquifer which is utilizable from annual precipitation; runoff from the catchment; base flows, including lean season flows; and predict cropping and irrigation intensities, the intensity of droughts in terms of number of villages likely to be affected by droughts, and summer water levels in wells.

3. About the Tool Kit

This toolkit lays down the important empirical analyses that are required to be carried out and the manner and sequence in which they should be performed to develop a decision support tool (DST) for predicting the quantum of utilizable groundwater resources and drinking water scarcity situation in a region, based on real time monitoring of the daily rainfall and pre-post monsoon ground water levels. The process of development of the DST has been validated for a block, viz., Jiwati of Chandrapur district of Maharashtra, which is hilly and underlain by hard rock geology. The tool kit however does not describe the various models which are part of the DST, as the models are specific to the region studied, i.e., Jiwati block of Chandrapur. For a new region, a new set of modes/tool will have to be developed to simulate the physical and socio-economic processes there, but using the process discussed in this document. The decision support tool, thus developed, can help better management of groundwater resources locally for drinking water security.

Where the tool kit can be applied?

The web based DST, as explained in this tool kit, was developed for a block (Jiwati) in Chandrapur district. The geographical area of the block is about 505 sq. km, comprising a forest area of about 254 sq. km. The average rainfall in the block is 1131.2 mm with maximum and minimum temperatures of 45^{o} C and 30^{o} C respectively.

As is the agro-climatic and geomorphological setting in the Jiwati block, the application of tool kit can be most relevant in regions having:

1] Hilly areas with hot sub-humid to semi-arid climate;
2] Mixed soil type mostly covered with black soil;
3] Hard rock aquifers with groundwater as the major source of water supply for both domestic and productive uses; and,
4] Majority of the crops grown under rain-fed conditions

Who can use this tool-kit?

The tool kit can serve a wide range of stakeholders. At the highest level, it can be used by the State Water Resources Department to be prepared with drought-management plans in case there is a likelihood of its occurrence based on the outputs generated using the DST. Various line agencies in the water sector such as Groundwater Survey and Development Agency (GSDA) and Maharashtra Jeevan Pradhikaran (MJP) can use it for the better planning of the rural water supply schemes. At the local level, various departments under Zilla Panchayat can use it for exploring alternate sources of water for domestic supplies and suggesting cropping pattern to farmers, especially during drought years. Informed farmers can also decide on cropping pattern for winter based on the rainfall conditions.

How to use the tool kit?

The tool kit can work like this. It can use the data obtained from real time monitoring on the 'date of monsoon arrival' obtained to predict incidence of droughts, i.e., estimating the probability of occurrence of a meteorological drought in that year. Using the data on groundwater level fluctuations during monsoon, again obtained from real time monitoring, another tool will estimate the monsoon recharge, using the data on specific yield of the aquifer. Based on the data on monsoon rainfall, different tools would perform the following: estimation of runoff (using the regression model established for the catchment), gross infiltration using the mathematical relationship between rainfall and gross infiltration worked out for the catchment; total base flow and utilizable groundwater recharge using the runoff data and the base flow coefficient derived for the catchment corresponding to the annual rainfall. The other set of tools in the kit will predict the socio-economic outcomes such as cropping and irrigation intensities based on the annual rainfall of the year; intensity of droughts in terms of number of villages likely to be affected; and summer water levels in wells.

4. Important STEPS

STEP 1: Establishing relationship between annual rainfall and rainy days

As a first step, a regression analysis can be undertaken to ascertain the nature of relationship between the 'annual rainfall' (dependent variable) with change in the number of rainy days (independent variable) or vice versa. This analysis is useful to examine whether changes in number of rainy days significantly affect the intensity of precipitation. Data on daily rainfall for at least 30-40 years will be required. A direct relationship between the two would mean that increase or decrease in number of rainy days does not influence the average precipitation intensity. It will be better if the data used for such analysis is available from 2-3 rain gauges for the selected region for a period of at least 30 years, owing to the spatial variation in quantum of rainfall and rainy days across India, including Maharashtra.

