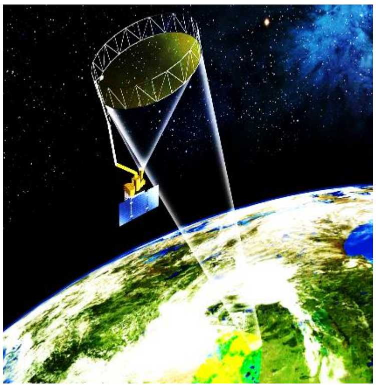
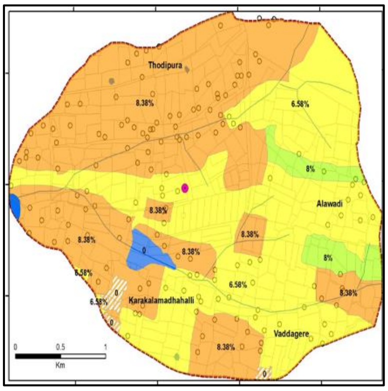
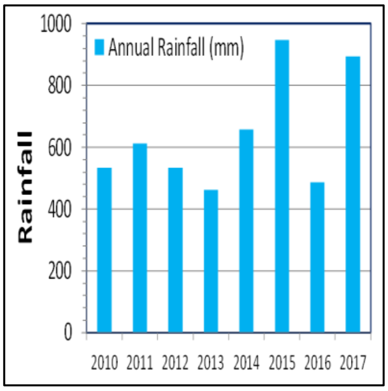
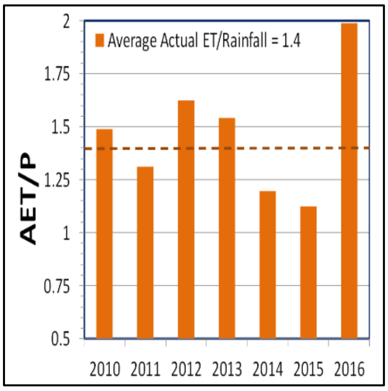
Draft Manual and Field Guide for Hydrological Activities

for the World Bank funded
Rejuvenating Watersheds for Agricultural Resilience through Innovative Development (REWARD) project









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Acronyms

AET	:	Actual Evapotranspiration
AMS	:	Agro-Meteorological Station
AMS		Agro-Meteorological Station
AWS		Automatic weather station
BM		Ground biomass
DGW		Depth tom Ground Water
DO		Dissolved Oxygen
EC		Electrical Conductivity
ET		Evapotranspiration
LAI	:	Leaf Area Index
PET	:	Potential Evapotranspiration
REWARD	:	Rejuvenating Watersheds for Agricultural Resilience through Innovative Development
RMSE		Root mean square error
SM		Soil moisture
SMAP		Soil Moisture Active Passive
SSM	:	Surface Soil Moisture
SSM		Surface soil moisture
STICS		Simulateur mulTIdiscplinaire pour les Cultures Standard
SWAP		Soil-Water-Atmosphere-Plant
SWAP		Soil Water Atmosphere Plant
TDR		Time Domain Reflectometer
WCM		Water cloud model

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1 Introduction

1.1 Preamble

Integrated hydrological assessment & monitoring, which is a component of Sujala III project focuses on detailed studies involving hydrological data gathering, behavior mapping & processes understanding in 14 selected pilot micro-watersheds located in 11 semi-arid and water stressed districts of Karnataka states.

The objective is that hydrological monitoring aided by advanced hydrological data & customized models developed under this project will aid in producing hydrological budgets at relatively higher temporal frequency (e.g., weekly/monthly) and also at the desired spatial granularity in small micro watersheds, for improved sustainable water management.

This manual is the outcome these studies. The lessons learned from the above-mentioned studies are generalized such as a ready reference for the future studies of similar nature, especially those which shall be commissioned under the World Bank funded REWARD program.

1.2 Importance of Agro-hydrological Monitoring

Agro-hydrology can be regarded as the study of hydrological processes and the collection of hydrological data, aimed at increasing the efficiency of crop production, largely by providing beneficial soil moisture conditions. However, the influences on the production of runoff and the ways that runoff affects the environment within which crops grow are very diverse and agro-hydrological study, of necessity, also includes the collection of information on climate, soils, vegetation and topography. Rainfall amount and its spatial and temporal distributions determine the quantity of water that reaches the land's surface. Temperature and humidity, the type, amount and distribution of vegetation cover determine what proportion of this water re-evaporates. Vegetation, soil conditions and topography determine how much water infiltrates into the soil, how much runs off the land's surface and where it goes. It is the interaction of these complex processes and the volumes of runoff that these processes produce that form the core research of agro-hydrology. Knowledge of the hydrological environment is necessary to determine whether or not opportunities to create optimal soil moisture conditions exist, and how these opportunities can be exploited.

The elements of agro-hydrology which is monitored/measured in experimental watershed include the following:

- Soil moisture (surface and profile)
- River levels and flows (runoff), and lake and reservoir levels
- Groundwater levels
- Evapotranspiration
- Water quality (chemical and physical) of surface water and groundwater

- Canopy variables (LAI, Biomass, crop yield, crop management activities)
- Weather variables (Rainfall, temperature, wind speed, relative humidity etc.)

1.3 Objectives

The objective of this manual is to provide guidance for the monitoring/measurements of hydrological variables. All the variables measured/monitored are explained in terms of the instrument used, operating principle, technical information, protocol for use in the field and example of application of the monitored variable. This manual is intended for the following purposes:

- To prepare hydrologic atlas for different watershed/sub-watersheds.
- To bring the homogeneity in the field data.
- To calibrate instruments.
- To make routine maintenance.
- To transfer the field knowledge among various persons involved in the field campaigns.

1.4 Suggested Approach of Developing the Hydrologic Atlas

In the watersheds, measurements of various soil and land use related information is being carried out and the information is available in Land Resource Inventory (LRI) atlas for each watershed. However, the LRI atlas does not have information on the dynamic information related to hydrology. Information required for a hydrological atlas can be estimated through the a) hydrological modelling, or b) hydrological measurements.

Hydrological model requires model parameters which are unknown or have uncertainty resulting in the uncertainty in the model outputs. On the other hand, hydrological measurements are time consuming, labor intensive and expensive.

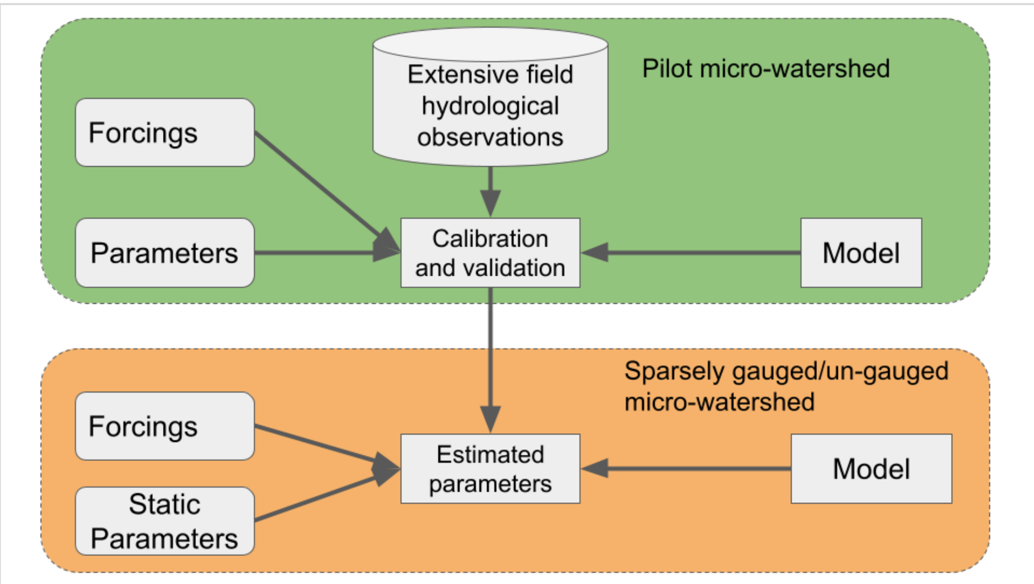

Figure 1-1: Suggested Approach to Estimate the Hydrological Information Required for Preparing the Atlas

In order to prepare the hydrological atlas, a combined approach (see Figure 1-1) is suggested. In this approach, hydrological measurements are carried out in pilot micro-watersheds. Hydrological modeling is also performed in these pilot micro-watersheds and the measurements are used to calibrate and validate the models. These calibrated/validated models along with the estimated parameters are to be used in the similar hydrological conditions to perform the hydrological modelling and estimate the required hydrological information to prepare the hydrological atlas.

1.5 Organization of the Manual

This manual is organized into four chapters and one annexure. In Chapter 1, context, objectives and overall approach adopted for the manual are described. In Chapter 2, various field measurement techniques are described. Procedures and methodology for relevant modelling techniques are discussed in Chapter 3. Preparation Hydrologic Atlas using the data generated via field measurements and modelling activities is documented in Chapter 4. A bibliography is given in Annexure A.

2 Field Measurements

In this chapter filed measurement techniques for 1) soil moisture (Section 2.1), 2) runoff, both discharge and water level (Section 2.2), 3) ground water level (Section 2.3), 4) evapotranspiration (Section 2.4), 5) variables related to water quality (Section 2.5), 6) canopy variables (Section 2.6) and 7) weather variables (Section 2.7) are discussed. The chapter concludes with a discussion on systematic recordings for field measurements (Section 2.8).

2.1 Soil Moisture

Surface Soil Moisture (SSM) plays a vital role in various processes occurring on the soil atmosphere interface. The evaporation is controlled directly by the surface soil moisture; the transpiration is controlled by the soil moisture present in the root zone. The precipitation passes through surface soil moisture to reach the root zone. Hence, surface soil moisture could be able to provide some insight into the root zone soil moisture. This means that surface soil moisture may be a useful variable to predict the hydrological cycle over land. Apart from hydrology, it is also useful in various other applications e.g., agronomy, drought management and in the improvement of disaggregation/downscaling of precipitation etc.

2.1.1 Surface Soil Moisture

The surface soil moisture is being measured currently for the three major purposes:

- Calibration/Validation (Cal/Val) of SAR satellite data
- To calibrate the STICS crop model
- To validate the radiometer satellite data

In the following two subsections, measurement of surface soil moisture using following two techniques are described:

- Volumetric Soil Moisture Measurements (Theta Probe)
- Gravimetric Soil Moisture Measurements

2.1.1.1 Volumetric Soil Moisture Measurements (Theta Probe)

Surface soil moisture is measured using ML2x theta probe (Delta-T devices, Delta-T Devices Ltd, Cambridge, UK), which measures soil moisture averaged over 0 to 5 cm depth and equipped with a HH2 meter for spot measurements and display. Accuracy of measurements is ± 1 %. Figure 2-1 depicts a Theta probe and HH2 meter (Delta T Devices) assembly. The operating principle, steps to be employed during measurements etc. of this probe is given below.

Operating Principle

Theta Probe measures soil parameters by applying a 100 MHz signal via a specially designed transmission line whose impedance is changed as the impedance of the soil changes. This impedance has two components; the apparent dielectric constant and the ionic conductivity.

The signal frequency has been chosen to minimize the effect of ionic conductivity, so that changes in the transmission line impedance are dependent almost solely on the soil's apparent dielectric constant. These changes cause a voltage standing wave to be produced which augments or reduces the voltage produced by the crystal oscillator, depending on the medium surrounding the measurement prongs. The difference between the voltage at the oscillator and that reflected by the rods is used by Theta Probe to measure the apparent dielectric constant of the soil. A linear correlation exists between the square root of the dielectric constant, ($\sqrt{\varepsilon}$), and volumetric moisture content, (θ), which is used to convert the measured dielectric constant to soil moisture[1].

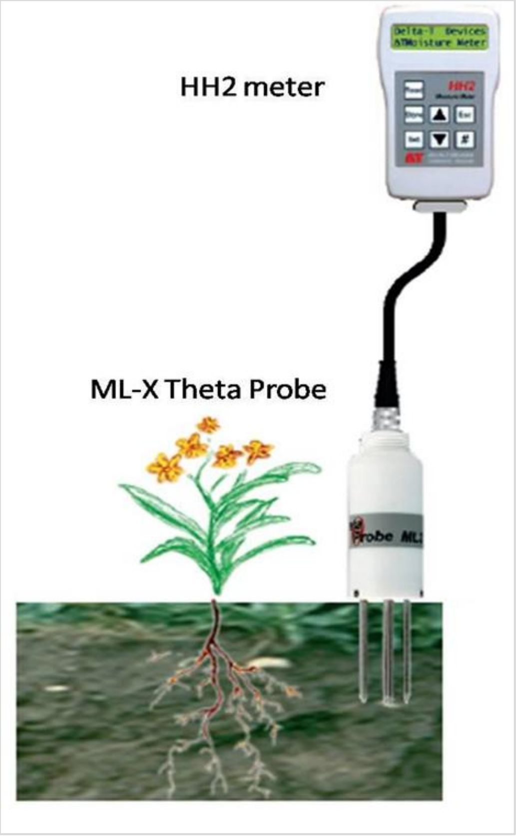

Figure 2-1: Theta probe and HH2 meter (Delta T Devices)

<u>Steps to be employed for the Measurement</u>

- The theta probe needles should be inserted (penetrated) fully into the soil vertically. Take care while inserting the probe in stony soils as it may damage the needle. In such cases if it is difficult to insert the probe in a particular location try a few other locations in the plot where the needles can penetrate without much force being applied.
- Three readings should be taken for each plot, to get the mean value that is representative of the field plot and variability.
- If the plot is with furrows and ridges (as in the case of turmeric), then take one reading at the top of the furrow, one in the ridge, one at another representative location.

[1] Detailed theory and calibration procedures are provided in the manual of the device or are also available at http://www.delta-t.co.uk/.

- If the plot is partially irrigated, take at least two measurements in the irrigated area and mark the reading as irrigated.
- If the plot is irrigated the previous day of measurement, note it down in the field note.
- At least one measurement has to be made within the 2 sq.m area adjoining the location where the access tube is installed.
- Note down the label number of the Delta-T probe. (Usually, each Theta probe is given an identification number by the field team, this will help us in calibration)
- Do not take soil moisture reading too close to a crop, as the probe may penetrate the root and measurements may be misleading.
- Do not take soil moisture reading in the loose soil as the presence of air gaps may affect the measurements.
- If the reading cannot be taken for the dry soil (hard to penetrate the needles), note down that in your diary. (This usually occurs in summer season in most soils)
- Note down the crop type.

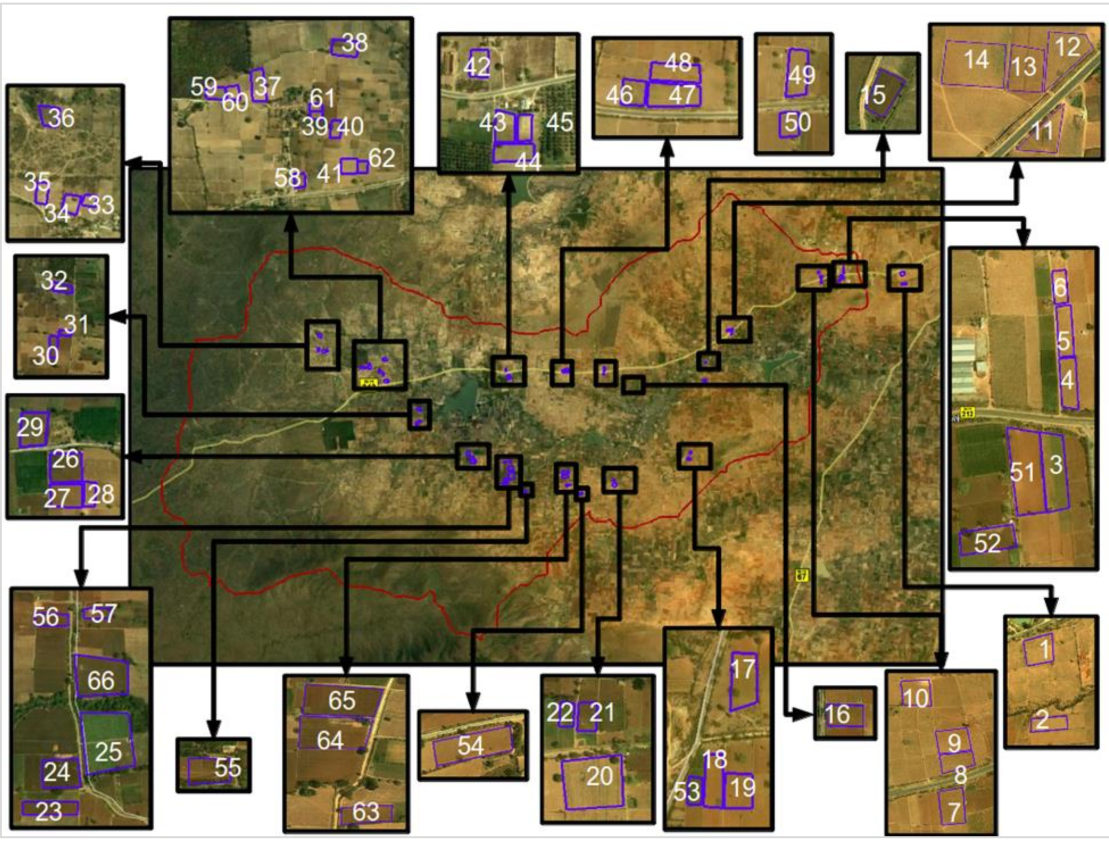

Figure 2-2: Map showing a Typical Layout for Soil Moisture Monitoring Field-Plots

2.1.1.2 Gravimetric Soil Moisture Measurements

The soil moisture content may be expressed by weight as the ratio of the mass of water present to the dry to the dry weight of the soil sample, or by volume as ratio of volume of water to the total volume of the soil sample. To determine any of these ratios for a particular soil sample, the water mass must be determined by drying the soil to constant weight and measuring the soil sample mass after and before drying. The water mass (or weight) is the difference between the weights of the wet and oven dry samples. The criterion for a dry soil sample is the soil sample that has been dried to constant weight in oven at temperature between 100 – 110° C (105° C is typical). It seems that this temperature range has been based on water boiling temperature and does not consider the soil physical and chemical characteristics. Typical procedure for the measurement is given hereunder.

Materials

- Oven with 100 –110 0 C temperature
- A balance of precision of ±0.001 g.
- Aluminum weigh tins
- Auger or tool to collect soil samples

Procedure

- Weigh aluminum tin, and record this weight (tare”).
- Place a soil sample in the tin and record this weight as (wet soil + tare).
- Place the sample in the oven 105o C, and dry for 24 hours or overnight.
- Weigh the sample, and record this weight as weight of (dry soil + tare).
- Return the sample to the oven and dry for several hours, and determine the weight of (dry soil + tare).

Computations

The moisture content in dry weight basis may be calculated using the following formula:

$$\theta_d = \frac{(wtofwetsoil + tare) - (wtofdrysoil + tare)}{(wtofdrysoil + tare) - (tare)}$$ Eqn. 2-1

Water content in volumetric basis is expressed as:

$$\theta_{vd} = \frac{Volumeofwater}{Volumeofsoil}$$ Eqn. 2-2

But,

$$Volume\ Of\ Water = \frac{wtofwater}{water\ density}$$ Eqn. 2-3

And,

$$Volume\ Of\ Soil = \frac{wtofdrysoil}{bulk\ density}$$ Eqn. 2-4

Hence,

$$\theta_{vd} = \frac{wtofwater}{wt\ of\ dry\ soil} X \frac{bulkdensity}{water\ density}$$ Eqn. 2-5

Hence,

$$\theta_{vd} = \frac{wtofwater}{wt\ of\ dry\ soil} X \frac{bulkdensity}{water\ density}$$ Eqn. 2-6

And,

$$\theta_{vd} = \theta_d X \frac{d_b}{d_w}$$ Eqn. 2-7

2.1.2 Soil Moisture Profile

This sub-section discusses the procedure for profile soil moisture measurements, the instruments used and their operating principle, calibration techniques. Profile soil moisture are being monitored/measured either continuously or intermittently at regular frequency in a watershed for cropped and uncropped areas.

2.1.2.1 TRIME-PICO IPH Soil moisture Sensor

Operating Principle

The TRIME device generates a high-frequency pulse (up to 1GHz) which propagates along the metal shells, generating an electromagnetic field around the probe. At the end of the shells, the pulse is reflected back to its source. The resulting transit time (3ps...2ns!) can be measured and enables determination of the propagation velocity, which is primarily dependent on the water content. The volumetric water content is then calculated by the velocity and is shown on the display panel immediately. The particular probe that is used to depict the procedure is T3/44, which has moisture measuring range from 0 to 60 % (volumetric water content) and an accuracy of ±2%. Measuring volume: The effective penetration depth of the probe T3 is about 15 cm with the highest sensitivity in the immediate vicinity of the access tube, and decreases exponentially as distance increases[2].

Installation of Access Tubes

Access tube of TRIME contains three parts, the tube (1 m or 2 m long) with a metal ring at the bottom, a rubber cork (to seal the bottom of the tube) and a plastic cap to cover the top of the tube. It is necessary to maintain close contact between the access tube and the soil material for reliable measurements; hence the tubes should be installed as recommended by the manufacturer. Alternatively, the access tubes can be installed by following the steps below.

1) Fix the rubber cork tightly inside the metallic ring at the bottom of the access tube, this can be fixed with the help of the auger provided with the instrument. (The specially designed auger has provision for tightening the rubber cork). Additionally, it is better to seal the bottom with cello tapes to ensure that no water seeps into the tube from the bottom. Close the top of the access tube with the plastic cap.
2) Drill a hole to the required depth (1 m or 2 m) using the auger provided by the manufacturer. Save soil in a small bucket to mix with water to form a well-blended mud. Pour the mud back into the hole until it is full.
3) Insert the Access Tube in an auger hole. Move the tube up and down (inside the hole) a few times to remove all air. Mud should come up to above surface level.

[2] Detailed technical specifications and calibration procedures are available in the TRIME-PICO IPH manual supplied with the instrument and may be obtained using following link:
http://www.imko.de/en/products/soilmoisture/soil-moisture-sensors/trimepicoipht3.

4) Fix the access tube in this position and insert the Probe into the access tube, slowly lower it to the bottom and note the readings, since the readings are taken immediately after installation all the readings should be in the high (40 to 50 %) and consistent.
5) Lower readings indicate the presence of air gaps which should be fixed immediately by following step 3.
6) Installation of access tubes can be carried out at least two weeks before the intended start of the experiment, since the newly installed access tube may take at least 10 days to settle.

   Note:

   In the cable (usually > 2 m long) connecting the sensor to the data logger, make markings at every 10 cm (using a white cello tape) so that we can be sure of the depth at which the measurement is being taken.

Figure 2-3: TRIMEPICO IPH for Profile Soil Moisture Measurements

<u>How to Measure</u>

- Open the cap of the access tube and insert the sensor slowly into the tube till the sensor is fully below the ground level. Note down the reading from the data logger.
- Now slowly push the sensor further down to the required depth (depth is marked in the cable with a white tape) and continue taking measurements. Continue this process till the whole of the access tube (1 m or 2 m) is covered.
- Note the reading and depth of measurement each time.

- Note also the crop type and general condition of the plot (like irrigated or rained etc.).
- In dry soil, sometimes it will be difficult to push the sensor inside the access tube, in such cases it is better to avoid taking measurements since the sensor may get struck inside the access tube and pulling it back by force may damage the connecting wires.
- Do not make the sensor or the data logger to hang from the cable while taking for field measurements since this will lead to wear and tear in the connecting cable and eventually the sensor unit may be disconnected from the logger. Always support the sensor and logger with hand or use the instrument box each time.

2.1.3 Continuous Soil Moisture Monitoring

Continuous monitoring of surface and profile soil moisture is essential to understand the controls of soil moisture in the watershed. Such data can help in irrigation scheduling, calibration and validation of satellite soil moisture products and in predicting drought. In this manual following three techniques are described for the continuous soil moisture measurement:

- EnviroSCAN soil moisture sensor,
- HYDRA Probe soil moisture sensor
- COSMIC ray soil moisture sensor.

2.1.3.1 EnviroSCAN Soil Moisture Sensor

The EnviroSCAN probe (see Figure 2-4) provides soil-water-content profiles for irrigation scheduling or other water movement systems.

Figure 2-4: EnviroSCAN Soil Moisture Sensor

The measurement range is oven dry to saturation. The probes measure soil moisture at multiple depths. The EnviroSCAN includes several water content sensors that measure soil water at multiple depths. Around each sensor, the probe creates a high frequency electrical field that extends through the access tube into the soil. Electrical capacitance is then measured and soil water content is determined from those measurements. EnviroSCAN can measure water content from a range of 0 to 65%.

Installation, Calibration and Data Collection

The entire setup of the EnviroSCAN sensor is usually installed by an expert deputed by the supplier. The setup consists of access tubes with caps, soil moisture sensor, solar power panel with batteries, connecting cables and specially designed auger set. The data collected is every 15 minutes and is transmitted via GPRS, alternatively it is also possible to retrieve the data on site using data loggers[3].

2.1.3.2 HYDRA Probe Soil Moisture Sensor

The Hydra Probe sensor (see Figure 2-5 & Figure 2-6) uses the Coaxial Impedance Dielectric Reflectometry method in soil moisture measurement. The Coaxial Impedance Dielectric Reflectometry method of soil moisture measurement employs an oscillator to generate an electromagnetic signal that is propagated through the unit (usually by metal tines or other wave guide) and into the soil. The probe sends electrical signals into the soil, measures the responses, and relays this information to a data collection device known as a data logger. Part of this signal will be reflected back to the unit by the soil, and the sensor will measure the amplitude of this reflected signal and the incident signal in volts. The ratio of these raw voltages is used in a mathematical numerical solution to Maxwell's equations to first calculate the impedance, then both real and imaginary dielectric permittivity which in turn is used to accurately estimate soil water content.

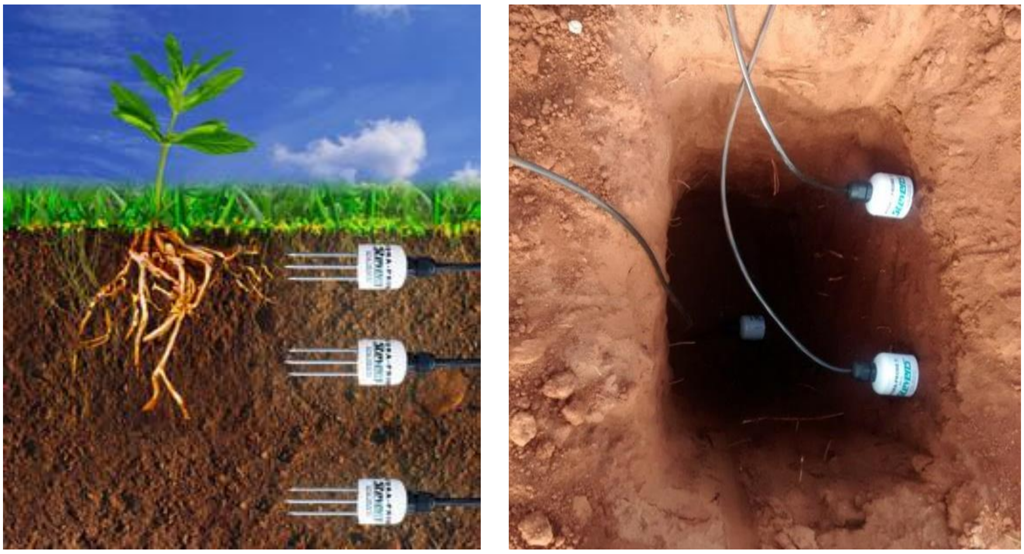

Figure 2-5: Schematic of HYDRA Probe Soil Moisture Sensor

[3] Details about installation and calibration is available in the manual supplied with instrument or is also available at http://www.sentek.com.au/.

Figure 2-6: Field Assembly of HYDRA Probe Soil Moisture Sensor

Installation and Calibration

- Excavate a hole no larger than 25” x 25” square and 25” deep for the sensor installation pit. To best re-create the original soil horizons, these soil layers should be replaced in the pit in the same order they were removed.
- Trench from the location of the power source and data logger to the sensor installation pit. Assemble rigid or flexible PVC conduit to protect the sensor wires.
- Check that there is enough cable length to reach up through the soil pit and through the conduit to the data logger. Label sensor wires with sensor depth or position at both ends – the sensor end and the end that will be hooked up to the data logger.
- Before installing sensors into the soil, connect the wires to the data logger and power source. Test each sensor separately in moist soil to make sure that it is working as expected. A small cup with moistened soil works well for testing because each sensor should give very close to the same reading for soil moisture and temperature.
- Install the 50cm, 5cm, and 5cm sensors along the pit face in a staggered pattern, carefully backfill the soil in the rest of the pit and leave drip loops in all the wires.
- Gather all the wires together at the surface and seal the end of the conduit with duct seal putty. When all the sensors are in place and the installation is complete, bury the conduit in the trench[4].

[4] Detailed installation and calibration techniques are available in the manual supplied along with the instrument or is available at http://www.stevenswater.com/soil_moisture_sensors/.

2.2 Measurement of Runoff

There are two situations when runoff will occur. If the intensity of rainfall exceeds the infiltration rate at the ground surface, ponding will lead to surface flow. Alternatively, when the soil surface is saturated, there will be surface flow when the rainfall intensity exceeds the percolation through the whole soil profile, a combination of downward movement to groundwater and lateral movement to seepage flow. The rate of runoff is required for the design of drains, canals and other channels, and for the prediction of water levels in streams and rivers. Quantity of runoff is required when storage is involved for irrigation, power generation, river transport etc.

Runoff from a given watershed can be measured either by directly measuring the discharge at its outlet by pre-calibrated measuring structures or by measuring water level at a river gauging site with well-established stage-discharge relationship. Measurement of runoff using pre-calibrated structures is discussed in Section 2.2.1 and measurement of river water level is discussed in Section 2.2.2. An example application

2.2.1 Measurement of Discharge by Pre-calibrated Measuring Structures

There exists a limited range of different weirs and flumes that have well-established relationships between head and discharge, and the most commonly used of these are described in the following sections. Only under reasonably favorable field conditions can the established formulae accurately predict the discharge, however. It is important therefore that, if a measuring structure is required to measure flow directly from water level readings, every care must be taken in the construction and operation of the device, and the most suitable formula be used. There is no substitute, however, for in-place calibration for all devices discussed here.

There are mainly three categories of measuring devices/structures:

- The various types of **thin-plate weirs** are generally employed in the *hydraulics laboratory and on small, clear flowing streams*; particularly where above average accuracy is desired and adequate maintenance can be provided, such as for small research watersheds.
- *On small streams and canals conveying sediment and debris and in other situations where the head loss associated with a thin-plate weir is unacceptable*, **flumes** are preferable. Certain types may also be used drowned, permitting operation with very small head loss but at some loss of accuracy.
- *On larger streams*, various types of **broad-crested**, **triangular profile**, and **round-shaped weirs** are frequently employed. On larger streams it is usually impractical as well as unwise to place such structures excessive in height above the normal streambed. When submerged flows may exist over some part of the discharge range, the discharge relationships presented may not apply as the discharge would cease to be a function solely of upstream level. In case of doubt, such structure should be field rated. The triangular profile weir may be operated successfully when drowned, with double gauging of water levels.

During the execution of Sujala Program under the Watershed Development Department, a broad crested weir was built at the outlet of the watershed to avoid the gully erosion and maintaining the uniformity of the stream course for discharge measurement and also to collect the sediment samples. Stilling well was built along with the weir for installing the stage level recorder to avoid damage from the debris and water current. Stage level recorder is operated by weight and float method with the support of pulley, which is used to measure the water stages (height) in the stream, in turn the stages have been converted into discharges.

Based upon this experience working principles and methodology associated with the following measuring structures are further elaborated in the next few sub-sections:

- Thin-plated Triangular-notch weirs
- Thin-plated Rectangular weirs
- Round-nosed horizontal-crested weirs
- Parshall flumes

2.2.1.1 Thin-plated Triangular-notch Weirs

Within the range of conditions for which the available experimental data are competent, the triangular-notch, thin plate weir (or V-notch) is one of the most precise measuring devices for clean water not carrying sediment, provided it is not submerged. It is inexpensive, simple to construct and install, and relatively insensitive to the installation environment, but is dependent on careful maintenance. A standard triangular-notch weir is shown in Figure 2-7, and consists of a symmetrical, V-shaped notch in a vertical, thin-plate.

The line which bisects the angle of the notch shall be vertical and equidistant from the sides of the channel. The weir plate shall be smooth and plane, especially on the upstream side, and it shall be perpendicular to the sides as well as the bottom of the channel. The crest surfaces of the notch shall be plane surfaces, which shall form sharp, right-angle corners at their intersection with the upstream face of the weir plate. The width of the crest surfaces (measured perpendicular to the face of the plate) shall be between 0.03 and 0.08 in (1 to 2 mm). It is particularly important that the upstream edges of the notch be sharp; that is, that they be machined or filed perpendicular to the upstream face of the weir plate, free of burrs and scratches, and untouched by abrasive cloth or paper. The down-stream edges of the notch shall be chamfered if the weir plate is thicker than the allowable crest width. The surface of the chamfer shall make an angle of not less than 60 deg with the surface of the crest.

The equation for discharge through a triangular, V-notch, thin-plate weir is as follows:

$$Q = \frac{8}{15}\sqrt{2g}C_D tan\left(\frac{\theta}{2}\right)h^{5/2} \qquad \textbf{Eqn. 2-8}$$

where, Q = discharge, C_D = coefficient of discharge, θ = angle included between sides of notch, and h = gauged head referred to vertex of notch.

The C_D values vary from 0.608 at h = 0.050 m to 0.585 at h = 0.381 for a 90° notch. There are generally three varieties of V-notch weirs -- 90°, ½ 90° and ¼ 90°.

For Standard tables for C_D values, installation instructions, applicability etc., readers are referred to the following guidelines:

- Manual on Stream Gauging Volume I – Fieldwork; 2010; WMO-No. 1044.
- Use of Weirs and Flumes in Stream Gauging; 1971; WMO-No. 280.

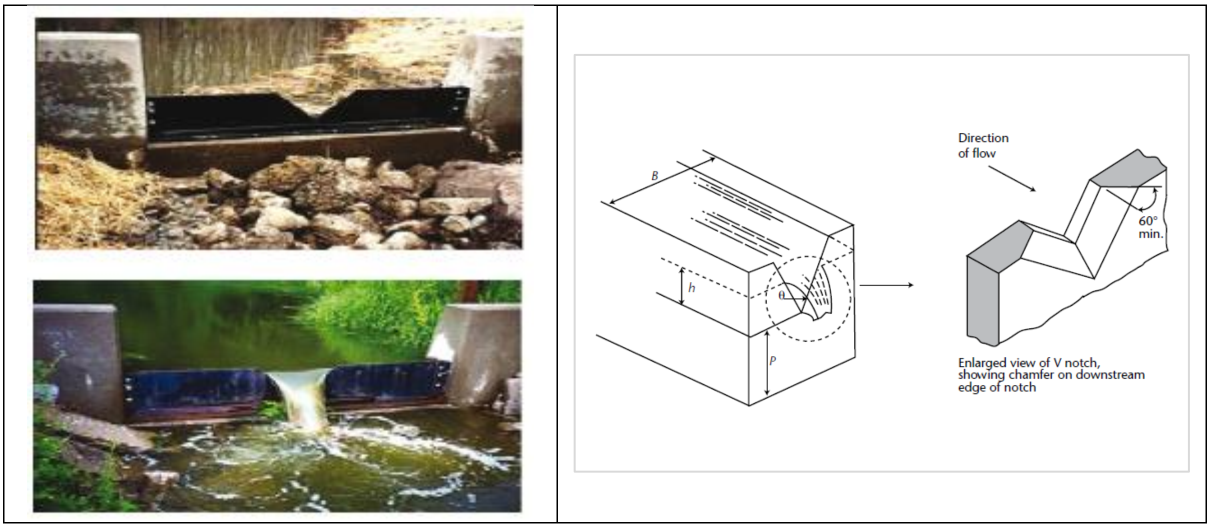

Figure 2-7: Thin-Plated Triangular Weir – Field Installation and Schematics

2.2.1.2 Thin-plated Rectangular Weirs

The standard rectangular, thin-plate weir shall consist of a rectangular notch symmetrically located in a vertical, thin-plate. The plate shall be smooth and plane, especially on the upstream side, and it shall be perpendicular to the sides as well as the bottom of the channel. The crest of the weir notch shall be a horizontal plane surface, which shall form a sharp right-angle corner at its intersection with the upstream face of the weir plate. The sides of the notch shall be vertical plane surfaces which shall make sharp 90·degree intersections with the plane of the crest, and which, in shape and width, shall be identical with the crest surface. Figure 2-8 shows standard Thin-Plated Rectangular Weir.

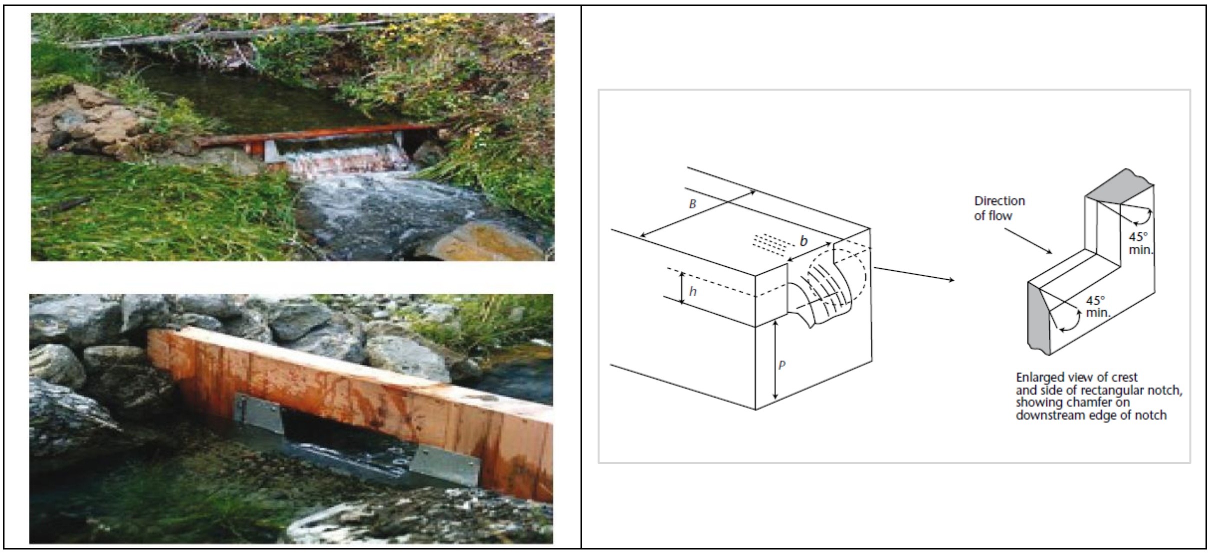

Figure 2-8: Thin-Plated Rectangular Weir – Field Installation and Schematics

The upstream edges of the sides and crest of the weir must be sharp; that is, they shall be machined or filed perpendicular to the upstream face of the weir plate, free of burrs and scratches. Abrasive cloth or paper must not be used because of the danger of rounding the edge. The downstream edges of the notch shall be chamfered if the weir plate is thicker than the allowable crest width. The surfaces of the chamfers shall make an angle of not less than 45 degrees with the surfaces of the notch.

If the length of the crest be equal to the width of the channel (i.e., a full width weir), it is especially important that the sides of the channel be vertical, plane, parallel and smooth in the near vicinity of the weir. The sides of the channel above the level of the crest of a full-width weir shall extend at least 0.3 ft (0.09 m) beyond the plane of the weir.

The discharge nappe shall be fully ventilated and unsubmerged. Provisions for ventilation of the nappe should ensure that the pressure over the sides and nappe surfaces is atmospheric. The tailwater level should be low enough to ensure that it shall not interfere with the ventilation or free discharge of the jet. The nappe shall not be permitted to cling to the downstream face of the weir.

The head on the weir shall be measured a sufficient distance upstream from the weir to avoid the regions of surface draw-down. On the other hand, it shall be close enough to the weir for the energy loss between the section of measurement and the weir to be negligible. The head measurement section shall be located a distance equal to between three and four times the maximum head.

The basic discharge equation for a rectangular thin-plate weir is as follows:

$$Q = C\,\frac{2}{3}\sqrt{2g}bh^{3/2} \qquad \textbf{Eqn. 2-9}$$

For Standard tables for C values, installation instructions, applicability and different variation of the basic equation etc., readers are referred to the following guidelines:

- Manual on Stream Gauging Volume I – Fieldwork; 2010; WMO-No. 1044.
- Use of Weirs and Flumes in Stream Gauging; 1971; WMO-No. 280.

2.2.1.3 Broad-Crested Round-nosed horizontal-Crested Weirs

Figure 2-9 depicts a standard Broad-Crested Round-nosed horizontal-Crested Weirs. The standard weir comprises a truly level and horizontal crest, between vertical abutments. The upstream corner should be rounded in such a manner that flow separation does not occur, and downstream of the horizontal crest there should be either i) a rounded corner, ii) a downward slope or iii) a vertical face. The weir should be set at right angles to the direction of flow in the approach channel. The dimensions of the weir and its abutments shall conform with the requirements indicated in Figure 2-9.

The general discharge equation for broad-crested weirs is

$$Q = C_v C_D\,(2/3)^{3/2}\sqrt{g}bh^{3/2} \qquad \textbf{Eqn. 2-10}$$

where, C_v is the coefficient of approach velocity h is gauged head, b is the width of flow over the weir and C_D is the coefficient of discharge. For the round-nosed horizontal crest weir, C_D is given by,

$$C_D = \left(1 - \frac{0.006L}{b}\right)\left(1 - \frac{0.003L}{h}\right)^{3/2} \qquad \text{Eqn. 2-11}$$

where L is the length of the horizontal section of the crest in the direction of flow.

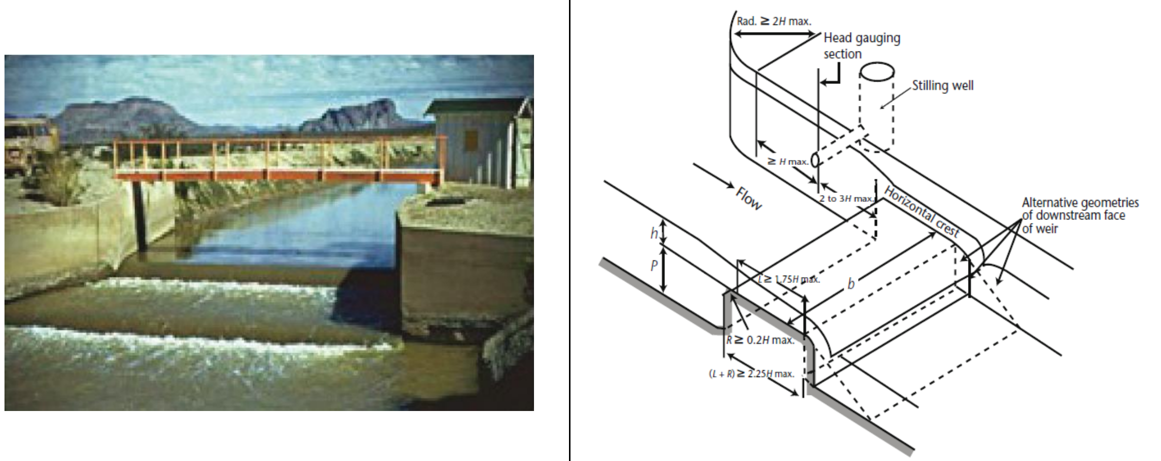

Figure 2-9: Standard Broad-Crested Round-nosed horizontal-Crested Weirs – Field Installation and Schematics

For Standard tables for C_D and C_v values, installation instructions, applicability and different variation of the basic equation etc., readers are referred to the following guidelines:

- Manual on Stream Gauging Volume I – Fieldwork; 2010; WMO-No. 1044.
- Use of Weirs and Flumes in Stream Gauging; 1971; WMO-No. 280.