STEP 2: Assessing the probability of occurrence of rainfall of different magnitudes

In next step, using the time series data of annual rainfall, rainfall probability curve is plotted which can be used to find out the minimum amount of annual rainfall that can occur with different degrees of probability (say, 50%, 75%, 90%), or vice versa. In order to assess this, data of average annual rainfall for 30-40 years from 2-3 locations is arranged in descending order and for each rainfall the probability of occurrence of rainfall equal to and above that magnitude (referred to as probability of exceedance) is estimated and plotted in a graph. The assumption here is that the lowest rainfall has the highest probability of occurrence. An example to assess the rainfall probability is presented in Table 1.

Table 1: Illustration to assess rainfall probability

Year	*Rainfall (mm)*	*Year*	*Rainfall arranged in descending order*	*Rank*	*Probability of occurrence of such rainfall [Rank/(Total number of observations+1)]*
2000	850	2005	1000	1	Solve [1/(6+1)]
2001	750	2003	950	2	Solve [2/(6+1)]
2002	900	2002	900	3	Solve [3/(6+1)]
2003	950	2000	850	4	Solve [4/(6+1)]
2004	800	2004	800	5	Solve [5/(6+1)]
2005	1000	2001	750	6	Solve [6/(6+1)]

The analysis can be carried out for either point rainfall of different gauging stations or for weighted average of the rainfall for each year.

STEP 3: Estimation of Standard precipitation Index (SPI) and drought frequency analysis

The standard precipitation index (SPI) is a measure of the intensity of drought in a region, which is the order of magnitude by which the rainfall departs from the mean value measured in terms of the number of standard deviations. It is useful when there is significant spatial variation in rainfall in a region. Daily rainfall data for 30-40 years (better if available for 50 years) is required for estimating yearly SPI. For transformation of the precipitation value in to SPI, software available at the following webpage can be downloaded and used as per the instructions in the manual:

http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx

Depending upon the SPI value, a rainfall event can be categorised as per the classification presented in Table 2.

Table 2: Classification of rainfall event as per the SPI values

SPI Values	*Classification*
2.0+	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2 and less	Extremely dry

Thereafter, the probability of occurrence of droughts of different intensities can be estimated by the SPI probability curve. For this, estimated SPI values should be arranged in ascending order and the probability of SPI value below that magnitude (referred to as probability of non-exceedance) is estimated (as done for the rainfall probability curve) and plotted in a chart. Here, the assumption is that both the wettest year and the driest year have the lowest probability of occurrence.

STEP 4: Generating the well hydrograph

This graphical representation is important to understand the season wise groundwater behaviour and the probable factors that can influence the net groundwater balance. For preparing the well hydrograph, data on depth to groundwater level for 30-40 years from 2-3 open wells and bore wells can be used. While the open wells generally reflect water level trends in the shallow weathered zone, which they tap, the bore wells would reflect the groundwater trends in the deeper strata. Generally, in hard rock regions with very low porosity and specific yield, the water level fluctuations during monsoon will be much steeper than that of alluvial areas having high porosity and specific yield, for the same magnitude of monsoon rainfall.

STEP 5: Establishing relationship between rainfall and water level fluctuations in open wells and bore wells

This step is important to establish change in groundwater availability with change in annual rainfall. For this, a regression analysis needs to be performed between the average annual rainfall (independent variable) and average change in depth to water level (water level fluctuation) in wells (dependent variable) between pre (usually May) and post (usually October) monsoon. Data on annual rainfall for 30-40 years from 2-3 rain gauge stations and data on depth to groundwater level for 30-40 years from 2-3 open wells and bore wells under observation is required.