2.2.1.4 Parshall Flumes

A standing-wave flume is essentially a streamlined structure built into an open channel to form a contraction through which the velocity of the flowing water is increased with a consequent fall in water level. The rectangular throated standing-wave flume is constructed at zero slope and features the measurement of head upstream of the throat in subcritical flow. These factors demand that free flow exists at all times and that special consideration be given to maintaining adequate velocity in the approach channel if sediment and debris exist in the flow to be measured.

R L Parshall proposed changes in the design of the standing-wave flume, the most essential of which was a drop in the floor. This drop stabilized the hydraulic jump that exists beyond the supercritical flow zone. While supercritical flow exists in the throat of the Parshall Flume, head is measured upstream in subcritical flow and may be affected by deposition of sediment and debris. Parshall flume will operate submerged.

The flume consists of a converging section with a level floor (see Figure 2-10), a throat section with a downward sloping floor, and a diverging section with an upward sloping floor.

Calibration is carried out against a piezometric head H_A measured at a prescribed location in the converging section, the downstream head H_B being measured in the throat. H_A and H_B are each set with the zero of the gauges at the elevation of the crest, or level floor.

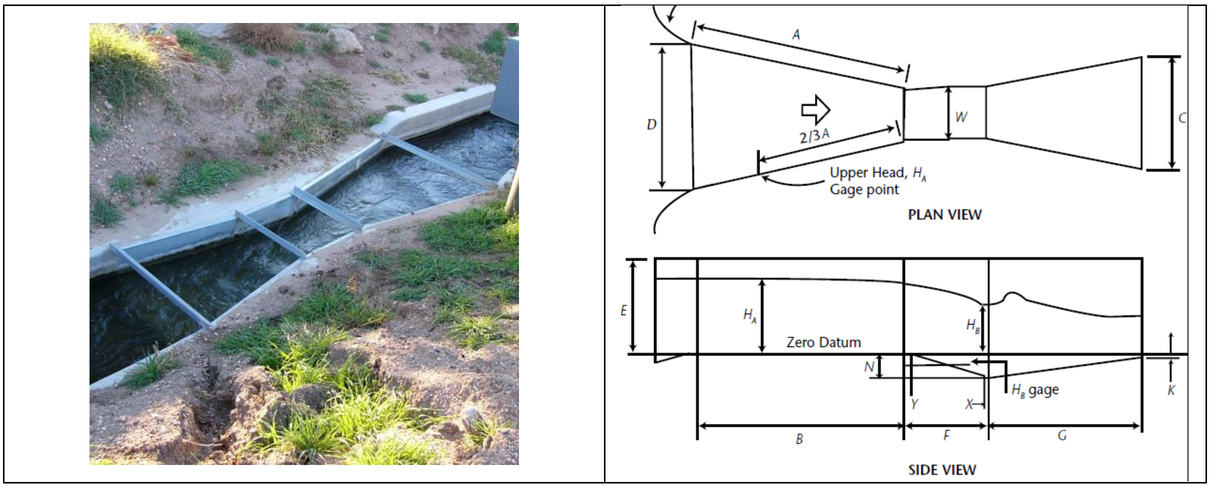

Figure 2-10: Standing-wave Parshall Flume – Field Installation and Schematics

For Standard tables for available Parshall Flumes with various sizes, installation instructions, applicability and the discharge formulae etc., readers are referred to the following guidelines:

- Manual on Stream Gauging Volume I – Fieldwork; 2010; WMO-No. 1044.
- Use of Weirs and Flumes in Stream Gauging; 1971; WMO-No. 280.

It is always recommended that the installation in the field, however, should be checked and calibrated with current meter measurements.

2.2.2 Measurement of River Water Level

2.2.2.1 Water Level Gauges

The level scale is the most important apparatus of a hydrometric station without which any long and reliable water level chronicle cannot be appointed. Level gauges are constituted on a staff installed along a section of the river, one gauge starting where the other ends, in one or several parts. They are referenced to a TBM or a survey pillar and they are useful for many purposes:

- to calibrate any kind of water level recorder;
- to supply a defective level recorder;
- to correct false level recordings.

The level is read once or several times daily, according to the stream level variation.

2.2.2.2 Water Level Recorders

They are several types of water level recorders:

- float devices (mechanic water level recorders, electronic shaft encoder);

- pressure sensors (hydrostatic pressure sensors, sensors based on the bubble in principle);
- ultrasonic sensors;
- radar sensors

The two first types are the most used. For the first type, mechanical water level recorders are no longer in use and are replaced by electric shaft encoders (example: Thalimedes).

2.2.2.3 Gauging with the Current Meter

It should be known that more than 80% of the gauging is carried out today with a hydrometric current meter, distances to the bank being measured on a cable tended of a bank to the other. Velocities are measured in several points of verticals chosen on the width of the cross section. The common technique is gauging "point by point". Velocity is obtained through the current meter propeller formula, $v = an + b$, with, a, b are constants of the propeller, and n the number of rotations per second of the propeller due to the water current.

- A unit flow (m^2/s) is obtained for each vertical, by integrating the velocity along the vertical, $q = \int vd(d)$, where q is the unit flow, d is the depth and v is the velocity.
- The flow (m^3/s) is obtained by integrating the unit flow along the section's width $Q = \int qd(w)$, where Q is the flow, w the width and q the unit flow.

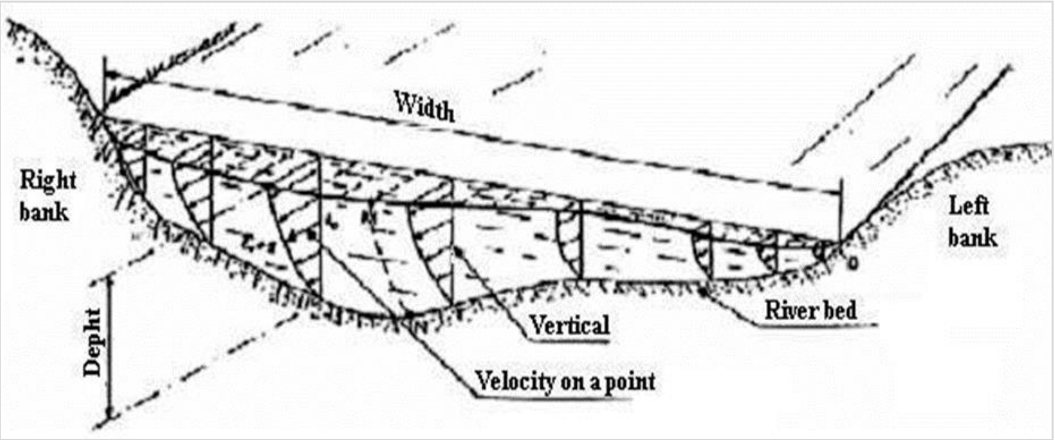

Figure 2-11: Schematics of Typical Flow Measurement Operation using Current Meter

Figure 2-11 shows a representation of verticals and points where velocity measures are made. Figure 2-12 shows a typical current meter assembly. Following points are to be noted:

- For depths higher than one meter, one will take five points distributed in the following way: one on the surface to 0.10 m in lower part of the water level, one at the bottom at the distance which the assembly of the current meter (bottom constant) allows, and three points distributed in the remaining height to the 2/10, 5/10 and 8/10 this height.
- For the depths ranging between 1 m and 0.50 m: three points, one on the surface, one at the bottom (as close as possible) and one in the medium or slightly lower to improve the precision of the layout in automatic examination by the method of the trapezoids.

- Below 0.50 m depth, take two points: one surface and one close to the bottom; with a pigmy current meter one can make 4 to 5 points on a 0.50 m. To calculate the total flow, we approximated the different integrations by the trapezoid method: $A = 0.5 \times (B + b) \times h$; where A is the trapezium's area, B is the big base, b is the small base and h is the height.

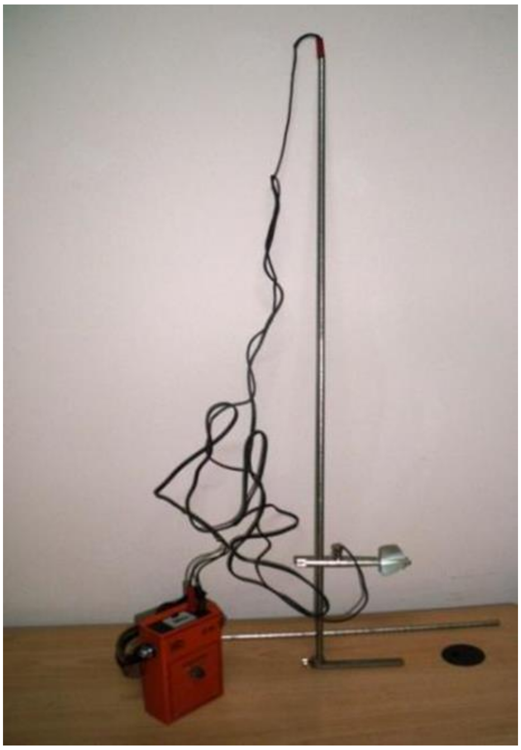

Figure 2-12: A Typical Current Meter Assembly

2.2.3 Example Application: Maddur Watershed

The Maddur hydrometric station has been set under the Maddur bridge, at the downstream side (Figure 2-13). Water levels are recorded every 15 minutes with a Thalimedes whose pipe is fixed on the left bank of the bridge wall. There is no level gauge and values acquired with the Thalimedes are controlled only during field trips with a portable piezometric sounding sensor from the top of the bridge. The Maddur stream flows all over the year, because the flow is sustained by several small dams upstream that were built for irrigations. Storm events happen only few times a year and most of the time the peak is in the middle of the night and the following morning the storm event is over.

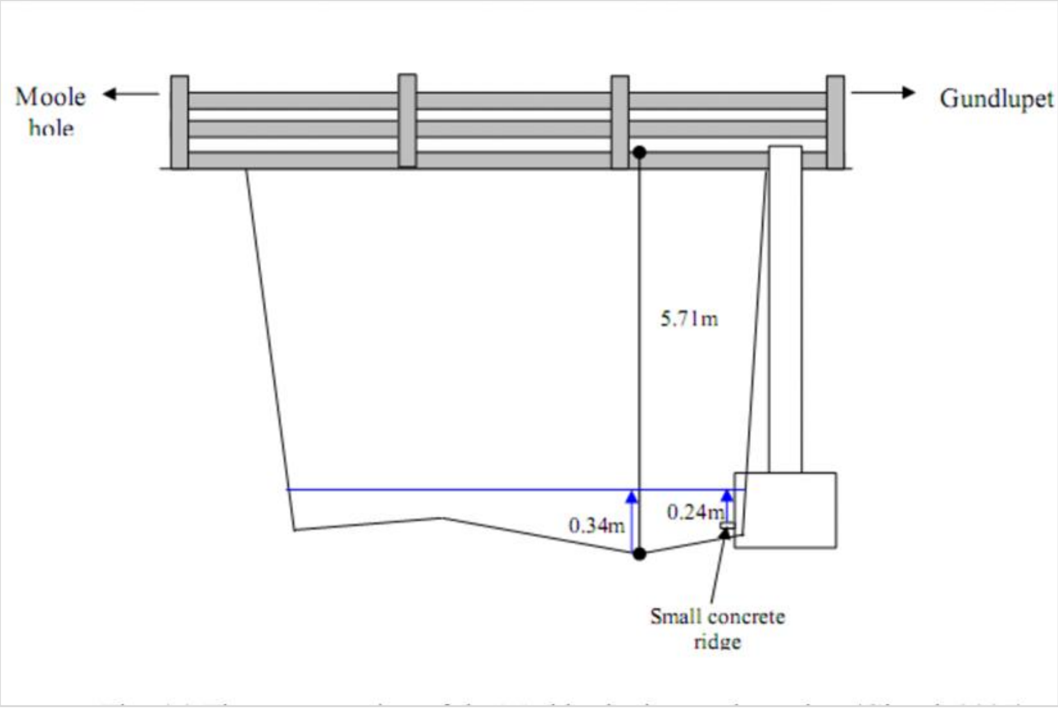

Figure 2-13: The Cross Section of the Maddur Hydrometric Station (Girard, 2007)

2.3 Ground Water Level

The groundwater level data is an important variable in the hydrological budget (e.g., estimation of recharge from rainfall or other sources) in micro-watersheds. Time series data of groundwater level is also useful in understanding the usage patterns of groundwater for irrigation. Such time series data is also useful in assessing the role of managed aquifer recharge or watershed practices in micro-catchments. The groundwater levels are gathered by the Central Groundwater Department or Department of Mines and Geology at a few permanent observation wells and typically there is one station in approximately 80 km^2 in Indian contexts. This spatial resolution can change depending on if the area is hilly, forested etc. Further, the groundwater level data is gathered once in 3 months or sometimes each month at the maximum. However, if one has to assess the impacts caused to groundwater in a micro-watershed of few sq Km due to land use changes or watershed conservation practices, then it is required to gather the groundwater level at a good spatial and temporal resolution in a micro-watershed.

2.3.1 Measuring Equipment

- A bore well/ dug well/ tube well for groundwater level sampling. In India, most farmers have such wells in their plots. These can be used for sampling the groundwater level. However, these are used for pumping water so before taking the level some caution is to be exercised, which will be discussed subsequently in this document under protocols.
- A groundwater level sensing probe with a graduated tape. Heron Instruments supplies a probe SKINNY DIPPER (http://www.heroninstruments.com/), which has slim ¼" tape and is ideal to use for bore wells fitted with submersible pumps and in narrow tubes and piezometers.

- A GPS to record the latitude and longitude of the groundwater level monitoring point.

(a) (b)

Figure 2-14: (a) Typical Bore Well in a Farmer's Plot; (b) A Groundwater Level Sensing Probe

2.3.2 Protocol to be Followed

Following protocol is given on how the groundwater level can be sampled in a micro-catchment.

1) Select as many bore wells or dug wells in the micro-catchment that can be monitored. Typically use ~20 wells for each one km^2 (100 hectares).
2) The groundwater level should be recorded once in a week or 15 days using the probe.
3) When the dipper probe with tape is gradually let into the bore well, one would hear a clear sound indicating that the probe is touching the water. If one lets the tape further, the sound is heard continuously as the probe is immersed in water. A few trials (at least 3) of pulling the tape out of the water and releasing it again so that the level at which the sound is recorded is clear and this will be the level of groundwater that should be recorded.
4) After recording the groundwater level, the station coordinates are recorded using the GPS.
5) The groundwater level should be gathered, at least 8 to 10 hours after the pump is stopped since pumping water. Often local electricity agency provides information on when the power was last supplied and this could be used before taking the levels in the bore wells.
6) The height of the metal tube above the ground for the bore well or the height of the cement ring above the ground for a dug well is also measured at each station.
7) The crop that is being grown under irrigation using the well is to be recorded. This should be done each time the groundwater level is recorded. If no crop, then this also to be recorded. Also, the area of the plot under irrigation is to be recorded.
8) The details such as HP of the pump is to be noted. The number of hours of pump under use in the well is to be recorded and this information is gathered once in two months.

2.3.3 Ground Water Sampling

Groundwater has become a vital resource to support many urban and rural populations in India. The intensive groundwater use in agriculture has grown exponentially leading to faster depletion than aquifer recharge. Therefore, understanding the basic processes about groundwater as well as the factors that can affect its quantity and quality is of vital importance in managing this significant resource. Monitoring provides data on groundwater quantity and quality for the integral aspect of groundwater management. Depending on the purpose of monitoring the sampling of groundwater should be carried out on a regular basis to test various parameters

1) To assess the groundwater quality status in the watershed against defined guidelines and standards
2) To understand the evolution of the groundwater chemistry
3) To assess the impact of land use changes, irrigation practices and groundwater abstraction on the groundwater quality.

The following discussion aims to provide simple groundwater sampling method for collecting representative and high integrity samples for the physical and chemical analyses.

<u>Required Materials</u>

- Polypropylene Bottles
- Flow cell
- pH, Conductivity, Temperature and Dissolved Oxygen electrodes
- Ultra-pure water (Milli Q or distilled water)
- Standards for the calibration of electrodes
- Filtration unit (Cellulose based membrane 0.45 µm)
- Operating manuals of respective meter and electrodes

<u>Sampling Plan</u>

It is important to design a good sampling plan to ensure the data quality and sample representativity for the defined purpose.

1. *Sampling Criteria*: Existing production boreholes in the watershed significantly define the potential sites for groundwater sampling. It is necessary to note the construction details to define from which strata the sample is being taken for analysis. In addition, it is recommended to integrate sampling of rainfall and surface water bodies (tanks, ponds) with the groundwater chemistry. The selection of optimal sample points is influenced by the purpose of sampling. The following criteria should be considered for the representative groundwater sampling.
   1.1. Diversity of groundwater use in the watershed including irrigation, drinking water supply etc.
   1.2. Representing the recharge and the extent of groundwater and surface water interaction, some boreholes can be selected close to the surface water bodies

   1.3. Considering various land uses such as intensive agriculture areas covering various crop type, irrigation practices, soil type, settlements etc. to address well the vulnerable sites in the watershed in terms of groundwater contamination
   1.4. The water level depth ranging from shallow to deep groundwater systems.
   1.5. Spatial and depth distribution throughout the watershed considering the groundwater flow paths
   1.6. Logistical issues should also be taken care for the continuous accessibility for the monitoring, such as bore ownership, working condition, road access etc.
2. *Sampling Frequency*: When designing a sampling plan, it is important to define the frequency and duration of groundwater sampling. For example, if the monitoring is for a basic groundwater resource assessment it is recommended annual sampling for basic quality indicators (e.g., pH, Electrical Conductivity (EC), Temperature (T) and Dissolved Oxygen (DO)) and as per the need for other water quality parameters. It is recommended to collect long-term data (one or more decades) on water level and chemistry for better understating the difficulties associated with groundwater availability and sustainability.
3. *Sampling Method*: As the stagnant water within a borehole is exposed to atmospheric conditions and can undergo changes to its physical and chemical characteristics, the bore purge method is followed to collect the representative sample by making sure the stagnant water within the borehole is removed. For this reason, boreholes should be purged before sampling by pumping a volume of water equivalent to at least 4 to 6 times the internal volume of the borehole. This purged water is wasted and followed by the groundwater sample collection for analysis. It is also not recommended to use an air lift pump as the introduction of dissolved oxygen to the ground water may alter the sample characteristics. The volume of the water in the bore casing is calculated using the following formula: $V = 3.14 \times r^2 \times L \times 100$, where, V is the volume of water (liter), r is the radius of the casing (m) and L is the length of the water column (m).
4. *Measuring Field Parameters:* Some physicochemical parameters should be readily measured on site as their characteristics change rapidly over a short time scale. Parameters that should be measured in the field include pH, Electrical Conductivity (EC), Temperature, Dissolved Oxygen (DO), Redox potential (Eh) and Alkalinity. It is recommended to measure field parameters using a multiparameter meter with an electrode for each parameter. Before using the meter, it is vital to calibrate accurately according to the standard operating procedures of the manufacturers. So, it is important to follow the instructions supplied with the equipment. During calibration of each electrode, it is necessary to record on a standard sheet the date, temperature and calibration readings. This will be a track record for us to check the performance of each electrode and provide evidence that quality procedures are being taken care during measurement.

2.3.4 Ground Water Sampling Record

Groundwater sample bottles should be clearly labeled with a unique borehole number so that subsequent lab analysis can be properly executed. Basic information like borehole number and date should be written in the label of the sample bottle and other relevant information should be recorded in the sample report. Table 2-1 and Table 2-2 are provided as an appropriate template in this regard.

Table 2-1: Template Table for Ground Water Sampling Report (1)

S. No	**Groundwater Sampling Description**		
1	Sample ID number		
2	Sample location	Latitude	Longitude
3	Date and time of sampling		
4	Nature of location		
5	Borehole depth		
6	Pump suction depth		
7	Year of borehole installation		
8	Sample Appearance (odour, colour, turbidity)		
9	Name of sample collector		
10	Remarks (details of onsite filtration and preservation)		

Table 2-2: Template Table for Ground Water Sampling Report (2)

S.No	**Date**	**Sample ID**	**Temp (^{0}C)**	**pH**	**EC (µs/cm)**	**DO (mg/l)**

2.4 Water Quality

Onsite measurement procedure for some of the water quality parameters (with particular reference to the ground water quality) is explained briefly hereunder.