One important point to take note of is that in hilly hard rock areas, the water level fluctuations in open wells may be less sensitive to the rainfall. This could be due to the fact that groundwater outflows from shallow aquifers (which the open wells tap) during the monsoon season is very significant. Further, the summer water levels may also remain steady irrespective of the rainfall magnitude. This is probably due to the reason that in good years, the natural discharge increase with increase in magnitude of rainfall, and the limited residual storage in the aquifer gets fully depleted in both good and bad years.

STEP 6: Estimation of total rainfall infiltration and utilizable recharge from rainfall

As explained in STEP 5, water level fluctuation in wells during monsoon and the net monsoon recharge could not be predicted using rainfall data owing to the tenuous relationship between the two in hilly, hard rock areas. Therefore, indirect methods have to be employed for estimating utilizable recharge. A hydrological parameter, which fully depends on rainfall magnitude, is total infiltration, and therefore can be predicted using rainfall figures. From this, utilizable recharge during monsoon can be estimated as per the following equation:

$$TI = NR_m + TGD \qquad (1)$$

Where, TI stands for total infiltration; NR_m is the net recharge during monsoon and TGD is the total groundwater discharge (base flow).

TGD can be estimated by multiplying total runoff by the base flow coefficient (ratio of base flow and runoff) corresponding to each rainfall. For this, 25-30 years data on: stream flows during monsoon and non-monsoon; and average annual rainfall for the catchment is required. Also, observed runoff and base flow values for different quantum of rainfall for a larger gauged catchment in the same region or for a topographically similar catchment from another region needs to be used so as to work out the base flow coefficient for each quantum of rainfall.

While the runoff coefficient (K_r) is found to increase with rainfall magnitude, the base flow coefficient (K_u) is found to reduce, though the absolute value of the base flow increases. Hence, the base flow coefficient can keep changing with the annual rainfall.

Now for estimating total infiltration, base flow during monsoon (BF_M) and net groundwater recharge (NGR) is required. For this, data on depth to groundwater level during pre and post monsoon seasons (25-30 years); specific yield of the aquifer; and total area of the selected catchment are used. The BF_M can be obtained by subtracting the lean season stream flows (which are actually base flow during the non-monsoon period) from the estimated TGD. NGR is calculated using the following equation:

$$NGR = WLF \text{ X } S_y \text{ X } A \tag{2}$$

Where, *WLF* stands for groundwater level fluctuation (as estimated in STEP 5); *Sy* is the specific yield of the aquifer; and *A* is the area of the selected catchment.

Thereafter, total infiltration is estimated as a sum of BF_M and NGR. TI can then be estimated using equation 1. Prediction of total infiltration for future rainfall can also be made by using the relationship established between total infiltration (dependent variable) and average annual rainfall (independent variable).

STEP 7: Prediction of Utilizable Recharge

In order to predict the utilizable recharge from future rainfall events, rainfall-runoff model can be developed using average annual rainfall and run off data for the selected catchment. Here, the runoff should be the 'virgin flows', instead of observed stream flow at gauging stations, in order to factor out the effect of various impoundments in the catchment. Using this 'rainfall-runoff model', the annual runoff for known values of future rainfalls could be estimated. From the estimated values of runoff, the total groundwater discharge/outflow could be estimated using the 'base flow coefficient' determined on the basis of annual rainfall. The net utilizable recharge can then be estimated by subtracting the total groundwater outflow from the 'total infiltration', the latter to be deduced from the regression model linking 'annual rainfall with total infiltration'. Table 3 provide a detailed process for predicting the net utilizable recharge.

Table 3: Prediction of utilizable recharge using rainfall

Average Annual Rainfall (mm)	*Annual Runoff (MCM)*	*Gross Infiltration (MCM)*	*Base flow Coefficient*	*Total base flow (MCM)*	*Utilizable Groundwater Recharge (MCM)*
A	**B**	**C**	**D**	**E**	**F**
Observed rainfall value from the rain gauge	Estimated using rainfall-runoff model	Estimated using relationship between annual rainfall and total rainfall infiltration (explained in STEP 6)	Ratio of base flow to runoff for similar catchment	(B X D)	(C – E)

STEP 8: Prediction of the Cropping and Irrigation Intensity Trends from Measures Values of Rainfall

First of all a regression has to be run between cropping intensity (dependent variable) and average annual rainfall (independent variable); and irrigation intensity (dependable variable) and average annual rainfall (independent variable). Generally, regions which lack adequate irrigation infrastructure, especially those which involve transfer of water from water-rich regions, the crop production will be heavily dependent on the monsoon performance. Once these models are established, they can be used to predict cropping and irrigation intensity for future rainfall events.

For this analysis, 30-40 years data on cropped area (CA); net sown area (NSA); gross irrigated area (GIA); and annual rainfall from 2-3 rain gauge stations are required. Cropping Intensity (CI) and Irrigation intensity (II) can be calculated using the following equations:

$$CI = \frac{CA}{NSA}\ X\ 100 \qquad (3)$$

$$II = \frac{GIA}{NSA}\ X\ 100 \qquad (4)$$

STEP 9: Prediction of the Occurrence of Meteorological Droughts

For this step, as a first step, the probability curve is established for early arrival of monsoon in each year, to estimate the probability of monsoon arriving on the normal date or with different days of delay or for early arrival of monsoon.

As the next step, analysis is carried out to examine whether relationship exists between the 'No. of days of delay in the onset of monsoon from the normal date of arrival' (independent variable)[1] and the 'extend of departure of monsoon rainfall from the normal value' (dependable variable) in percentage terms. The results can be used to predict extent to which the monsoon rains would depart from the normal values (+/-) or assess the probability obtaining a normal monsoon or deficit monsoon or a surplus monsoon, with a one day or one week delay in the onset of monsoon using the real time data on the 'date of on-set of monsoon'.

Also, a relationship between 'departure of onset of monsoon from the normal date' and 'SPI' can be established to ascertain the nature of precipitation (surplus rainfall or deficit rain) that can occur with early or late arrival of monsoon, with some degree of probability, and its intensity.

Data on daily rainfall for at least 30-40 years will be required, which would also help us determine the date of arrival of monsoon in each year. It will be better if the data is available from 2-3 rain gauges in the selected region. Normal date of arrival of monsoon is considered as one during which first rainy day (i.e., rainfall > 2.5 mm) is

[1] Negative values will be used if there is early arrival of monsoon, and positive values for delayed arrival of monsoon.

recorded for most number of times. Normal annual value of rainfall will be its mean over 30-40 years.

STEP 10: Prediction of Summer Water levels and Drinking Water Scarcity based on Known Trends in Rainfall

For predicting summer water levels, a mathematical relationship is established between annual average rainfall (independent variable) and depth to groundwater level during summer (dependent variable). Using the model outputs, summer water level can be predicted for a given value of rainfall in future. However, it is important to note that the model is not very robust, as rainfall explains summer water levels by only 41%. As is evident, there are many factors other than annual rainfall which explains the summer water levels, which include the natural discharge of groundwater and abstraction during winter and summer months. For this, 30-40 years of data is required on: depth to groundwater level during summer months from 2-3 observation wells; and observed rainfall values from 2-3 locations in the selected region.

Similarly for drinking water scarcity, relationship needs to be established between departure of annual rainfall from the normal in terms of number of days and value (independent variables) and number of villages affected by drinking water scarcity during summers (dependent variable). Using the model outputs, drinking water scarcity in terms of no of villages affected by drinking water shortage during summers can be estimated from the real time data on the 'date of on-set of monsoon'. Departure of rainfall from the normal in terms of value can be estimated using the model developed in STEP 9. 30-40 years data is required on: no of villages affected by drinking water shortage in summers; and the observed daily rainfall for the region.