1) ***pH***: Groundwater pH is a fundamental property that describes the acidity and alkalinity and largely controls the amount and chemical form of many organic and inorganic substances dissolved in groundwater. The ability of the water to transport harmful substances is significantly controlled by pH and determines the suitability of groundwater for various uses. As pH varies with temperature, the pH meter measures pH along with temperature, and adjusts the reading according to the temperature of the sample and the results are given in pH units.
2) ***Electrical Conductivity***: Electrical conductivity (EC) is a measure of the total amount of solids dissolved in water. It is also an indirect measure of water salinity, and one of the most common methods used to test water. Electrical conductivity is significantly affected by the temperature, so all results should be normalized to a standard temperature of 25°C. The EC is also highly influenced by the ionic composition of water. In which chloride (Cl^-) and sodium (Na^+) are the major ions influencing groundwater EC. Other ions such as carbonates, sulphates, magnesium, calcium and potassium also contribute to the water salinity. EC is an important parameter to calculate total dissolved solids which is also used as an indicator to determine the general water quality.
3) ***Dissolved Oxygen***: Dissolved oxygen (DO) is a measure of the quantity of oxygen present in water. Generally, groundwater will have low dissolved oxygen, as there is a lack of direct contact with atmosphere and it is also being utilized in chemical and microbiological processes. Depletion of DO highly activates microbial reduction processes in groundwater. The oxygen supply is either due to recharge by oxygenated water or the air transfer through the unsaturated medium above the water table. A dissolved oxygen meter with an electrode is a device in which oxygen diffuses across a membrane in a submerged electrode, to complete an electrical circuit. This device measures the dissolved oxygen concentration in milligrams per liter or percentage saturation. The advantage of this type of meter is that you can measure directly in the groundwater samples. The amount of dissolved oxygen in a sample can vary with depth, temperature, and biological demand. Measurements of dissolved oxygen can be most accurately obtained by placing the electrode within a closed flow cell, which excludes atmospheric contact with the water.
    a) ***Note:*** A wide variety of meters are available, but the most important part is the electrode. Use reliable electrodes and strictly follow the manufacturer’s instructions for proper maintenance and calibration using standard solutions. Improperly maintained electrodes are subject to corrosion, which affects the accuracy of the parameters. Periodically measure the standards of various electrodes to test its measurement accuracy. If it has drifted, recalibrate the electrode using a new standard solution. After each field work is completed or if you find any sign of electrode poor performance, clean the electrode according to the manufacturer’s recommendation.
4) ***Filtration:*** Need of groundwater sample filtration protocol depends on the purpose of monitoring. Generally, the borehole construction, purging and sampling techniques used should minimize the turbidity of the groundwater sample so that there is no need to filter for certain applications. As there is a delay between sampling and laboratory analysis, it is often necessary to filter samples onsite to preserve certain parameters such as cations, anions, trace elements and some isotopes.

2.5 Evapotranspiration

The demand for fresh water is on a steady rise due to ever expanding human activities. Moreover, in the light of climate change; least and less developed nations are facing the threat of acute shortage of water in the future decades. The distribution of water is not the same across the globe and it is the top priority of the scientists in the field to understand the different processes of the hydrologic cycle and estimating the quantum of water available in each phase of the cycle at regional and country levels. In India, though stream flows and groundwater levels are observed periodically, reliable data on the quantity of water reaching the atmosphere through evapotranspiration (ET) is not available. This lack of data causes high uncertainties in closing the water budget and estimating the quantum of water available for human consumption. ET is a critical component of the hydrologic cycle and moreover, it is the terrestrial link to the atmosphere as it connects the energy and water cycle. Accurate estimation of ET is a major requirement for land surface modeling, numerical weather prediction and irrigation supply to crops etc.

ET is 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. Evaporation is the process whereby liquid water is converted to water vapor (vaporization) and removed from the evaporating surface (vapor removal). Transpiration consists of the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere.

2.5.1 ET Measurement using Agro-Meteorological Stations

Evapotranspiration is not easy to measure. Specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine evapotranspiration. The methods are often expensive, demanding in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel. However, there are other indirect methods like the Bowen ratio energy balance and the eddy covariance available to estimate ET (refer to the relevant sections in Chapter 3). These indirect methods require input from data on several variables measured in Agro-Meteorological Stations install in the field.

ET is estimated at any given site using the measurements from the 10 m tall micrometeorological tower (popularly called Agro-Met Station and abbreviated as AMS). The various instruments and the measured variables are listed in Table 2-3. Figure 2-15 presents a picture of the AMS tower.

Table 2-3: List of Different Instruments and Observed Weather Variables at The AMS Tower

Observed parameter	**Instrument**	**Height(s) of installation**
Air temperature	Platinum resistance thermometer	2 m, 4 m and 6 m
Relative Humidity	Capacitor Type	2 m, 4 m and 6 m

Observed parameter	Instrument	Height(s) of installation
Wind speed and wind direction	Cup Anemometer	2.5 m, 5 m and 10 m
Atmospheric pressure	Transducer	2 m
Rainfall	Tipping Bucket rain gauge	1 m
Net radiation ● Shortwave incoming ● Shortwave outgoing ● Longwave incoming ● Longwave outgoing	Four component net radiometer	3 m
Diffuse radiation	Shaded pyranometer	3 m
Soil heat flux	Flux plate	-0.05 m, -0.2 m
Soil temperature	Soil Thermometer	-0.05 m, -0.15 m and -0.3 m

Figure 2-15: A typical AMS Tower Installed in the Field

All the parameters are measured at 5 m intervals and averaged for 30 m. The data for every half hour is stored in a data logger and also transmitted through a yagi antenna to pre-determined server.

<u>Protocols for retrieving data from the flux tower</u>

1. Open the enclosure box of the data logger using the key and press Esc key to bring the data logger to active state.
2. Ensure that the pen drive supplied by Komoline Electronics is fixed in the logger
3. Press the Backup data button in the logger. The display in the logger will show progress and once the transfer is complete, a status message confirming the same will be displayed.
4. Remove the pen drive from the logger and put it in the laptop.
5. There will be a text file named DATAFILE. Copy the file to the laptop. Ensure the file is copied to the laptop.
6. Delete the DATAFILE from the pen drive. The pen drive should be made empty after data is copied to the laptop.
7. Place the pen drive back in its original position in the data logger.
8. Close the enclosure box of the data logger.

<u>Some Important Considerations</u>

- Whenever you go to the field, adjust the ring of the diffuse skylight pyranometer so that the shadow of the ring falls over the sensor. This should be done during every field visit whereas the flux tower data should be retrieved once every month.
- Laptop needs to be carried to the field for retrieving data from the flux tower. So keep the laptop packed when starting to go to the field.
- It should be ensured that the data logger and the fence is locked before leaving the flux tower site.
- There will be a cardboard sheet in the data logger enclosure explaining the steps for data retrieval from the tower. Consult the sheet always and keep the sheet safe in the enclosure.
- Only the pen drive given by the Komoline Electronics will work for retrieving data. Hence always keep it in the data logger and never replace it with any other pen drive.

The data from AMS tower can also be used for estimating potential evapotranspiration (PET) and Reference crop evapotranspiration (ET_0). ET_0 can be estimated using the Penman-Montieth equation (see FAO drainage and irrigation paper no.56). FAO had also developed a software for estimating ET_0 (http://www.fao.org/nr/water/eto.html). Apart from this PET is estimated from the Soil-Water-Atmosphere-Plant (SWAP) model.

2.6 Canopy Variables

All crop related measurements described below will be primarily used for hydrological applications. Leaf Area Index (LAI) and biomass data will be used for soil parameter estimation by inverse approach using crop model. LAI data will be used as a vegetation descriptor in water cloud model for estimating soil moisture.

2.6.1 Leaf Area Index (LAI)

On the outset, following points are to be noted:

- LAI should be collected within the 2 m^2 area adjoining the location where the access tube is installed.
- Mark at least five plants for LAI measurement within the 2 sq. m, so that you measure the LAI of same plants for every field visit.
- This marking can be done by making some identification mark in the stem or leaf of the plants with permanent marker, which can be easily visualized.

In the following sub-sections LAI measurement using three different techniques is presented.

2.6.1.1 Laser Leaf Area Meter (CI – 202)

The CI-202 (CID Bio-science), see Figure 2-16, meter directly measures length, width, area, and perimeter through calculating ratio and shape factor after the measurement is completed.

Figure 2-16: Laser Leaf Area Meter

<u>Operating Principle</u>

The CI-202 directly measures length, width, area, and perimeter through calculating ratio and shape factor after the measurement is completed.

Each time the control unit detects that the scanner has progressed 1 mm, the computer will check to see if the width reading is non-zero.

- If the width measurement is non-zero, the computer takes the following actions:
- The length measurement is increased by 1 mm.
- The width measurement is added to the area accumulator.
- If the width measurement is greater than the currently stored maximum width, the maximum width is updated.
    - Computing Ratio and Shape Factor

Aspect ratio and shape factor information can be easily calculated from the other information gathered. These derived quantities are calculated whenever necessary for the purposes of display or data dumping. The calculations used are shown below.

Aspect ratio is the ratio of the leaf length to its maximum width. It can be calculated from the equation:

$$r = \frac{l}{W_m} \qquad \text{Eqn. 2-12}$$

where, r is the aspect ratio, W_m is the maximum width and l is the length.

Shape factor is the ratio of the leaf area to the leaf perimeter, corrected so that the shape factor of a circle is equal to 1. It can be calculated from the equation:

$$f = 4\pi \frac{a}{p^2} \qquad \text{Eqn. 2-13}$$

Where, f is the shape factor, a is the area and p is the perimeter[5].

How to use

- The CI-202 can be used for plants with shorter leaves, for eg. Turmeric and sunflower.
- For other crops like maize, sorghum, marigold, horse-gram and groundnut, it is better to collect the crop samples and then measure the LAI in the lab.
- At least three crop samples should be measured.
- All leaves of a plant should be measured.
- Maintain a constant speed for moving the scanner in the platform as the measurement accuracy may vary with speed.
- Before starting to use CI-202, it is better to take a measurement without any leaf in the scanning area, this should ideally give a LAI of zero, but in some cases, it may give a smaller LAI value which has to be subtracted from the final measurements.
- Avoid using CI-202 during early morning hours as some dew may be present in the leaf, which will damage the scanning platform.
- Usually, the leaves at the bottom have some soil particles sticking to it, whip it out with a cloth before using the scanner.
- Though it is mentioned that the instrument needs no calibration, we can check the accuracy of the instrument by scanning a leaf of known area (usually we cut a leaf in rectangular or square shape and measure the area by scale) and compare it with the area which the instrument gives after scanning. Thus, we can have an idea of any instrument error that may occur due to repeated usage of the device for long time.

2.6.1.2 LAI – 2200C Plant Canopy Analyzer

The LAI-2200C Plant Canopy Analyzer (see Figure 2-17) calculates Leaf Area Index (LAI) and other canopy structure attributes from radiation measurements made with a fisheye optical sensor (148˚ field of view). Measurements made above and below the canopy are used to

[5] More details on technical specifications is available in the following website, http://www.cid-inc.com/products/leaf-area-lai/portable-laser-leaf-area-meter

determine canopy light interception at five angles, from which LAI is computed using a model of radiative transfer in vegetative canopies.

Figure 2-17: LAI-2200C Plant Canopy Analyzer

Operating Principle

The LAI-2200C Plant Canopy Analyzer computes LAI from measurements made above and below the canopy, which are used to determine canopy light interception at five angles. These data are fit to a well-established model of radiative transfer inside vegetative canopies to compute LAI, mean tilt angle, and canopy gap fraction. The optical sensor of the LAI-2200C consists of a fisheye lens and an optical system. The fisheye lens takes in a hemispherical image, which the optical system focuses onto the five-ring photodiode optical sensor[6].

How to use

- Licor – 2000 can be used for all plants, either grasslands or row crops or forests.
- It is better to use Licor during morning and evening when sun rays fall atan angle and there will be minimal shadow effect, and usually the light intensity during morning and evening will not vary much within measurements.
- For measuring at a location in a plot, first reading should be made above the canopy (which you are going to measure), usually this reading is the reference reading and should be taken on shade (either your shade or any nearby tree), then the instrument is placed below the canopy such that direct sunlight does not fall on the sensor, and four measurements are made at different points.
- At the end of the fourth measurement, the instrument itself calculates the mean LAI and its standard deviation.
- This procedure has to be repeated at two more locations within the same plot (five measurements, one above canopy ad four below canopy)

[6] Detailed operating principle and the equations or models used in calculating LAI is available in the manual of LAI-2200C,
http://www.licor.com/env/products/leaf_area/LAI-2200C/lit.html

- Make sure that the intensity of sunlight remains same within a measurement (means one above canopy and 4 below canopy), from my experience, we can avoid most of the light related problems if we take measurements after say 4.30 pm[7].

2.6.1.3 Fisheye Lens (Fully Circular Hemispherical Lens)

Operating Principle

Hemispherical canopy photography is a technique for studying plant canopies via photographs acquired through a hemispherical (fisheye) lens from beneath the canopy (oriented towards zenith) or placed above the canopy looking downward. A hemispherical photograph provides a permanent record and is therefore a valuable information source for position, size, density, and distribution of canopy gaps. It is able to capture the species, site and age-related differences in canopy architecture, based on light attenuation and contrast between features within the photo (sky versus canopy). Hemispherical photographs generally provide an extreme angle of view, generally with a 180-degree field of view (see Figure 2-18).

Figure 2-18: Hemispherical Fisheye Lens

How to use

- The camera with fish-eye lens can be used for all plants in our watershed.
- For crops below 1 m height, the photograph should be taken with lens pointing vertically downwards, from a height of approximately 1 m from the top of the canopy.
- For crops above one meter height, the camera should be kept in the ground with lens pointing vertically upwards (towards sky).
- Note down the image number and the focal length for each photograph.
- At least three photographs should be taken in a plot.
- Since the lens is hemispherical it gives a circular image, part of the body of the photographer may fall in the image, to minimize this stretch the hands with camera as much as possible as shown in the image below.

Processing of the Images

The images acquired using the fish eye lens can be processed using the CAN-EYE software developed at INRA, Avignon, France (http://www6.paca.inra.fr/can-eye).

[7] A Video demonstration on how to use LAI-2200C for several crops is available in the following link.http://www.licor.com/env/products/leaf_area/LAI-2200C/applications.html.

Figure 2-19: Example of taking Photograph Using Hemispherical Lens

2.6.2 Biomas

Following procedure are to be adopted for measuring plant biomass in a given micro-watershed:

- Biomass has to be collected by harvest or destructive sampling method.
- Biomass of short-term crops like maize, sorghum, marigold, sunflower and horse-gram has to be collected in every field visits. Biomass of long-term crops like turmeric shall be collected once in a month.
- The minimum number of samples is three; this can vary depending upon the farmer's willingness to provide us the crop sample.
- The biomass sample should not be collected within the 2 sq. m area marked for LAI measurements, instead it should be collected from anywhere within the plot. But make sure that the sample collected should be representative of the crop growth of the entire plot.
- All plant parts including dry leaves, fruit/seeds/flowers if any and roots should be collected. The sample collected for biomass can also be used for LAI measurements, so take care not to crush the leaves while collecting the crop sample.
- The collected biomass has to be sealed in an air tight cover. Fresh weight (before oven drying) and dry weight (after over drying) should be noted for all biomass samples.

2.6.3 Crop Yield

Following procedure are to be adopted for measuring crop yield in a given micro-watershed:

- Yield of crop (flower or root or fruit) has to be collected at the time of harvest for most crops.
- In marigold, since there are usually seven harvest (7 times picking flower), yield (flower) has to collected for every field visit from the flowering stage. In case of marigold note the number of flowers and buds of each sample. For crops like turmeric, the yield which is in the root has to be collected at harvest.
- For crops like sunflower, maize, sorghum and horse-gram the yield has to be collected at harvest. Since the biomass (along with yield) is collected in each field visit for crops other than turmeric, the yield at different stages of the crop can be noted.
- Fresh weight (before oven drying) and dry weight (after over drying) should be noted for all samples.
- For crops like sunflower, maize, sorghum and horse-gram, the yield is measured in terms of the weight of the grain/seed. Hence the seeds/grains have to be removed from the oven dried sample and weighted separately to obtain the original yield.

2.6.4 Crop Growth and Management Activities

Following information are to be noted about crop growth and management practices in a given micro-watershed:

- On-field activities like sowing, fertilizing, irrigation, pest control and harvest has to be noted as and when it is practiced.
- Different stages of crop growth like sowing, germination, flowering and harvest should be noted in each field visit.
- Sowing: Date of sowing, quantity of seeds used, variety of seed (usually given in the packet containing seeds), sowing depth etc.
- Fertilization: Date of fertilization, frequency and quantity of fertilizer used, brand name of the fertilizer (like DAP, Potash, Urea etc.)
- Pest control: Date of pest control, frequency and quantity of pesticide used, brand name of the pesticide.
- Irrigation: Date and frequency of irrigation, depth of irrigation (in case of furrow irrigation), bore-well details (depth, pump capacity), electricity hours etc.
- Harvest: Date of harvest, type of harvest (picking or cutting), yield as recorded by the farmer, last year’s (or previous year’s yield of the same crop), market price of the commodity etc.
- Stages of crop growth: Date of sowing, flowering, maturity (beyond this stage there will not be any growth in stems and leaves) and harvest.
- Date of flowering implies the day when at least 50 % of the crops in the plot is flowering.
- Sometimes interview (simple talking) with farmers is essential to know one or more of these details, this can be done in any field visit as and when the farmer is available in his farm.

2.7 Weather Variables

Automatic Weather Station (AWS) is designed to store real time weather data. The agro meteorological data will be useful for the various fields i.e., crop irrigation, water management, agriculture practices / activities to reduce risk in agriculture products, weather information purposes etc. The following variables are measured in an automatic weather station.

- Air temperature
- Relative humidity
- Air pressure
- Wind direction
- Wind speed
- Solar Radiation

Figure 2-20 shows an installed AWS (CIMEL, type ENERCO 407 AVKP) which has been used for daily records of air humidity, wind velocity, maximum and minimum temperature, precipitation and global radiation.

Figure 2-20: Automatic Weather Station installed in the Field

2.8 Recording of the Field Observations

Systematic recording of the field observations is of paramount importance. With advent in GIS and Information Technology, it is now possible to directly transfer the field observations into a mobile application. This application in turn remains connected to cloud-based servers where this data is stored into databases. Furthermore, the same data once stored into the servers' databases may be viewed, downloaded and queried upon via customized web-applications or web-portals. With these technologies in place, preliminary quality control and data compilation during the field measurement phase of the studies can be accomplished on a near-real time basis.

The **Sat2Farm** mobile applications, developed by Satyukt Analytics Private Limited is an excellent tool which may be used for this purpose. It is also linked with the Sat2Fam web application which may be customized for viewing, querying, downloading and providing preliminary quality control as the project under consideration. Figure 2-21 shows the Sat2Farm mobile application interface and a snapshot from Sat2Farm web application is shown in Figure 2-22.

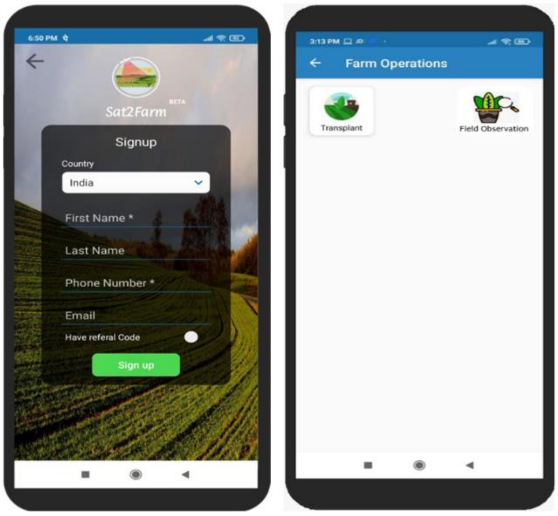

Figure 2-21: Sat2Fam Mobile Application

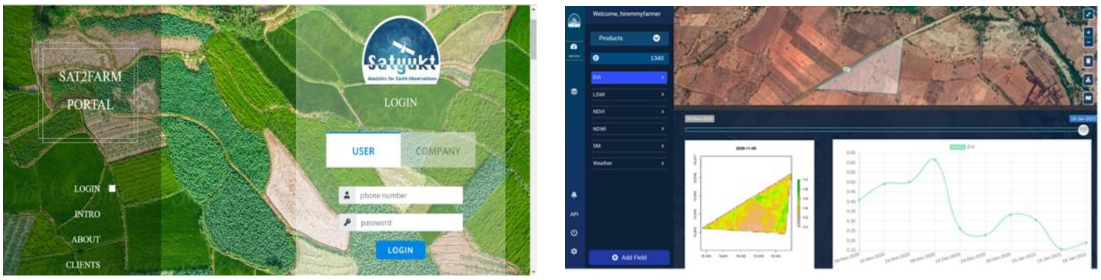

Figure 2-22: Sat2Fam Web Portal

3 Modelling

This chapter describes the methodology to be adopted to estimate the values of key hydrologic variables using the data from field measurement, satellite remote sensing and relevant secondary sources. The procedures included are based on the previous experiences during the execution of the Sujala program in the pilot watersheds across the Karnataka.

3.1 Runoff Modelling

In general, the amount of runoff generated from a particular location depends upon the soil type, LULC, and rainfall intensity. However, runoff from the outlet of a watershed also depends upon additional factors e.g., height of the bund, farm pond and other water conservation mechanisms being applied in the watershed. Following two approaches are recommended to compute the runoff potential:

(i) SWAT model:

SWAT (Soil Water Assessment Tool) hydrological model categorizes the watershed into hydrological response units (HRU) for computing the runoff based on the Curve Number (CN) approach. HRU is defined based on the similar soil type, land use and slopes. SCS Runoff Curve Number method is developed by the United States Department of Agriculture (USDA) and the Soil Conservation Service (SCS). The method has been used widely for the estimation of runoff.

Mockus expresses the empirical relationship between the retention (rainfall not converted into runoff) and runoff properties of the watershed and the rainfall as:

$$\frac{F}{S} = \frac{Q}{P} \qquad \text{Eqn. 3-1}$$

where, $F = P - Q =$ actual retention after runoff begins;
Q = actual runoff
S = potential maximum retention after runoff begins
P = potential maximum runoff (i.e., total rainfall if no initial abstraction).
$P - I_a$= potential maximum runoff (rainfall available for runoff)

$$\frac{P - I_a - Q}{S} = \frac{Q}{P - I_a} \qquad \text{Eqn. 3-2}$$

Where $I = 0.2S$ and

$$S = \frac{1000}{CN} - 10 \qquad \text{Eqn. 3-3}$$

Where the CN is known as curve number and standard tables/software are available to estimate its value given the climatic conditions and other catchment characteristics. Required input data for running the SWAT model is provided in Table 3-1.

Table 3-1: Source of Required Inputs for SWAT

Input Data	Source
Elevation	Cartosat-DEM from NRSC
Climate	From nearest weather station
Land Use Land Cover	LRI Atlas
Soil type	LRI Atlas

(ii) EStimation of Agricultural RUnoff potential (ESARU)

A method for the estimation of agricultural runoff potential was developed by UAS, Raichur for Sujala-III program to compute runoff by accounting for the local factors e.g., height of the bund, farm pond and other water conservation mechanisms being applied in the watershed.

The ESARU model utilized the distribution of the rainfall intensities (as shown in Figure 3-1) and utilized these for the computation of runoff. An excel file is developed to compute the potential runoff under, i) existing conditions, and ii) with interventions and provided with this manual. Table 3-2 provides the required input data for the model.

Table 3-2: Source of Required Inputs for ESARU Model

Input Data	Source
Elevation	Cartosat-DEM from NRSC
Climate	From nearest weather station
Land Use Land Cover	LRI Atlas
Soil type	LRI Atlas
Length of bund per ha	Google Earth Imageries, Field Survey

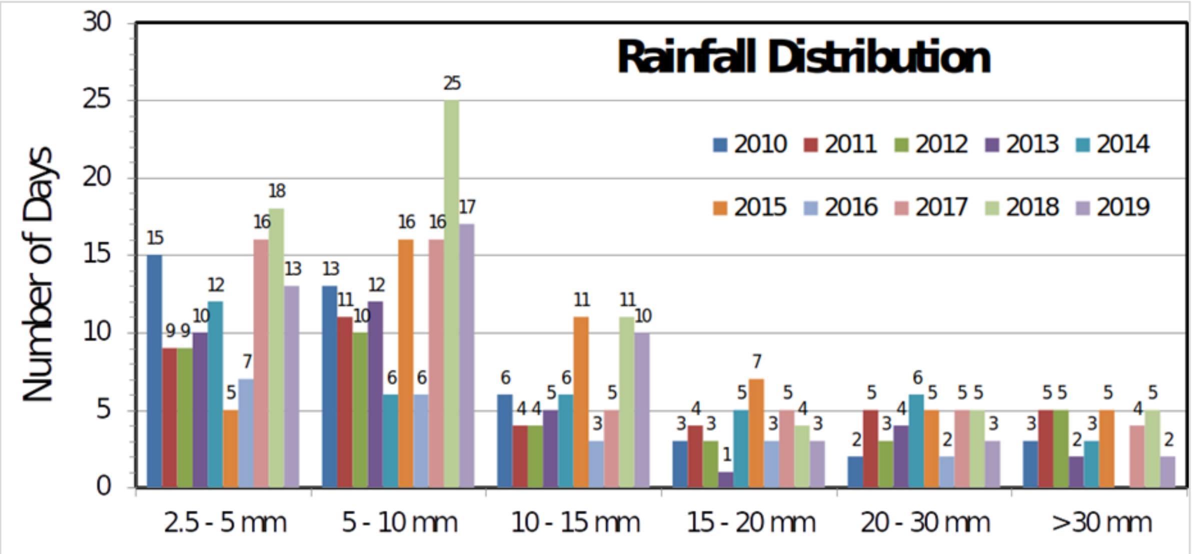

Figure 3-1: Rainfall Distribution Graph

3.2 PET Modelling using Weather Station Data

The CROPWAT 8.0 software is a freely available software that can be used for the estimation PET which uses the Penman-Monteith equation. CROPWAT is a tool developed by the Land

and Water Development Division of FAO (Food and Agriculture Organization). PET (mm/day), on a daily basis can be estimated based on long term meteorological data obtained from weather stations such as air temperature, wind velocity, relative humidity and sunshine hours. The FAO–Penman-Monteith equation as given in FAO Irrigation and Drainage Paper No. 56 as,

$$\mathrm{PET} = \frac{0.408 \times \Delta \times (R_n - G) + \gamma \times \frac{900}{T_{mean} + 273} \times u_2 \times (e_s - e_a)}{\Delta + \gamma \times (1 + 0.34 \times u_2)}$$ **Eqn. 3-4**

where,

PET reference evapotranspiration $[mm/day]$

R_n is the net radiation at the crop surface $[MJm^{-2}day^{-1}]$

G is the soil heat flux $[MJm^{-2}day^{-1}]$

T_{mean} mean daily air temperature $[°C]$

u_2 wind speed at 2 m height $[ms^{-1}]$

e_s saturation vapor pressure $[kPa]$

e_a actual vapor pressure $[kPa]$

Δ slope of the vapor pressure curve $[kPa\ °C^{-1}]$

γ psychrometric constant $[kPa\ °C^{-1}]$

3.3 AET modelling using Weather Station Data

Performing ground measurements towards estimation of AET is critical for calibrating and validating satellite-based outputs. There exists a variety of ground-based instruments and methods such as: (i) lysimeter, (ii) Eddy covariance (EC) technique, (iii) Flux gradient (or) Bowen ratio energy balance method, (iv) Scintillometer etc. In this manual the Bowen Ratio Energy Balance (BREB) method is discussed following the experience learned from the studies undertaken in the Berambadi experimental watershed (Sekhar, et al., 2016).

The BREB method is suitable for vegetated surfaces, especially croplands. This method requires the measurement of air temperature and relative humidity to be measured at two different heights above the vegetation canopy to estimate Bowen Ratio (β, defined as the ratio of sensible to latent heat fluxes). Combining β with surface radiative fluxes (from the net radiometer) and the soil heat flux (from the soil heat flux plates buried underground below the flux tower), AET can be measured. Typically, the measurements will be carried out at intervals of 1 minute to 5 minutes and will be averaged over half an hour. The basic principles and equations for estimating AET from these measurements are described in the following paragraphs.

The partitioning of energy at the surface into its various components is given by the surface energy balance equation (Brutsaert, 1982),

$$R_n - \lambda E - H + LF_p - G + A_d = \frac{dw}{dt}$$ **Eqn. 3-5**

where,

R_n is the net radiation at the surface $[Wm^{-2}]$

λE is the latent heat flux $[Wm^{-2}]$ i.e. ET is expressed in energy terms where, λ is the latent heat of vaporization and E is the mass of water converted into vapor.
H sensible heat flux $[Wm^{-2}]$
LF_p is the is the energy used by the vegetation for fixation of CO_2 during photosynthesis
G is the soil heat flux going into the surface $[Wm^{-2}]$
A_d is the horizontal advection of energy $[Wm^{-2}]$
$\frac{dw}{dt}$ is the rate of energy storage per unit area $[Wm^{-2}]$.

All the energy fluxes towards the surface are considered positive and all the fluxes going away from the surface are considered negative in Eqn. 3-5. However, LF_p, A_d and the rate of energy storage will be small relative to the other terms and hence, for all practical purposes, Eqn. 3-5 can be simplified into,

$$R_n - \lambda E - H - G = 0 \quad \text{Eqn. 3-6}$$

The net radiation, R_n is composed of four components: incoming shortwave, outgoing shortwave, incoming longwave and outgoing longwave and expressed as,

$$R_n = R_{sd} - R_{su} + R_{ld} - R_{lu} \quad \text{Eqn. 3-7}$$

The sign convention followed in Eqn. (3-7) is the same as that of Eqn. (3-5). Substituting the definition of Bowen Ratio ($\beta = H/\lambda E$) in the simplified surface energy balance equation (Eqn. 3-6) and rearranging, we get,

$$\lambda E = \frac{R_n - G}{1 + \beta} \quad \text{Eqn. 3-8}$$

Sensible heat flux can be estimated as a residual of Equation (3-6), assuming perfect energy balance closure at the surface. Now with this, we proceed onto developing equations for Bowen Ratio. The flux gradient equations for estimating H and λE are given as,

$$\lambda E = \frac{\rho_a C_p}{\gamma} k_w \frac{(e_{a2} - e_{a1})}{(h_2 - h_1)}, \quad \text{Eqn. 3-9}$$

$$H = -\rho_{a.} C_a k_h \frac{(T_{a2} - T_{a1})}{(h_2 - h_1)} \quad \text{Eqn. 3-10}$$

where,
ρ_a is the air density $[kgm^{-3}]$
C_p specific heat of air at constant pressure= $1005\, Jkg^{-1}{}^\circ C^{-1}$
γ is the psychrometric constant $[Pa{}^\circ C^{-1}]$
k_h and k_w are the eddy transfer coefficients for water vapor and heat, respectively

The vapor pressure (e_{a1} and e_{a2}, in Pascals) and air temperature (T_{a1} and T_{a2}, in °C) can be estimated/measured at two levels (h_1 and h_2) above the canopy with level 1 being the lower level and level 2 at the higher level. The Actual vapor pressure and psychrometric constant are given as,

$$e_a = \mathrm{RH} \times 0.611 \times \exp\left(\frac{17.27 T_a}{273.3 + T_a}\right) \quad \text{Eqn. 3-11}$$

$$\gamma = \frac{pC_p}{0.622\lambda}$$ **Eqn. 3-12**

Here, RH is the relative humidity expressed as a fraction between 0 and 1, T_a is air temperature (°C), p is the atmospheric pressure (Pa) and λ is the latent heat of vaporization for water (= $2.501 \times 106 - 2370 \times T_a\ Jkg^{-1}$). Assuming k_w and k_h are equal, β was calculated as,

$$\beta = \gamma \frac{(T_{a2} - T_{a1})}{(e_{a2} - e_{a1})}$$ **Eqn. 3-13**

The BREB method for λE estimation becomes unreliable when β approaches – 1 and this will happen mostly during sunrise, sunset and at night times. Hence to remove highly uncertain λE values, $\beta < -0.7$ will be discarded (Ortega-Farias, et al., 1996). Perez, et al., (1999) developed an inequality for checking the integrity of meteorological data for estimating β,

$$\frac{(e_{a2} - e_{a1}) + \gamma(T_{a2} - T_{a1})}{R_n - G} > 0$$ **Eqn. 3-14**

The inequality expressed in the Eqn 3-14 must be always greater than zero. Data fulfilling this inequality alone were used in estimating β and λE. The gradient of vapor pressure curve becomes low during night times and in order to reduce the uncertainty in λE, the β values observed only during the daylight hours (defined as the time period of a day during which $R_{sd} - R_{su} > 0$) should be considered for calculating daily values of λE. β values are estimated at half hourly intervals (from the meteorological measurements) and then are averaged over the entire daytime to get daily daytime averaged Bowen ratio (β_{day}). From the net radiometer measurements, the half hourly measured values of $R_n - G$ are also averaged for the same time period to get the daytime averaged $R_n - G$, $(R_n - G)_{day}$. Time averaged latent heat flux (λE_{day}) is calculated as,

$$\lambda E_{day} = \frac{(R_n - G)_{day}}{1 + \beta_{day}}$$ **Eqn. 3-15**

This latent heat flux is converted into volumetric units of ET expressed in mm/day using the following conversion,

$$ET\left(\frac{mm}{day}\right) = \lambda E_{day}\left(\frac{W}{m^2}\right) \times daytime\ hours \times \frac{3600}{2.45 \times 10^6}$$ **Eqn. 3-16**

The daytime averaging should be done only for days on which more than 70% of the data were available in order to ensure reliable ET estimate. Apart from λE_{day}, the daily averaged values of the two latent heat ratios, evaporative fraction (EF_{day}, defined as the ratio of latent heat flux to net available energy) and the fraction of incoming solar radiation converted into latent heat flux ($RsdFact_{day}$) are also estimated as given below:

$$EF_{day} = \frac{1}{1 + \beta_{day}}$$ **Eqn. 3-17**

$$RsdFact_{day} = \frac{\lambda E_{day}}{(R_{sd})_{day}}$$ **Eqn. 3-18**

Here, $(R_{sd})_{day}$ is the daily daytime averaged value of incoming solar radiation in Wm^{-2}. The EF_{day} and $RsdFact_{day}$, estimated using Eqn. 3-17 and Eqn. 3-18, are used to validate the outputs derived from satellite data.

3.4 AET Modelling using Satellite Remote Sensing Data

The AET can be estimated using Satellite Data products with sufficient accuracy. During the execution of Sujala Program under the Watershed Development Department, AET dataset with a spatial resolution of 0.05° lat-lon (~5 km grid size) over Karnataka state at a temporal resolution of 8 days has been developed and used. Over selected watersheds, the 5-km AET products were disaggregated to 1 km resolution for finer level planning and management. AET was generated using a semi-empirical Triangle Model which was also tested over the different regions in India using the satellite products (Eswar, et al., 2017a), (Eswar, et al., 2017b).

3.4.1 AET using Semi-Empirical Triangle Model

AET from the Triangle Model is estimated combining satellite data from MODIS sensor along with reanalysis data from reanalysis products such as MERRA-2 and Indian Monsoon Data Assimilation and Analysis (IMDAA). Table 3-3 summarizes the list of satellite-derived products that have been used for the previous studies.

Table 3-3: Input Datasets required for the Generation of AET Products using The Triangle Model

Variable(s)	Data source
Land Surface Temperature (LST), Surface Emissivity (ε_s) and Satellite overpass time (t_{pass})	MOD11C2 – MODIS 8 days LST CMG at 0.05°
Surface reflectance	MOD09A1 – MODIS 8 days 7- bands surface reflectance at 500 m resolution
Air temperature (T_a)	MERRA-2/IMDAA Reanalysis product
Incoming global solar radiation (R_{sd})	MERRA-2/IMDAA Reanalysis product
Elevation	GMTED2010 DEM at 30 arc seconds resolution

MODIS sensor is already in use for 20 years now and if the sensor stops operating during the course of the project, data from the recent VIIRS sensor is used. The data products from the VIIRS sensor are available in sync with the data products from the MODIS sensor. This AET modelling approach requires meteorological inputs such as air temperature and solar radiation. Reanalysis models are a good source of meteorological variables as there is a continuous availability of data. Hence, data on air temperature and solar radiation are obtained from the MERRA-2 or IMDAA reanalysis. AET from the triangle model is estimated as,

$$ET_{8-day} = \frac{RsdFact(R_{sd})_{8-day} \times 24 \times 3600}{2.45 \times 10^6} \qquad \text{Eqn. 3-19}$$

where, ET_{8-day} is the AET averaged over an 8-day period, $RsdFact$ is the ratio of the latent heat flux to the total incoming solar radiation for the 8-day period and $(R_{sd})_{8-day}$ is the 8-day average incoming solar radiation from the reanalysis product. The other numerical values are the conversion factors between energy units (Wm^{-2}) to depth units ($mm\ day^{-1}$). $RsdFact$ is estimated from the triangle model which is based on the contextual relationship between Land

Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI). The schematic of this relationship is shown in Figure 3-2.

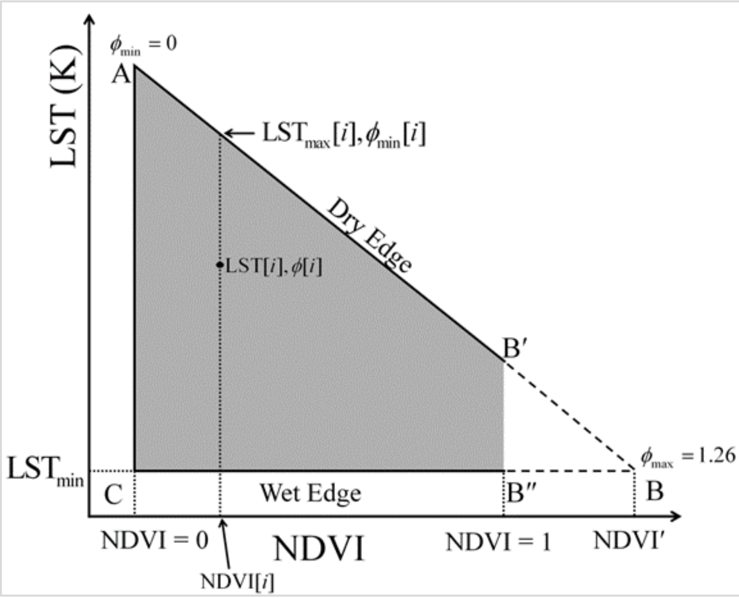

Figure 3-2: Schematic of the LST-NDVI Relationship used in the Triangle Model

For the detailed theoretical background about this model the readers are referred to Eswar, Sekhar and Bhattacharya (2017b) and references therein.

The triangle model provides the value for Evaporative Fraction ($EF = \lambda E/[R_n - G]$), which is then converted into $RsdFact$ as given below,

$$RsdFact = \frac{EF \times (R_n - G)_{\text{inst}}}{(R_{sd})_{inst}} \qquad \text{Eqn. 3-20}$$

Where, the subscript $inst$ indicates the energy components estimated at the instant of satellite overpass. The net available energy ($R_n - G$), is estimated using a model developed by Mallick et al. (2009) and R_{sd} is obtained from reanalysis products. It has been observed that the solar radiation data from the reanalysis products is biased and has to be corrected for the same to improve the accuracy. The solar radiation data is bias-corrected using a simple statistical bias correction approach developed and tested by Jain et al., (in preparation). The comparison between the AET estimated using the triangle model approach, AET estimated using the data from the Agrometeorological Station (AMS) located at Berambadi watershed and MODIS 16 ET product is given in Figure 3-3. Validation plot for AET products derived using the Triangle Model at Gopalpura micro-watershed is shown in Figure 3-4.

For applications at a relatively finer spatial level during the Sujala Program, the estimated ET products with 5 km spatial resolution are disaggregated over selected micro watersheds to 1 km spatial resolution using λE-NDVI contextual approach developed in Eswar, Sekhar and Bhattacharya (2017a).

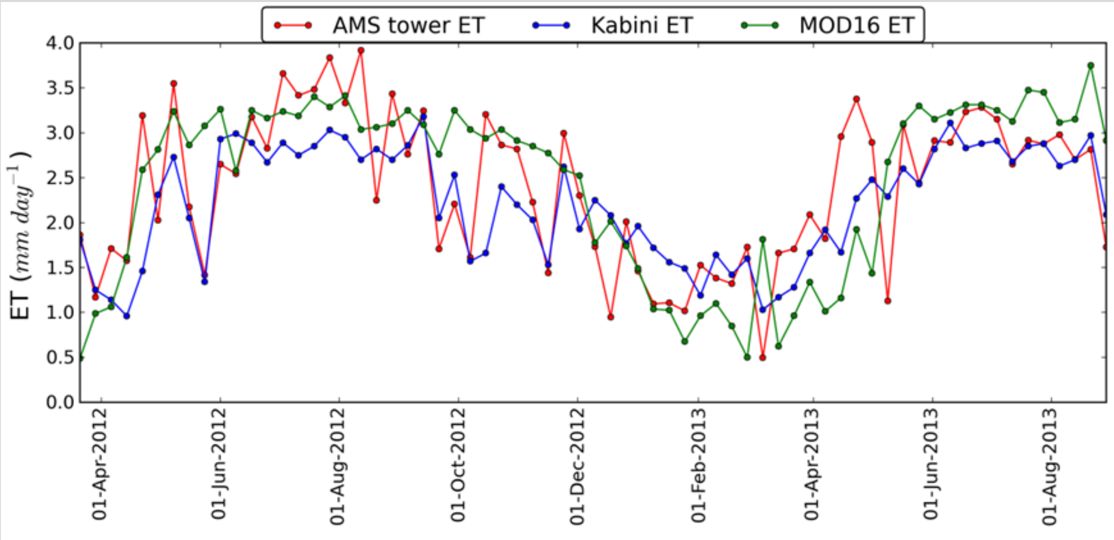

Figure 3-3: Comparison among AET Estimated using Triangle Model, AMS Data and MODIS 16 ET Products

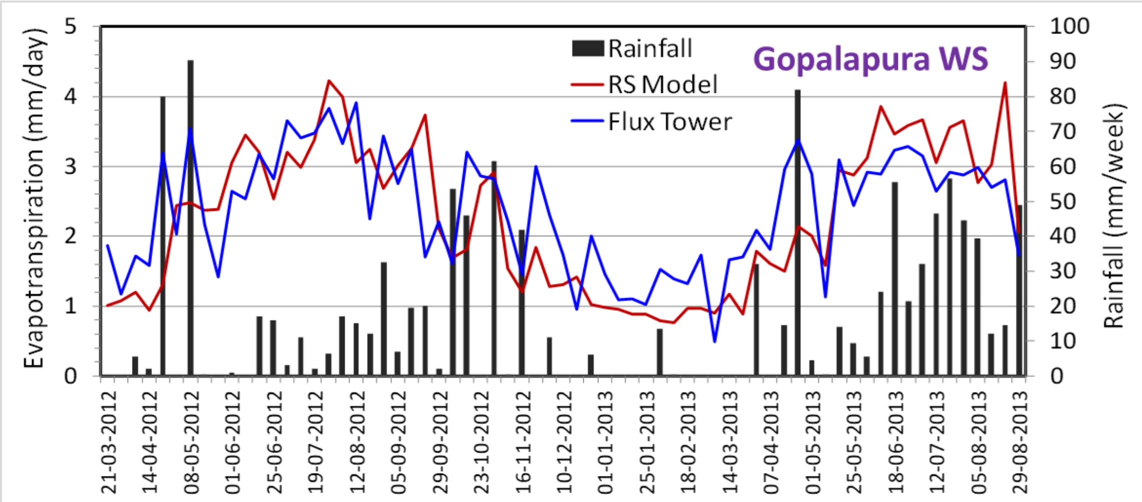

Figure 3-4: Validation Plot for Estimated AET using Satellite Remote Sensing Data at Gopalpura Watershed

3.5 Soil Moisture Modelling using Satellite Remote Sensing Data

The conventional way of measuring soil moisture is to install soil moisture sensors in the ground which measures the volumetric water content indirectly by using the properties of the soil, such as electrical resistance, dielectric constant, or interaction with neutrons etc. But this method is time-consuming and has limited coverage. Hence a number of methodologies are developed globally utilizing the satellite data to retrieve relative soil moisture which provides a better coverage compared to the former method. The optical wavelengths have relatively weaker relationship with SM, and cannot penetrate the clouds (prevalent during Kharif season) and vegetation during the crop growing season. On the other hand, microwave wavelengths have all weather capability and a better relationship with SM. Soil moisture data is provided by passive and active microwave sensors.