Further, frequency analysis showing extent of drinking water scarcity with change in rainfall (as % of normal) can also be prepared (please refer to Table 4). Departure of annual rainfall from the normal (in %) should be subtracted from 100% to arrive at rainfall as % of normal.

Table 4: Frequency analysis format to show change in no. of affected villages with increase in rainfall magnitude

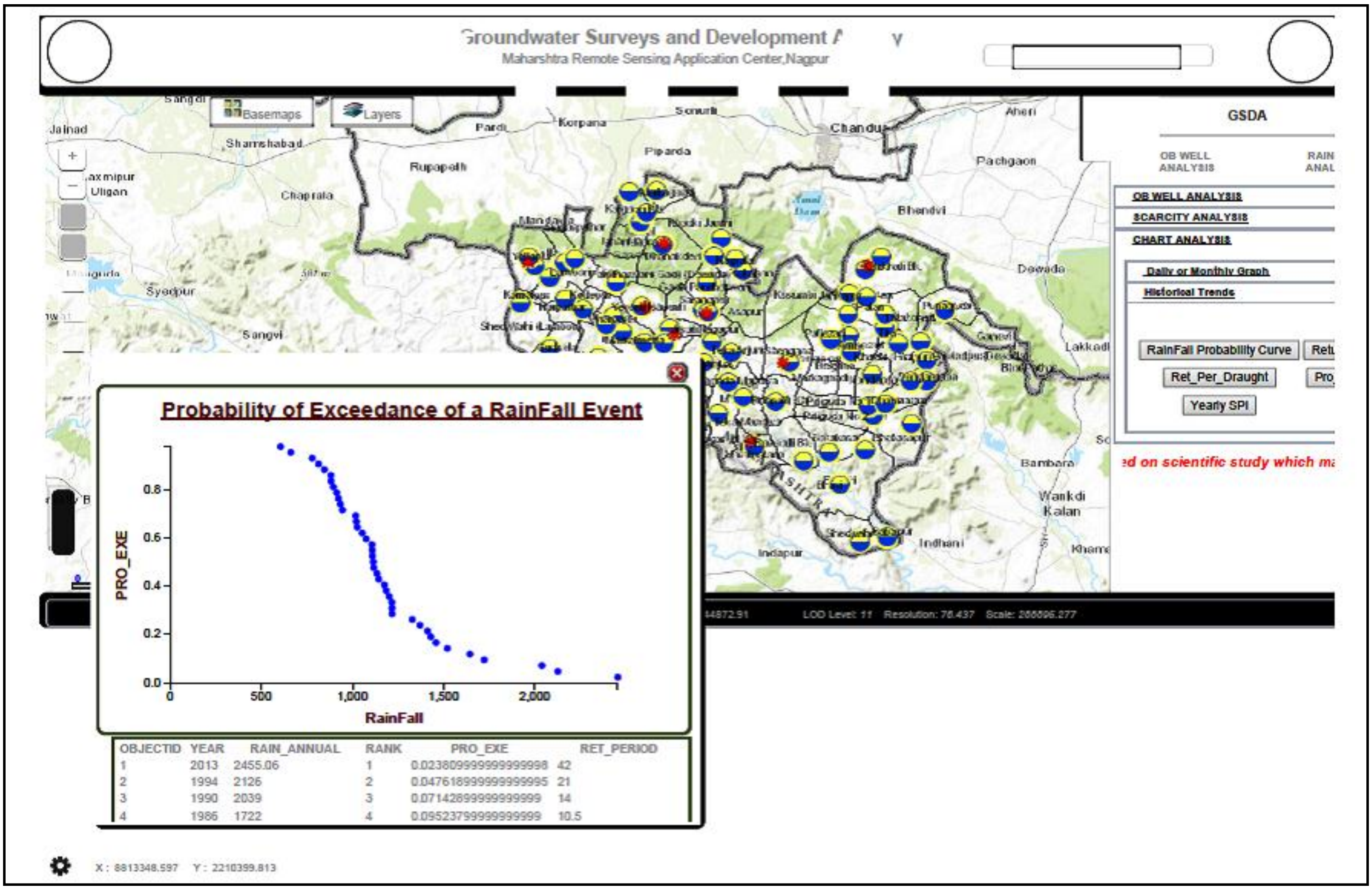
Rainfall as % of normal	*Avg. no. of villages with drinking water scarcity*
Less than 55%	
55-80%	
80-120%	