Passive microwave sensors provide soil moisture globally at a coarser spatial resolution whereas active microwave sensors have a higher spatial but low temporal resolution (2–4 weeks). Using soil moisture data directly from any of these sensors will have compromised spatial or temporal resolution.

Active microwave sensors have the spatial resolution up to 10 m which is useful for agriculture applications. Several empirical, semi-empirical and machine learning based models have been developed to estimate the SM, however these approaches require a vast amount of data for the calibration and are difficult to scale given the spatial variability present in agriculture in India. Physically based approaches are easy to scale, however require extensive information on surface roughness and vegetation canopy structure and are not suited for operational applications. An overview of the commonly used approaches for retrieving SM along with their physical principles, advantages and limitations can be found in Moran et al. (2004).

For the operational estimation of SM, time series-based models have been developed which utilizes the difference between a dry and wetter image Backscatter Coefficient (BC) to minimize the impact of soil and vegetation on BC. Tomer et al. (2015) extended the temporal change detection approach by taking an empirical CDF transformation (CT) to normalize the BC. The CT approach did not require the site-specific calibration, and was rather based on the available global soil properties (field capacity and wilting point) data. CT approach was validated using the RADARSAT-2 satellite data over 50 plots in an experimental watershed named Berambadi (see www.ambhas.com for details) situated in South of Karnataka state and was found to be working well with a RMSE up to 0.07 m3/m3.

Though active microwave sensors have higher spatial resolution, they are limited in terms of temporal resolution and to improve the temporal resolution of SM products, Tomer et al. (2016) developed an approach MAPSM (Merging Active and Passive Soil Moisture) to merge the daily soil moisture products of a passive microwave satellite (see Figure 3-5). The approach was tested by combining the active microwave (RADARSAT-2) and passive microwave (SMOS) data in the Berambadi watershed by using the field data collected over the 50 farms during 4 years. MAPSM was able to provide the daily SM products with a RMSE of up to 0.04 m3/m3 at a spatial resolution of 20 m and a RMSE of 0.02 at a spatial resolution of 0.02 m3/m3.

Soil Moisture products using these methodologies later was integrated into an Android-based mobile application, named Sat2Farm. The services provided by this application (freely available from Google Play Store) may be availed for any target watershed in future.

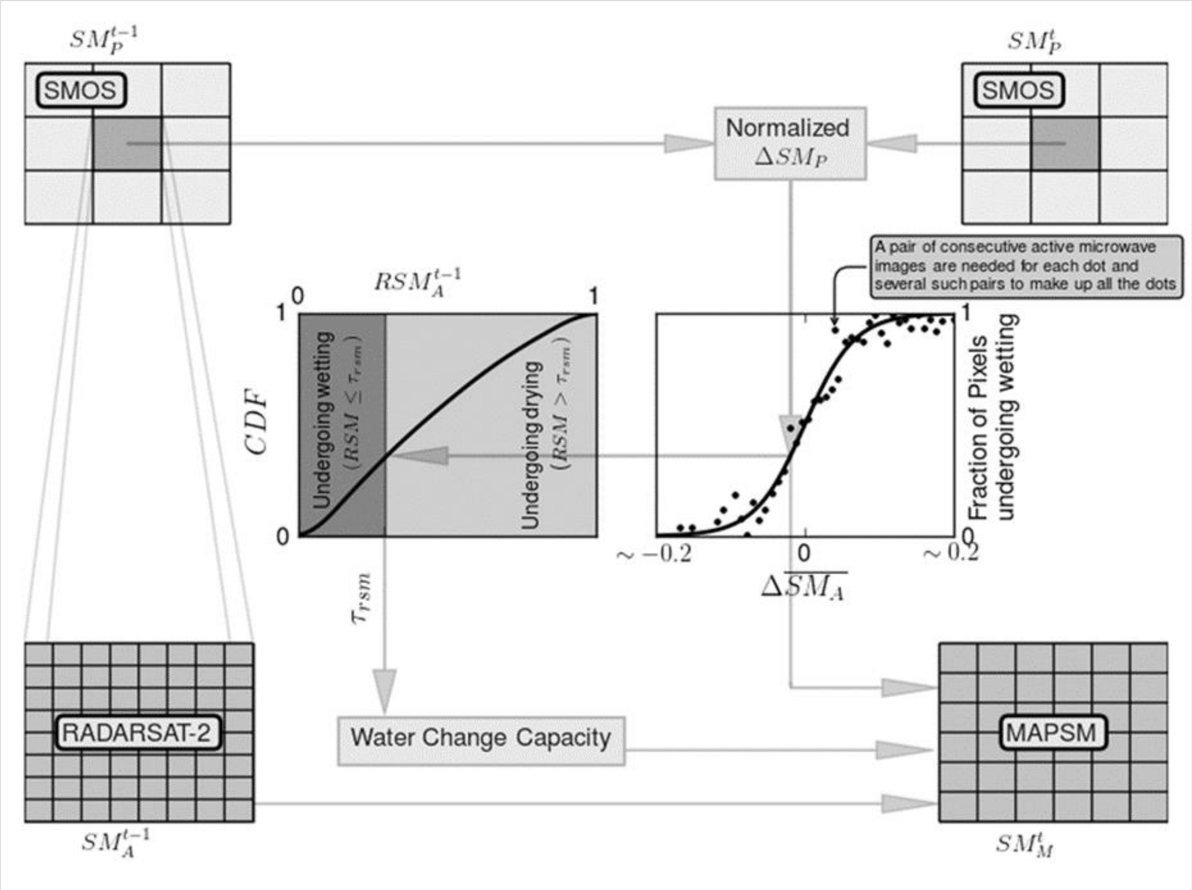

Figure 3-5: Schematic of the MAPSM Algorithm. Subscripts “A” and “P” are for Active and Passive Microwaves

3.6 Ground Water Modelling

Groundwater modelling can be performed using the modules of Ambhas Groundwater Flow models developed at IISc. Ambhas-1D model estimates the parameters such as specific yield (S_y) and annual rainfall-recharge factor and simulates the draft and lateral groundwater discharge. Table 3-4 provides the required input data for the model.

Table 3-4: Input Dataset used/required for Groundwater Modelling Using Ambhas GW Model

Variable(s)	Data source
Groundwater level	(i) CGWB, and (ii) Department of Mines and Geology (DMG)
Rainfall	From Central or State managing agencies
Drainage Layers	Satellite data
Geology of underlaying rock	Published reports, articles
Number of wells	Mi Census
Area irrigated for each village	Mi Census
Actual evapotranspiration	Satellite derived AET Products

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta y^2} = \frac{S_y}{T}\frac{\delta h}{\delta t} + \frac{Q}{b} \quad \text{Eqn. 3-21}$$

Eqn. 3-21 is solved vertically for the source/sink term (Q/b). When the vertical solution is used i.e., no spatial variability is assumed, the solution is similar to a lumped model.

The source/sink terms are the recharge to groundwater and groundwater abstraction for irrigation. The solution for the recharge/abstraction is done independently for each cell, and this can be expressed as,

$$\frac{dh}{dt} = \frac{1}{S_g}(-\lambda h + R - D_{net})$$ **Eqn. 3-22**

where, R is the recharge to groundwater $[LT^{-1}]$, D_{net} is the net groundwater draft $[LT^{-1}]$, and λ is the base flow parameter. This equation is similar to the equation derived by Park and Parker (2008) except for one additional term for draft. The solution of Eqn. 3-22 is described in Subash et al. (2017).

The Ambhas-1D model relaxes the assumption of zero lateral flow which is made while applying in hard rock aquifers. Since, Ambhas-lD model is applied by considering the groundwater level dynamics over longer duration, the estimation of parameters is more robust. The Ambhas-1D model also estimates the temporal variability in recharge and draft, which provides an opportunity to generate future scenarios.

Groundwater recharge is estimated by using the time series of depth to groundwater observations and AMBHAS-GW model which models the change in groundwater level as,

$$S_y \frac{\nabla h}{\nabla t} = rR - D_{net} - (1 - pd)(h - h_{min})\ if\ h > h_{min}$$
$$= rR - D_{net}, otherwise$$ **Eqn. 3-23**

where, h is groundwater level [L], S_y is specific yield [-], h_{min} is the groundwater level at which baseflow is zero [L], pd is parameter for discharge [-], r is recharge factor [-], R is rainfall [L/T], D_{net} is net groundwater draft [L/T]. Figure 3-6 depicts a sample comparison time series plot of the observed DGW and DGW simulated using AMBHAS-GW model.

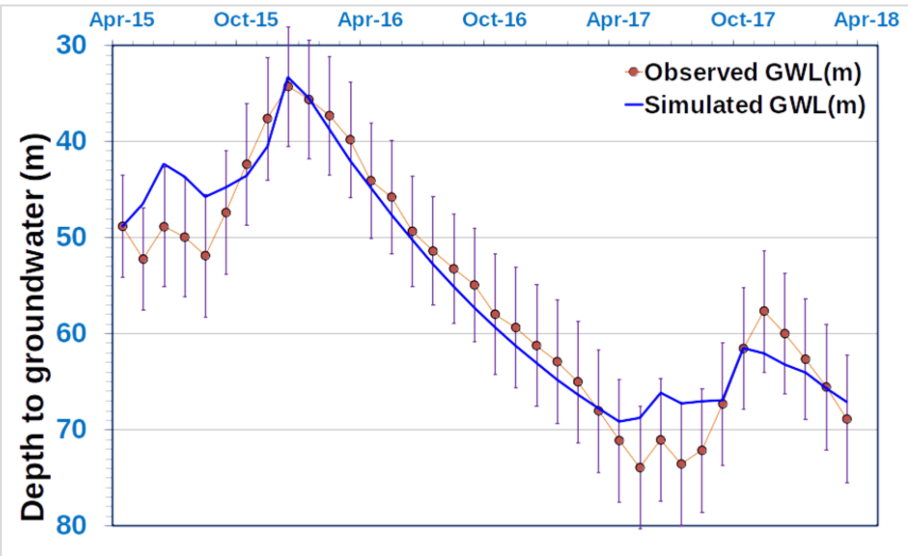

Figure 3-6: A Sample Plot showing the Time Series of Simulated and Observed Depth to Groundwater

An inverse modelling is performed to compute the annual groundwater recharge. Annual groundwater recharge is used to compute the groundwater recharge factor (recharge/rainfall). Figure 3-7 depicts the validation plot for estimated groundwater level and recharge for Gopalpura Watershed.

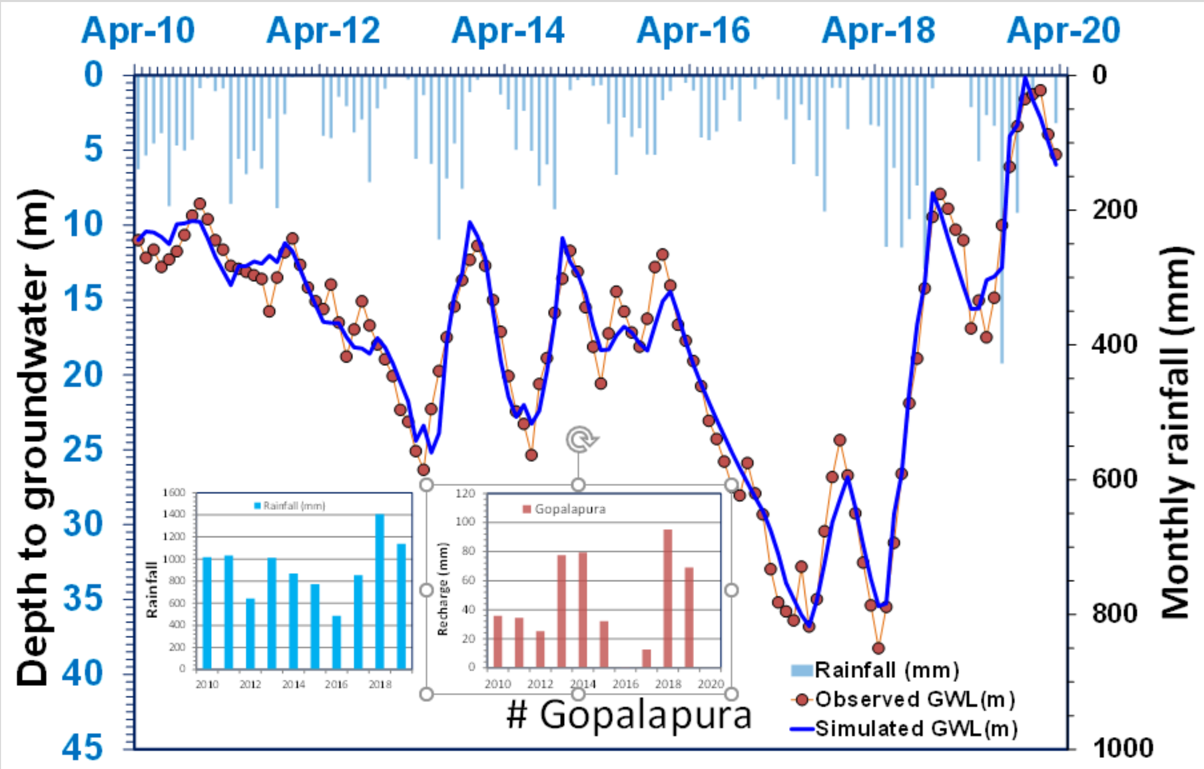

Figure 3-7: Validation Plot for Estimated Groundwater Level and Recharge for Gopalpura Watershed

4 Preparation of Hydrologic Atlas

Integrated Hydrological Assessment & Monitoring involves hydrological data gathering, behavior mapping & processes understanding at micro-watersheds scale. The objective is that the hydrological monitoring aided by advanced hydrological data & customized models developed in the process will aid in producing hydrological budgets at relatively higher temporal frequency (e.g., weekly/monthly) and also at the desired spatial granularity in small/micro watersheds, for improved sustainable water management.

The focus is to assess the links between groundwater conditions in the watersheds and design of soil & water conservation measures; groundwater level changes & water yields in hard rock aquifers; impacts of water stress on crop productivity; and land management changes and impacts on groundwater recharge & runoff. Further the additional objective is to integrate the hydrological variables & water budgets with the land resource inventory mapping for developing robust integrated watershed management plans.

In the previous two chapters (Chapter 2 and Chapter 3), the procedures to be adopted for field measurements and various modelling procedures have been documented. Once these procedures are implemented for a given watershed and compilation of required primary and secondary data is done, the next step is to use these data to prepare several elements for the hydrological atlas for the watershed. In this chapter, methodology for computation and analysis associated with the preparation of hydrologic atlas is discussed.

4.1 Location and Index Maps for the Study Area

At the very beginning of the study a number of hydrological and other required information are collected about the study area. Some of these are boundary and geographical location, location of monitoring sites, drainage network, habitation, cadastral boundaries, sub-watershed boundaries etc. This information is then transformed into a number of thematic GIS layers and then show them in map. As an example, index map for Madahalli micro-watershed is shown in Figure 4-1.

4.2 Rainfall Indices

The first task is to compile a catchment-averaged time series by combining the available rainfall data from several sources with lowest possible frequency and longest possible record. Depending upon data availability and context of the project objectives multiple such rainfall series may be prepared. Once that is done, many types of summary time series are to be prepared for the hydrological Atlas.

4.2.1 Summary Time Series Plots

For the Madahalli micro-watershed following four types of summary time series plots are prepared using the available rainfall data.

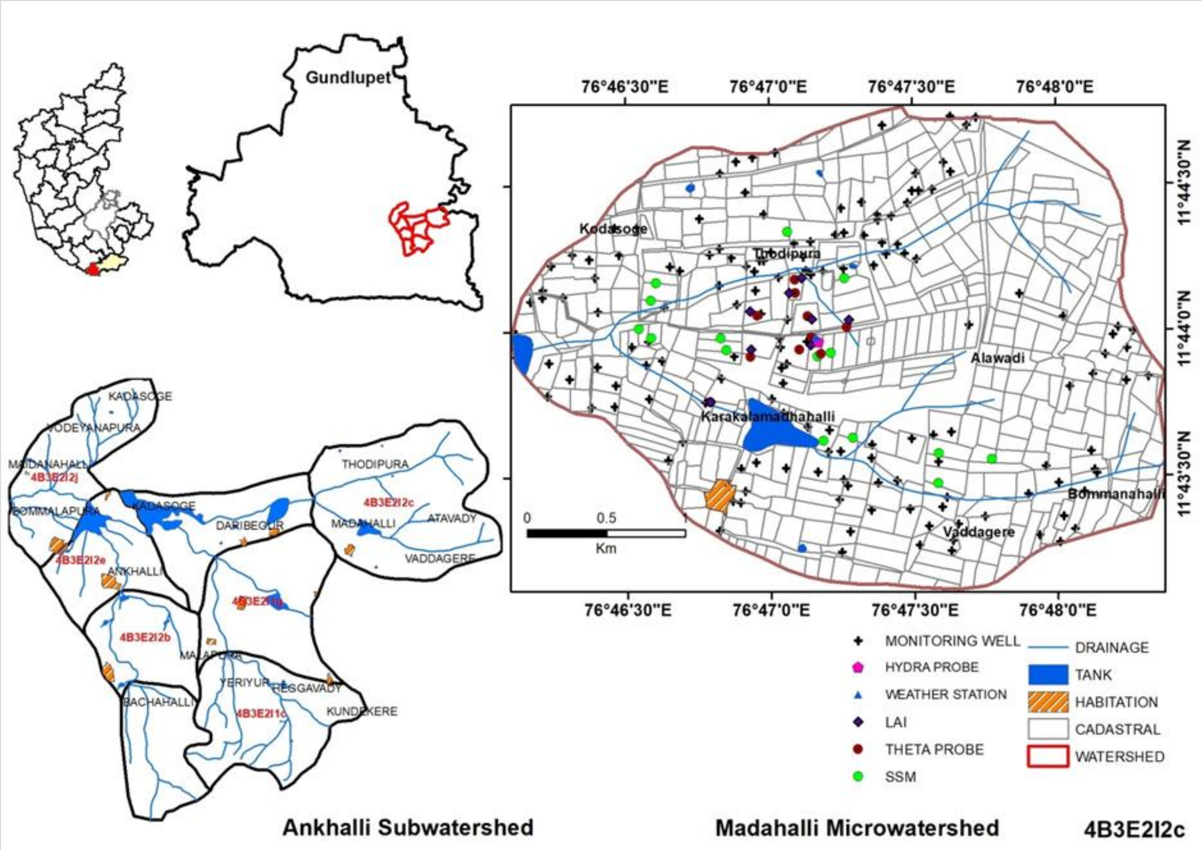

Figure 4-1: Index Map for Madahalli Micro-Watershed

- Annual Rainfall Time Series: These are prepared by aggregating the available daily (and sub-daily, as the case may be) rainfall over the calendar year for the period of record. See Figure 4-2 (a).

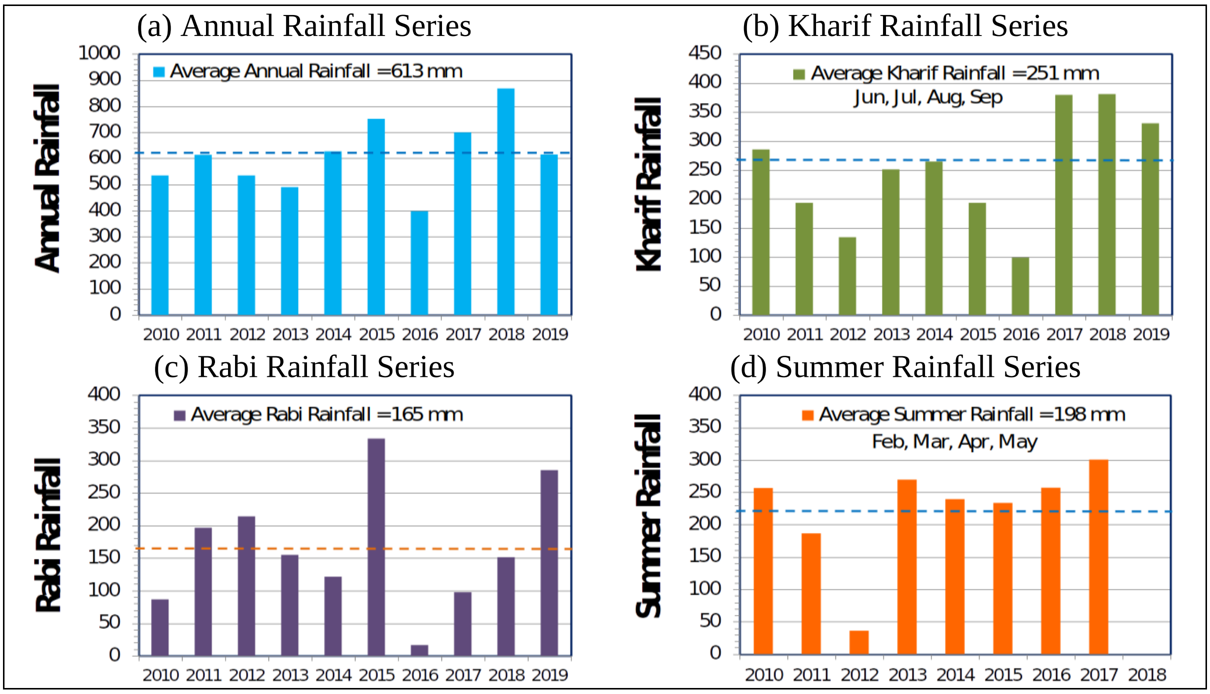

Figure 4-2: Summary Time Series Plots for Rainfall

- Kharif Rainfall Series: The period from June to September has been considered as Kharif season for a particular calendar year and the corresponding time series is to be prepared in similar way as that of the annual series. See Figure 4-2 (b).
- Rabi Rainfall Series: The period from October to January has been considered as Rabi Season for a particular calendar year and the corresponding time series is to be prepared in similar way as that of the annual series. See Figure 4-2 (c).
- Summer Rainfall Series: The period from February to May has been considered as Summer Season for a particular calendar year and the corresponding time series is to be prepared in similar way as that of the annual series. See Figure 4-2 (d).

4.3 Runoff Potential

Runoff potential for the target watershed is computed using either SWAT or ESARU model as discussed in Section 3.1. The runoff potential information is thus generated are then converted into spatial maps and the data are depicted as shown in Figure 4-3.

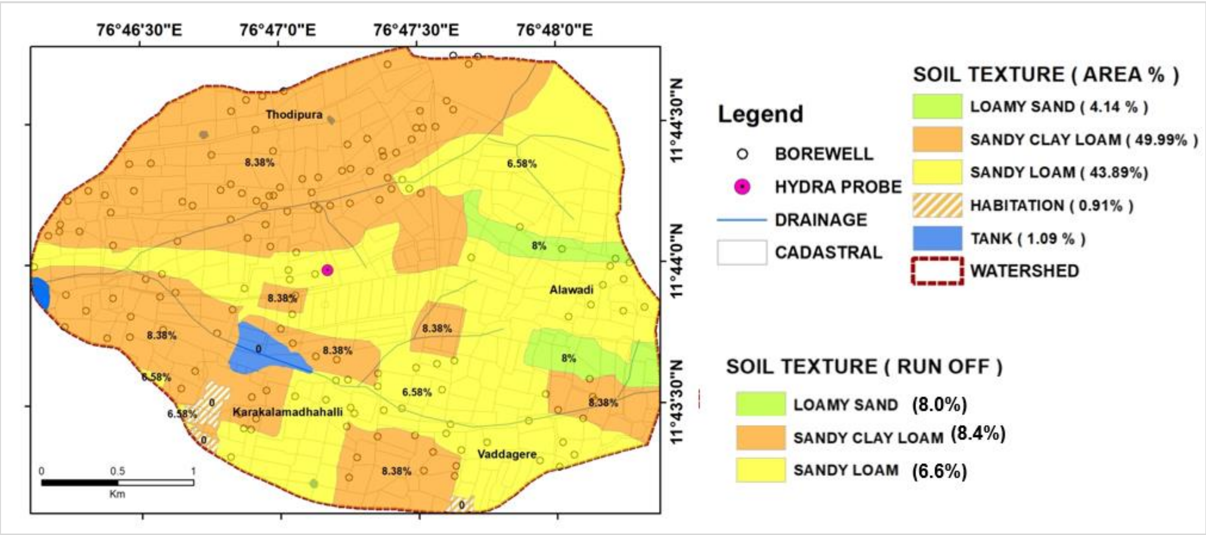

Figure 4-3: Depiction of Runoff Potential Information for Madahalli Watershed

Figure 4-3 depicts the simulated runoff for Madahalli micro-watershed using ESARU model. The average annual runoff simulated for the entire watershed based on higher intensity (>20 mm) rain events during the years 2010-17 was 44mm. This was approximately same for various years since the higher intensity rain events were about the same in each year. The peak runoff as a percentage of average annual rainfall was 10% and it was about 57 mm.

4.4 Evapotranspiration and Associated Indices

Several types of indices are developed using available time series of Actual Evapotranspiration (AET). Generally, AET time series are compiled at daily time step and with catchment-averaged values. Using this time series data following summary time series are prepared and presented in graphical & tabular forms as part of the Atlas.

4.4.1 Summary Time Series Plots

- Annual total AET series over the period of record; from this series Annual Average value of AET for the given catchment is also computed. See Figure 4-4.
- Annual Average AET series for each of the calendar month. In this case, temporal averaging is done over all the years in the period of record. Using this Monthly Average AET series following two types of summary plots are prepared:
    - Month wise comparison of AET and Rainfall over the period of record. See Figure 4-5.
    - Month wise of variation in AET over two consecutive decades, depending upon the length of available time series of AET. See Figure 4-6.

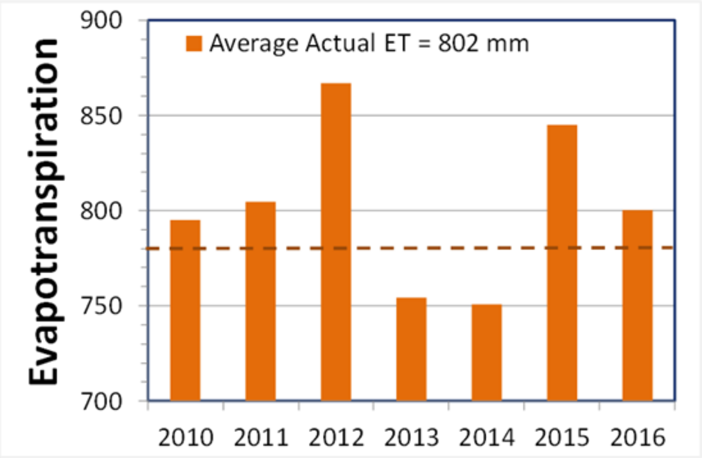

Figure 4-4: Annual AET over the Watershed under Consideration

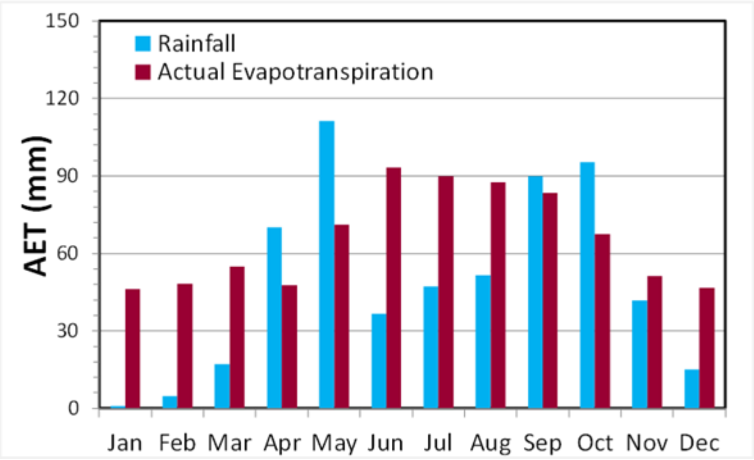

Figure 4-5: Month wise Comparison between Annual Average AET and Rainfall

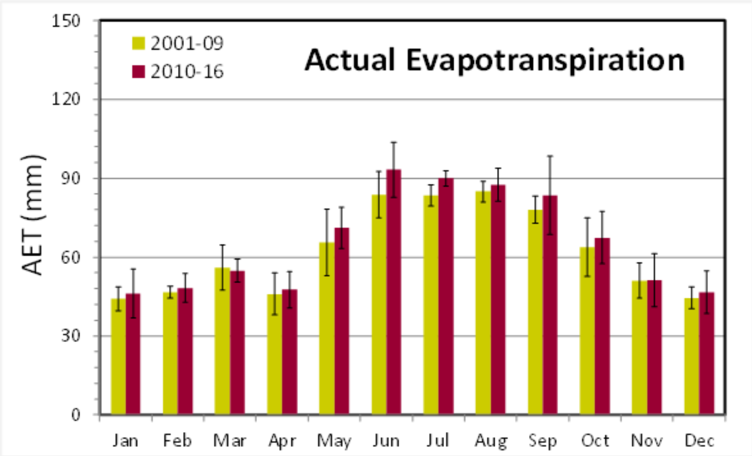

Figure 4-6: Month wise Variation in AET Values over two Consecutive Decades

4.4.2 Budyko Curve and ET Indices

The Budyko Curve (Budyko, M.I., 1974. Climate and Life. Academic Press, New York.) is a semi-empirical expression of the coupled water-energy balance at the catchment scale. It describes how the ratio of atmospheric water supply, i.e., precipitation, and water demand, i.e., potential evaporation, drives the partitioning of precipitation into streamflow and evaporation. The Budyko Equation is given by,

$$\frac{\overline{AET}}{\bar{P}} = \sqrt{\left(1 - e^{-\overline{PET}/\bar{P}}\right)\frac{\overline{PET}}{\bar{P}} tanh(\bar{P}/\overline{PET})} \quad \text{Eqn. 4-1}$$

where, $\overline{AET}$, $\overline{PET}$, $\bar{P}$ are long term average Actual Evapotranspiration, Potential Evapotranspiration and Rainfall, respectively, at the catchment scale for a given catchment. This equation gives rise two ET-based indices for a given catchment,

- ✓ Evaporative Index = $\frac{\overline{AET}}{\bar{P}}$, and
- ✓ Dryness Index = $\frac{\overline{PET}}{\bar{P}}$.

Given a catchment, Budyko Curve is to be interpreted as follows (refer to Figure 4-7):

- Budyko Curve provides a "business as usual" reference condition for the water balance.
- Water Limit ($\overline{AET} = \bar{P}$) -- a site/catchment cannot plot above the blue line unless there is input of water beyond precipitation.
    - ○ 'Water limited' implies dry conditions i.e., AET is limited by the amount of water that is available.
- Energy Limit ($\overline{PET} = \bar{P}$) -- a site cannot plot above the red line unless precipitation is being lost from the system by means other than discharge.
    - ○ 'Energy limited' implies wet condition i.e., AET is limited by the amount of thermal energy that is available.
- With increasing values of dryness index, the catchment's climatic condition becomes warmer and drier.

- With increasing values of evaporative index, the catchment's hydrological condition becomes drier i.e., less runoff.

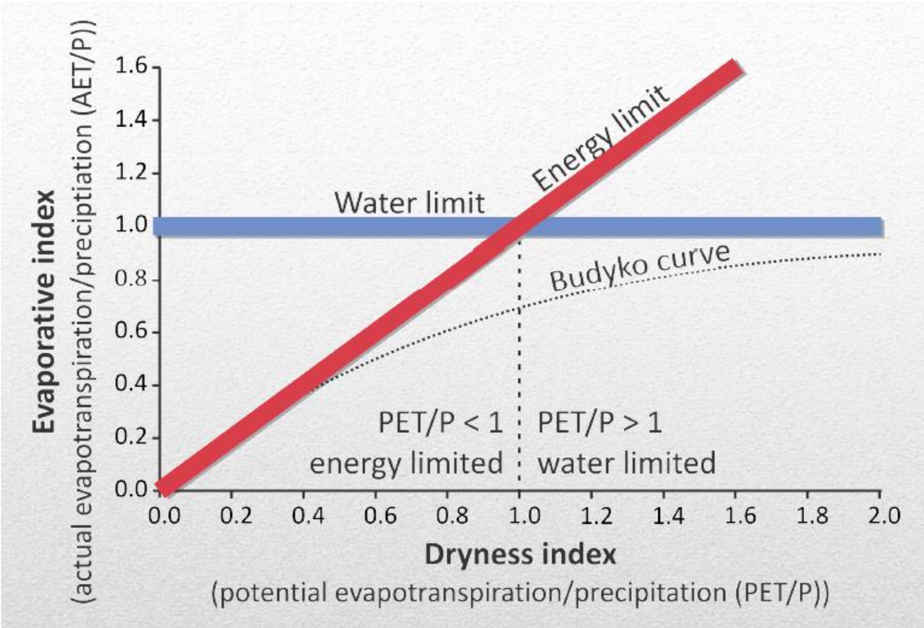

Figure 4-7: Interpretation of Budyko Curve

- For any given catchment long-term values for evaporative index and dryness index are calculated and then plotted along with the Budyko Curve in the $\frac{\overline{AET}}{\overline{P}}$ vs $\frac{\overline{PET}}{\overline{P}}$ space and then its deviation from the Budyko Curve is noted along $\frac{\overline{AET}}{\overline{P}}$ axis.
  - ***Positive deviation represents an upward shift and a decrease in Q (less water yield);***
  - ***Negative deviation represents a downward shift and an increase in Q (more water yield).***

As an example of such computation Figure 4-8 and Figure 4-9 as given below.

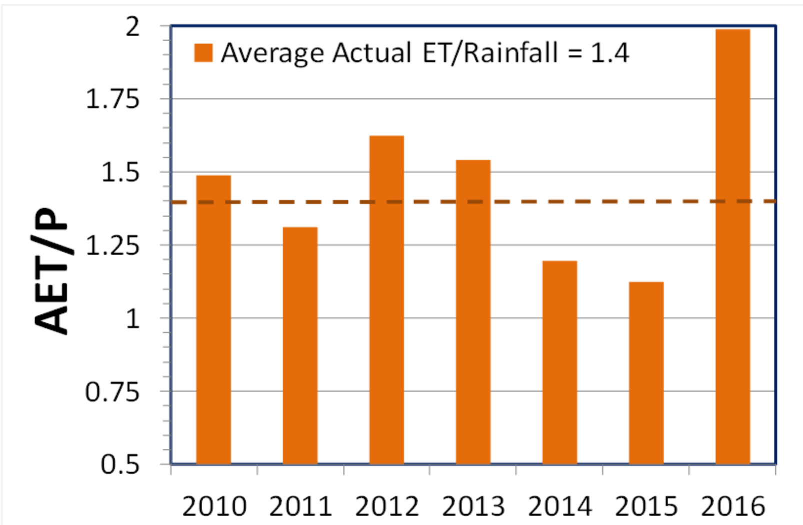

Figure 4-8: Computation of Long-term average Evaporative Index for a given Catchment

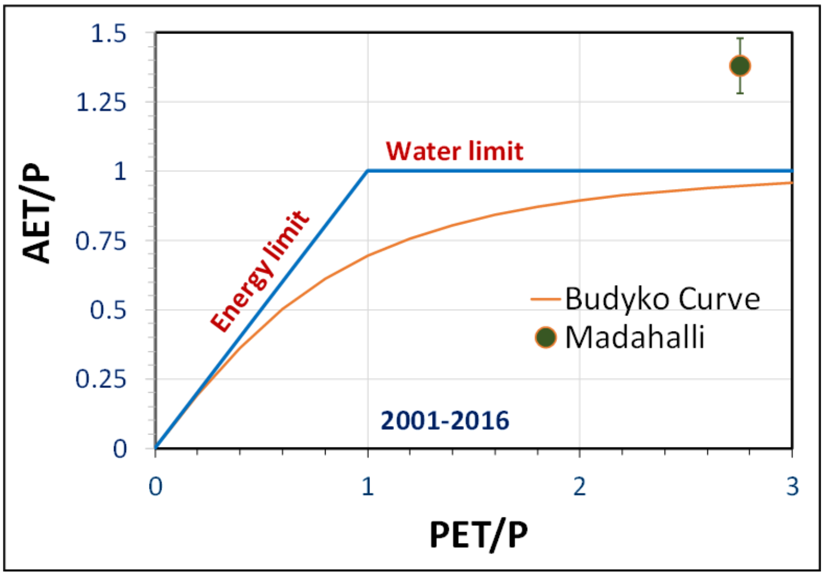

Figure 4-9: Plotting of (Evaporative Index, Dryness Index) Values in Budyko Space along with Budyko Curve for Madahalli Micro-Watershed

4.5 Water Budgeting

The concept of Water Budgeting aims to use water judiciously for people, agriculture and livestock with a view to optimizing benefits in the context of climate variability, erratic rainfall and drought. Water budget studies consider the volumes of water within the various reservoirs of the hydrologic cycle and the flow paths from recharge to discharge. Water budgets need to consider this information on a variety of spatial and temporal scales.

In simple terms a water budget for a given area can be looked at as water inputs, outputs and changes in storage. The inputs into the area of investigation (precipitation, groundwater or surface water inflows, anthropogenic inputs such as waste effluent) must be equal to the outputs (evapotranspiration, water supply removals or abstractions, surface or groundwater outflows) as well as any changes in storage within the area of interest.

So, given a watershed under consideration, a water budget equation may be developed over various time periods, Monthly, Seasonal, Annual etc., depending upon the context.

For example, using the available concurrent data on Precipitation (P), Runoff (Q), Actual Evapotranspiration (AET) and Ground Water Recharge (R) for the period April-October over the years 2015-2018 following water budget equation has been developed for the Madahalli Watershed,

$$P = Q + AET + R + S$$

Eqn. 4-2

where all the variables are expressed in mm unit. Inserting following known values, $P = 501, Q = 44, AET = 540, R = 85$ into this equation, we get, $S = -168$ mm. This implies that over the considered time period, precipitation was lower than evapotranspiration. This negative balance when combined with runoff and recharge results in a net negative soil water store for the Rabi season.

4.6 Spatial Distribution of Depth to Groundwater

Depth to groundwater (DGW) should be measured as described in Chapter 2. DGW is point data and needs to be interpolated to prepare the spatial maps. Any of the following approaches can be used to convert the point data into spatial maps:

1. Inverse Distance Weighted (IDW) Approach: In IDW, value at an unknown point is estimated by giving weights proportional to the inverse of the distance (between the known locations and the unknown location) raised to the power value p. Typically, a value of $p = 2$ is used, however, care should be taken that it should not result in spurious behavior in any part of the map. In that case, different values of p should be tried.
2. Kriging-based Interpolation: Kriging provides the best linear unbiased estimation at an unknown point giving the values at known locations. Before performing the Kriging, variogram analysis is performed to understand the underlying statistical distribution of the process.

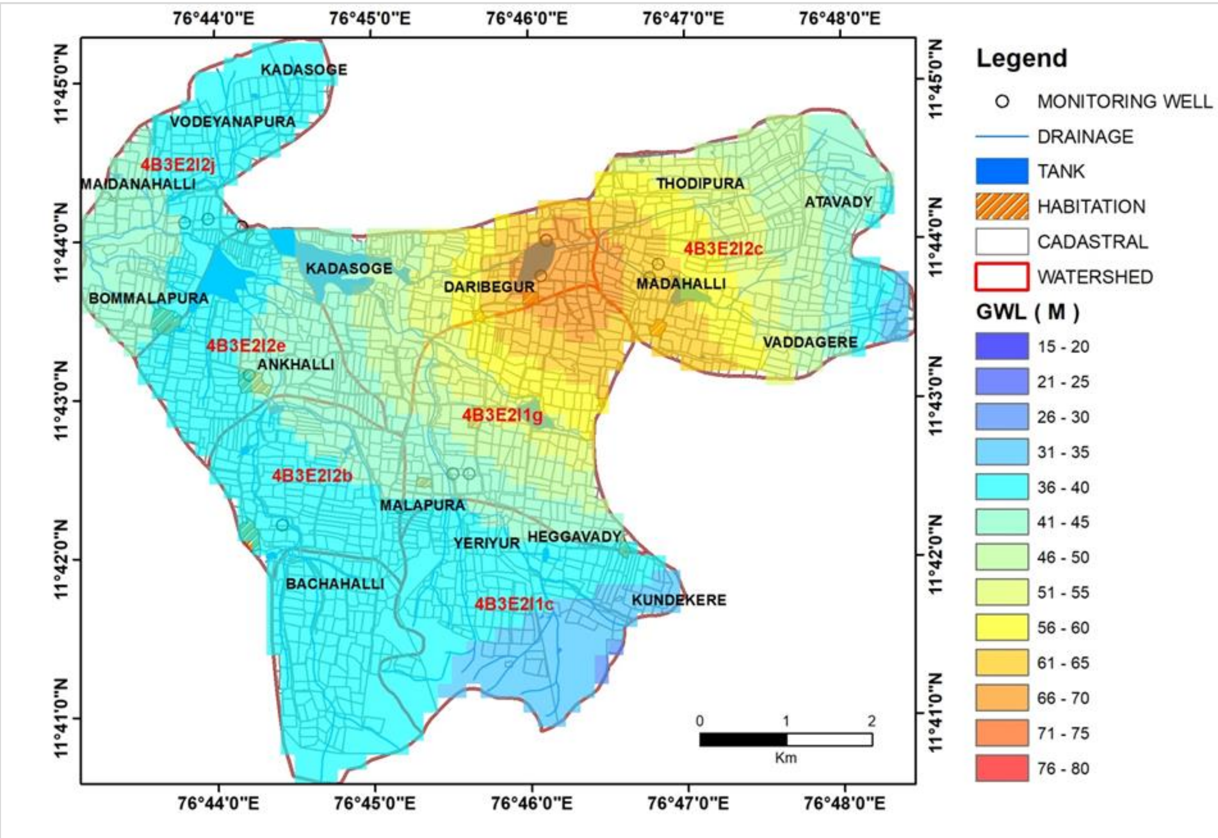

Figure 4-10: Spatially Interpolated Map of DGW Values over the Madahalli Micro-Watershed

4.7 Ground Water Recharge

Figure 4-11 depicts Annual Recharge and Mean Annual Recharge Factor computed for Madahalli Micro-Watershed.