STEP 11: Estimation of Groundwater Discharge during Lean Season

This will require a use of the real time groundwater monitoring which will provide figures of water level fluctuations. These figures can be used to estimate the net monsoon recharge using equation (2). The gross infiltration during monsoon can be obtained using the model established in STEP 6. The difference between the two will give the groundwater outflow during monsoon (gross infiltration minus net recharge). The total groundwater outflow can be estimated from the annual runoff estimates using the 'base flow coefficient', determined on the basis of rainfall (STEP 7). The difference between 'total base flow/total groundwater outflow' and the outflow or discharge during the monsoon would yield estimates of 'lean season flow' in the streams.

STEP 12: Development of a web based decision support tool

The web based platform for prediction of drinking water scarcity and droughts in the selected region would use a Decision Support Tool, and will be based on real time monitoring of rainfall and groundwater levels in the selected region. The web-based programme can have three distinct features: Analysis and interpretation of historical data (as illustrated in STEP 1 to 4); computation of hydrological outcomes used for water supply planning using mathematical models (illustrated in STEP 5, 6 and parts of STEP 7 to 10); and prediction of hydrological and socio-economic outcomes (illustrated in STEP 7 to 11), which can help forecast droughts and drinking water scarcity, using a set of mathematical models, which define the relationship between various physical processes