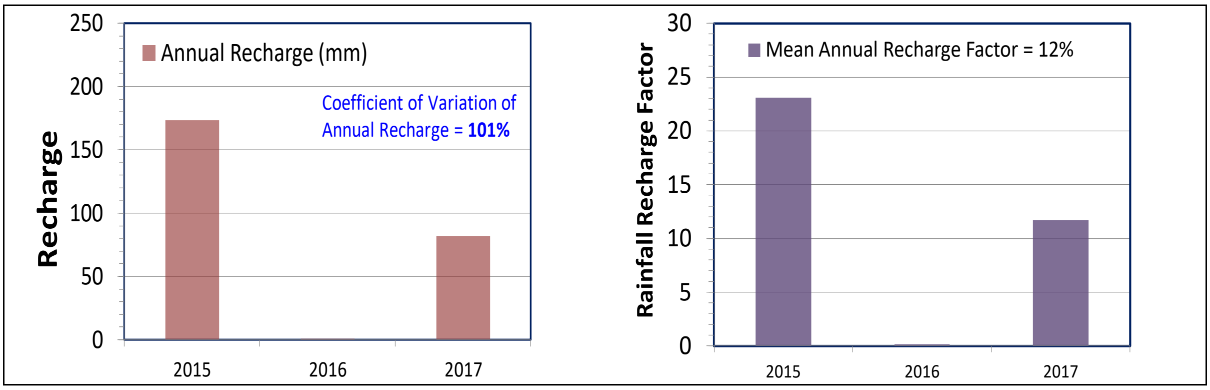

Figure 4-11: Sample Plot showing Annual Recharge and Mean Annual Recharge Factor for Madahalli Micro-Watershed

4.7.1 Well Yield

Yield of the well should be monitored by filling a container of known volume and measuring the time required to fill the container. By taking the data of each monitoring well, a map of groundwater well yield shall be prepared following the IDW or Kriging method of interpolation. A sample map of groundwater well yield is provided in Figure 4-12.

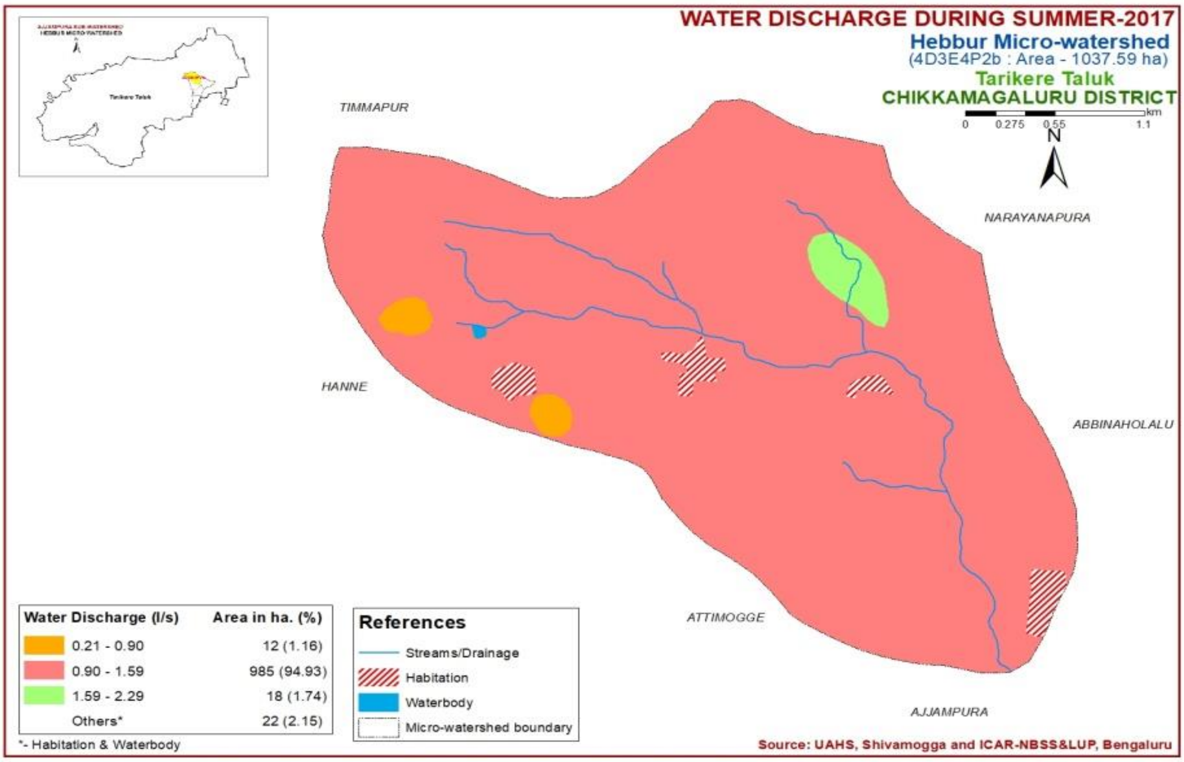

Figure 4-12: Sample Plot showing Spatially Interpolated Well Yield Values for the Hebbur Micro-Watershed

4.8 Water Quality Maps

Following the procedure mentioned in Chapter 2, prepare the map of groundwater quality parameters following the IDW or Kriging method of interpolation. For example, Figure 4-13 shows spatially interpolated values of Electrical Conductivity over Hebbur Micro-Watershed.

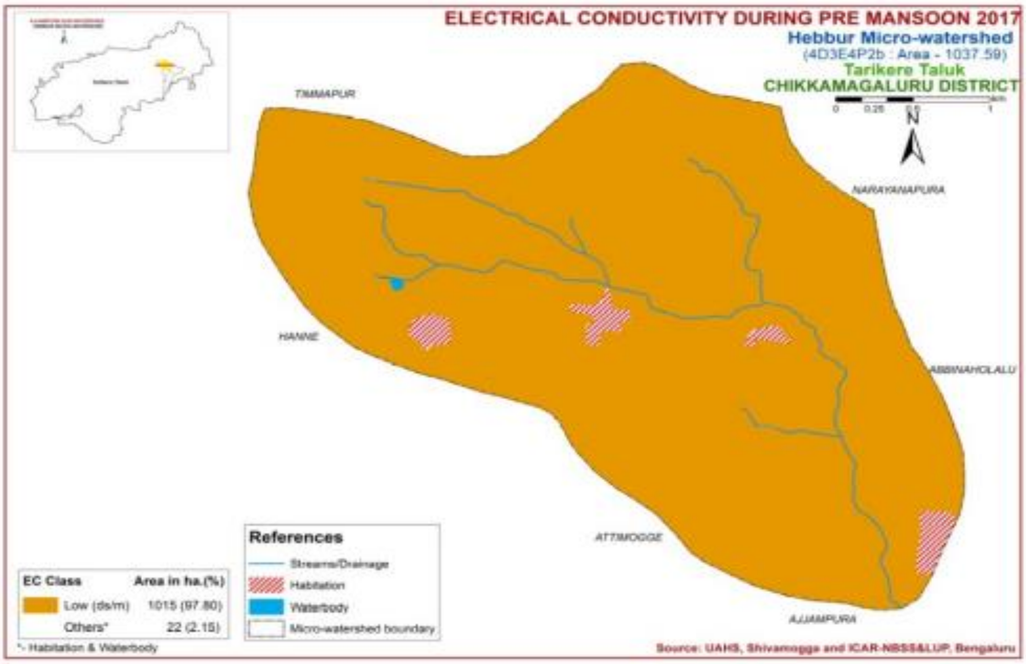

Figure 4-13: Sample Plot showing Spatially Interpolated Electrical Conductivity Values for the Hebbur Micro-Watershed

4.9 Depiction of Surface Soil Moisture Data

Surface soil moisture data are generally depicted either as time series plot or as raster maps over the whole watershed.

4.9.1 Spatial Maps

Figure 4-14 shows sample surface soil moisture maps over a given micro-watershed for Kharif and Rabi Seasons. These maps are prepared using satellite remote sensing products as discussed in Chapter 3. Following facts are to be noted:

- Seasonal maps are prepared by aggregating multiple images over the watershed.
- Cadastral maps are always overlaid on top of soil moisture rasters.

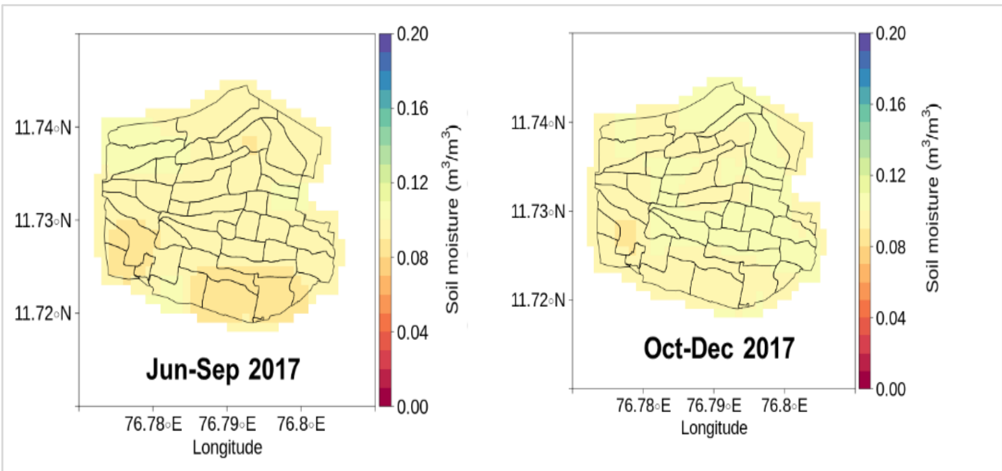

Figure 4-14: Satellite-derived Surface Soil Moisture Maps over a Study Watershed for Kharif and Rabi Seasons

4.9.2 Time Series Plots

Aggregating the surface soil moisture data over the study watershed a catchment aggregated soil moisture time series are prepared to assess the temporal variability. Figure 4-15 shows one such plot as sample.

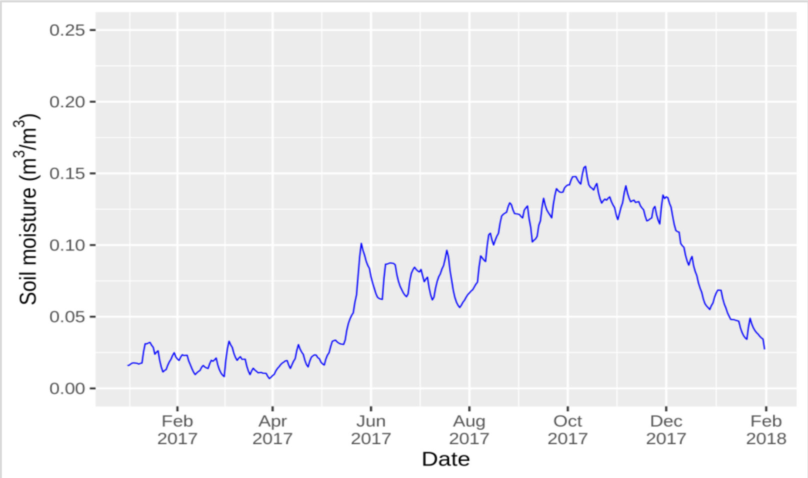

Figure 4-15: Time Series Plot of Surface Soil Moisture over a Study Watershed

Soil moisture comparison plots (see Figure 4-16) should also be created to evaluate the coincidence of the field and satellite observations in order to cross check the data accuracy from both the sources.

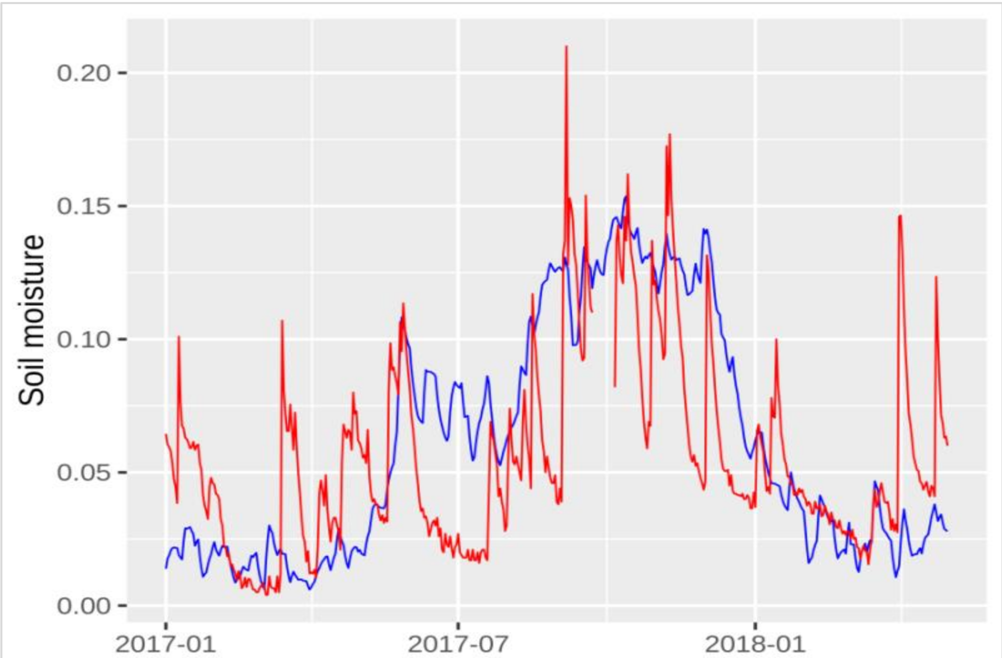

Figure 4-16: Comparison of Satellite-based and Manual Observation-based Surface Soil Moisture Data

The root zone soil moisture data (see Figure 4-17) is observed for dominant field crops in rainfed conditions. Subsistence irrigation may be required for attaining the potential productivity of these crops currently in practice.

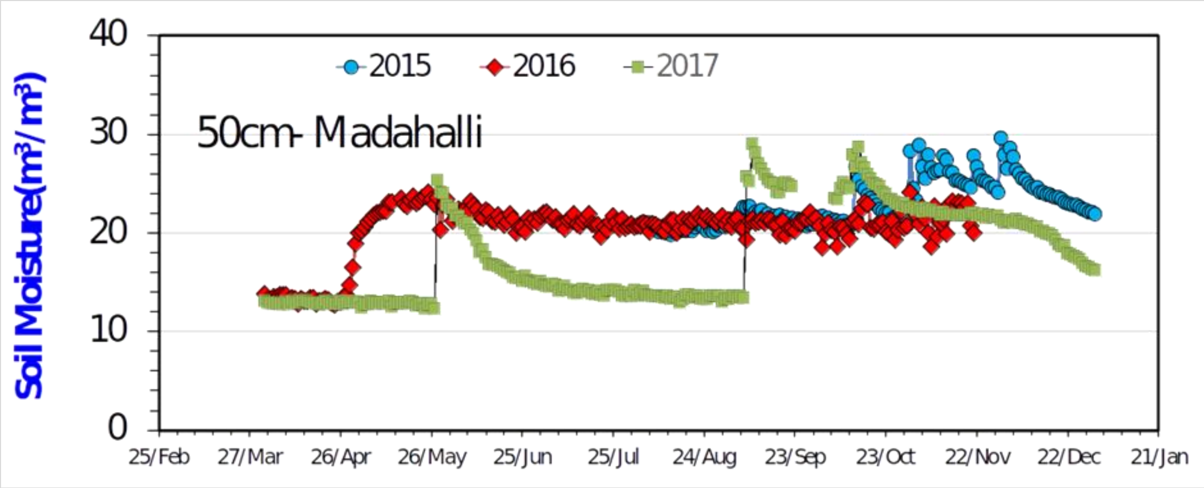

Figure 4-17: Root Zone Soil Moisture Time Series Plot at the particular location in the Study Watershed

4.10 Depiction of Profile Soil Moisture Data

Following two considerations are to be noted for profile soil moisture data,

- Profile soil moisture should be observed every 10 days.
- Depth-wise measurements should be taken for an increment of 10 cm, up to the depth of 80 cm.

As sample soil profile plot is shown in Figure 4-18.

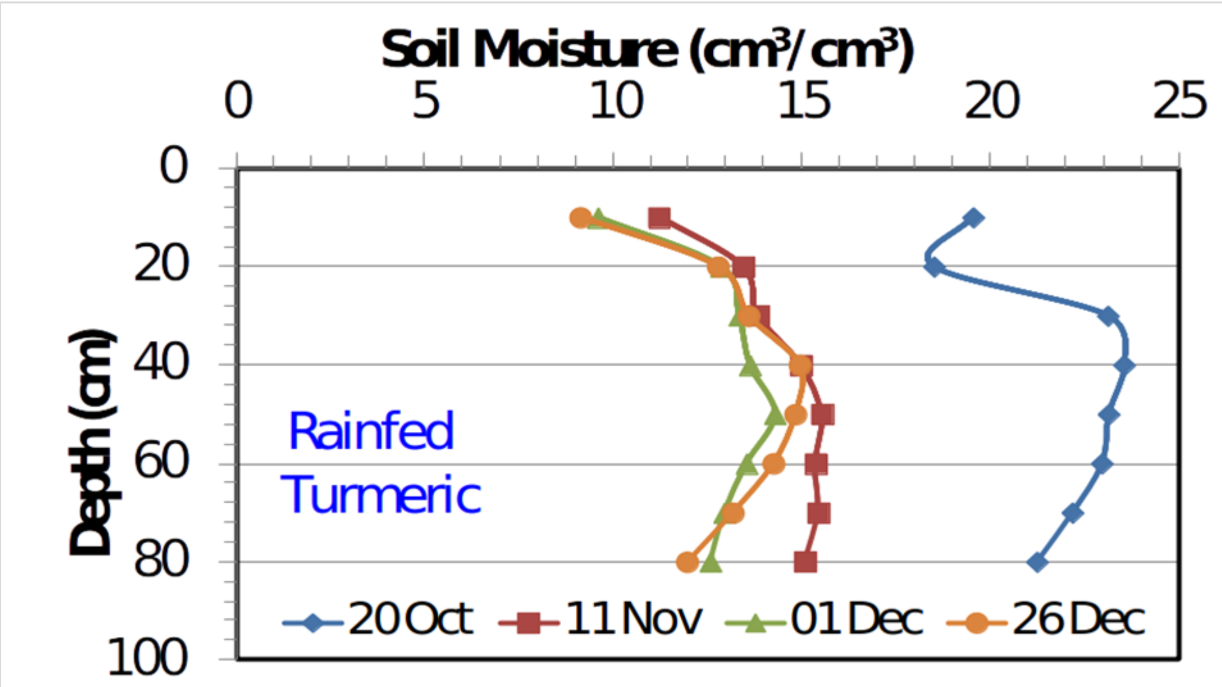

Figure 4-18: Sample Profile Soil Moisture Plot

4.11 Preparation of Crop Growth Characteristics Curves

Crop Growth Rate Characteristic Curve is a best curve through the observed Leaf Area Index data for a particular crop at the given location/farm. LAI observations are taken at every 10 days and then best fitted curve is computed and plotted as Crop Growth Characteristics Curve. For example, Figure 4-19 shows an example of Crop Growth Characteristics Curve developed using information generated in Madahalli micro-watershed.

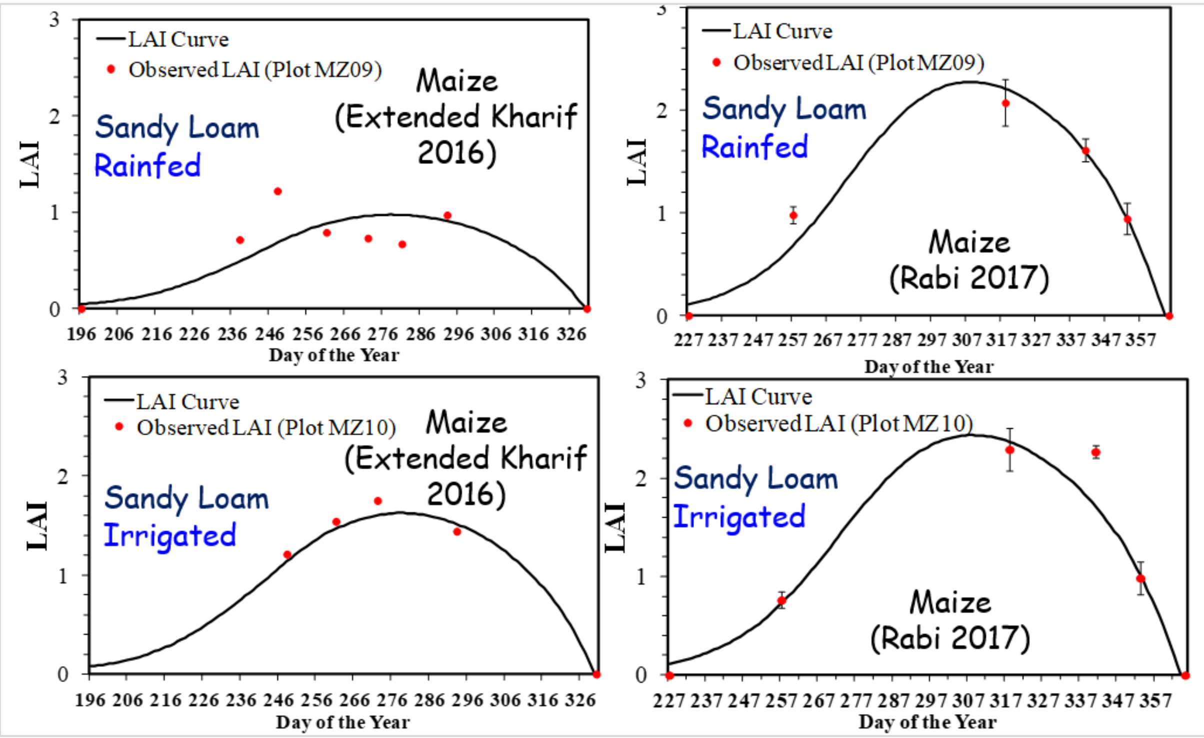

Figure 4-19: Sample Crop Growth Characteristics Plots

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