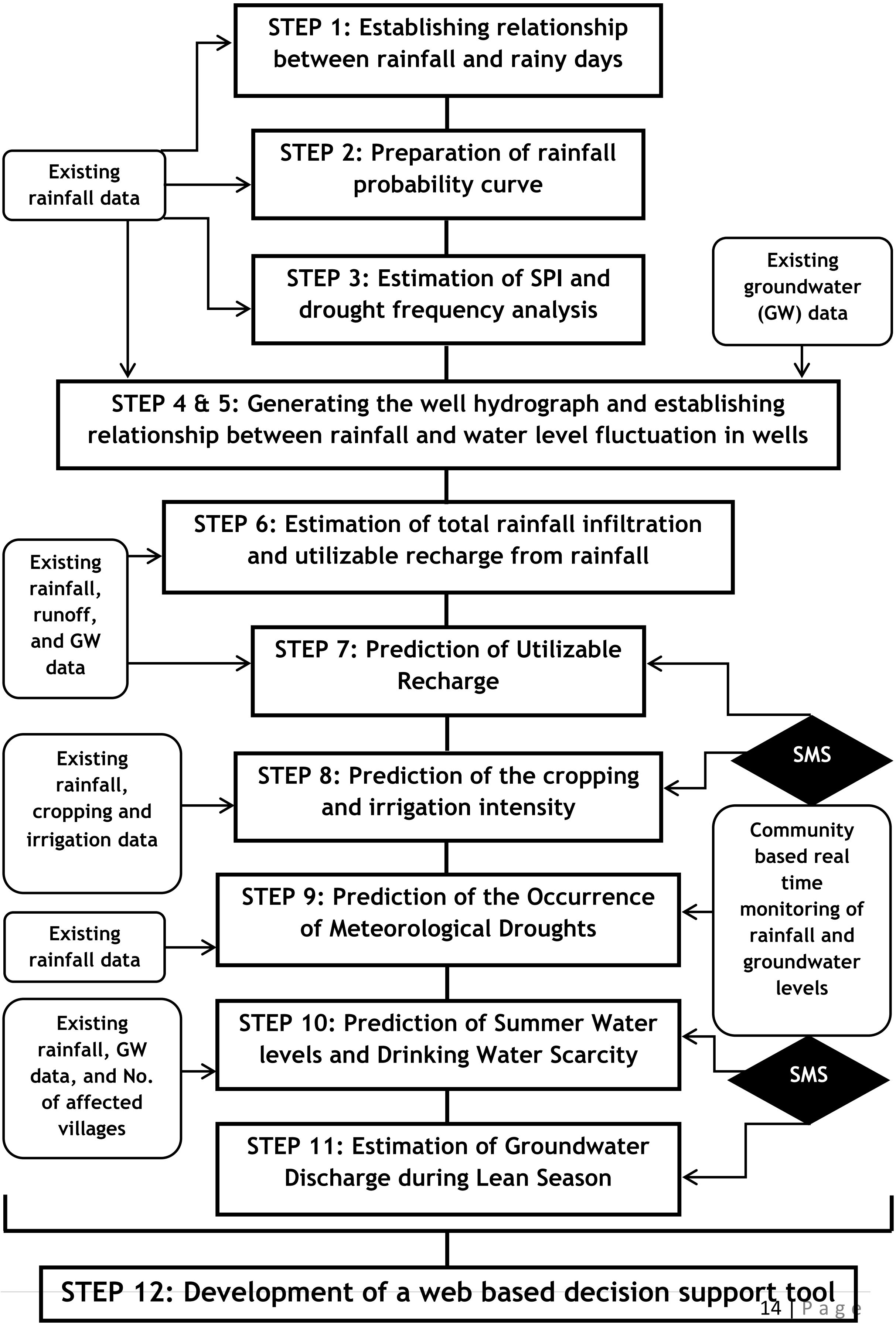
OBJECTID	YEAR	RAIN_ANNUAL	RANK	PRO_EXE	RET_PERIOD
1	2013	2455.06	1	0.0238099999999998	42
2	1994	2126	2	0.0476189999999995	21
3	1990	2039	3	0.0714289999999999	14
4	1986	1722	4	0.0952379999999999	10.5

and physical processes and their socio-economic outcomes (please refer to Figure 1).

Figure 1: Snapshot of a web based decision support tool under development for Jiwati block, Maharashtra

The entire task of real time monitoring can involve local communities to make it efficient and cost effective. The proposed system envisages periodic collection of relevant data on rainfall and predetermined indicators illustrating status of groundwater in terms of quantity. For rainfall, daily recordings are required, whereas for groundwater, recording can be done every fortnightly. The data collection could be at the village level and be communicated periodically by 'SMS' technology to a central node for further tabulation and analysis for prediction of groundwater availability and quality situation, and probability of occurrence of droughts and summer scarcity. This will help inform the existing decision makers for a more proactive response to ensure ground water safety and security.

5. Summary of key steps



6. Timeline for Setting up the Web-based DST for a Catchment

Sr. No.	Activities	Time period (month)					
		1st	2nd	3rd	4th	5th	6th
1	Assessment of water situation in the selected catchment through discussion with community and local government agencies						
2	Identification of rain-gauging stations; stream gauging sites; and wells under observation						
3	Training of village level volunteers for collection of data on rainfall and ground levels						
4	Collection of historical data on daily rainfall, stream flows, groundwater level, cropping pattern, no of villages affected by summer water scarcity etc.						
5	Data processing						
6	Analysis and interpretation of historical data						
7	Establishment of various mathematical models[2]						
8	Development of a web-based programme to predict various hydrological and socio-economic outcomes of hydrological events						
9	Monitoring of daily rainfall and groundwater levels by representatives of village community						
10	Transmission of data from real time monitoring to the web based programme						
11	Prediction of droughts and drinking water scarcity						

[2] To simulate the physical and socio-economic processes relating to water availability and water scarcity