Hydrological Modelling for Agricultural Water Management

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Hydrological Models Simulate

- Surface Runoff
- Soil moisture (Surface, Profile)
- Water Demand - Potential (Reference) Evapotranspiration
- Water Use - Actual Evapotranspiration
- Ground water recharge
- Soil Salinity
- Flood discharge and Spatial inundation
- ....
Hydrologic Models

A hydrological model is the mathematical representation of the exchanges of water and its constituents on the land surface or subsurface environment.

Very first known model estimating water discharge over a landscape is proposed by Mulvaney (1850).

A simple model relating water leaving a small rural watershed based on precipitation (Ireland):

\[ Q, \text{ Peak Discharge} = CIA \quad (C-\text{Constant}; \ I-\text{Rain Intensity}; \ A-\text{Watershed Area}) \]

Later termed as Rational Formula.

Empirical Equations developed over India:

- Barlow’s Tables (for UP): \[ R = K_b \times P \]
- Strange’s Table (for Maharashtra and Karnataka): \[ R = K_s \times P \]
- Inglis Formula (for Ghat region of western India): \[ R = 0.85P - 30.5 \]
Model Classifications: Hydrologic model classifications are generally based on the method of representation of the hydrologic cycle or a component of the hydrologic cycle.

- Physical --- Mathematical
- Continuous --- Event / Discrete
- Descriptive --- Conceptual
- Deterministic --- Stochastic
- Lumped --- Distributed
- Complete --- Partial
- General --- Special purpose
- Forecasting --- Retrospective
- Calibrated Parameters --- Measured Parameters
Geo-Spatial Data & Hydrological Modelling

- Hydrological response has a functional dependency of many dynamic and stationary parameters.

- Spatial heterogeneity and time variant behaviour of these parameters are critical inputs into Hydrological models.

- Land Surface Process models incorporate functional dependency of multiple parameters which control and influence the hydrological behaviour patterns.

- Earth Observation (EO) data from multitude platforms providing enormous contribution for the creation of spatially distributed parameters relevant for hydrological budgeting and modeling.

- Repeatability of observations allows the generation of a time-series account of dynamic terrain parameters and provide capability to quantify and forecast the hydrological variables and water balance components.
LULC spatial data are useful for

- Employing *distributed hydrological modelling*
- Characterizing *hydrological response* as a function of in-situ land use/land cover in association with other terrain parameters
- **Partitioning of Precipitation** into Evapotranspiration, Soil Moisture, Runoff
- Quantification of changes in surface runoff and associated hydrological fluxes due to changes in LULC
- LULC time series data represents the changes in forest cover, urban area (impervious surfaces), flood-plain encroachment, river-congestion and are useful for quantifying long-term variations in surface runoff (quantity, time-distribution), flood inundation/hazard and the water resources availability
- LULC is one the primary input into Hydrological models (Water Resources Assessment, Flood Forecasting, Flood Damage Assessment)
- LULC is also being used for spatial extrapolation of hydro-meteorological data
Hydrologic Models – Surface Runoff

Soil Conservation Service (SCS)

- an empirical relationship estimating initial abstraction and runoff as a function of soil type and land-use
- rainfall-runoff relationship visualized as initial abstraction ($I_a$), direct runoff ($Q$), and actual retention ($F$)
- the resulting direct runoff can be solved directly for various CN
- CN embodies the empirical observation of impact of soil type, condition, and land-use (mostly controlling depression storage)
- an implicit assumption is that precipitation depth $P$ is greater than 20% of maximum storage depth $S$, i.e. the curve-number method is inaccurate for small precipitation events
Runoff Computation Using SCS Model:

The expression used in SCS method for estimating runoff is

\[
Q = \frac{\{P - I_a\}^2}{\{(P - I_a) + S\}}
\]

Where, 
- \(Q\) = Accumulated storm runoff, mm
- \(P\) = Accumulated storm rainfall, mm
- \(S\) = Potential maximum retention of water by the soil.

For Indian conditions \(I_a\) can be taken as 0.3S or 0.2S (Handbook of Hydrology)

\(S\) value was derived from curve number (CN) using the following formulae

\[
S = \frac{25400}{254} - 254 \quad \text{CN}
\]
<table>
<thead>
<tr>
<th>Description of Land</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paved parking lots, roofs, driveways</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>Streets and Roads:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paved with curbs and storm sewers</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>Gravel</td>
<td>76</td>
<td>85</td>
<td>89</td>
<td>91</td>
</tr>
<tr>
<td>Dirt</td>
<td>72</td>
<td>82</td>
<td>87</td>
<td>89</td>
</tr>
<tr>
<td>Cultivated (Agricultural Crop) Land*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without conservation treatment (no terraces)</td>
<td>72</td>
<td>81</td>
<td>88</td>
<td>91</td>
</tr>
<tr>
<td>With conservation treatment (terraces, contours)</td>
<td>62</td>
<td>71</td>
<td>78</td>
<td>81</td>
</tr>
<tr>
<td>Pasture or Range Land:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor (&lt;50% ground cover or heavily grazed)</td>
<td>68</td>
<td>79</td>
<td>86</td>
<td>89</td>
</tr>
<tr>
<td>Good (50-75% ground cover; not heavily grazed)</td>
<td>39</td>
<td>61</td>
<td>74</td>
<td>80</td>
</tr>
<tr>
<td>Meadow (grass, no grazing, mowed for hay)</td>
<td>30</td>
<td>58</td>
<td>71</td>
<td>78</td>
</tr>
<tr>
<td>Brush (good, &gt;75% ground cover)</td>
<td>30</td>
<td>48</td>
<td>65</td>
<td>73</td>
</tr>
<tr>
<td>Woods and Forests:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor (small trees/brush destroyed by over-grazing or burning)</td>
<td>45</td>
<td>66</td>
<td>77</td>
<td>83</td>
</tr>
<tr>
<td>Fair (grazing but not burned; some brush)</td>
<td>36</td>
<td>60</td>
<td>73</td>
<td>79</td>
</tr>
<tr>
<td>Good (no grazing; brush covers ground)</td>
<td>30</td>
<td>55</td>
<td>70</td>
<td>77</td>
</tr>
<tr>
<td>Open Spaces (lawns, parks, golf courses, cemeteries, et.)</td>
<td>49</td>
<td>69</td>
<td>79</td>
<td>84</td>
</tr>
<tr>
<td>Fair (grass covers 50-75% of area)</td>
<td>39</td>
<td>61</td>
<td>74</td>
<td>80</td>
</tr>
<tr>
<td>Good (grass covers &gt;75% of area)</td>
<td>39</td>
<td>61</td>
<td>74</td>
<td>80</td>
</tr>
<tr>
<td>Commercial and Business Districts (85% impervious)</td>
<td>89</td>
<td>92</td>
<td>94</td>
<td>95</td>
</tr>
<tr>
<td>Industrial Districts (72% impervious)</td>
<td>81</td>
<td>88</td>
<td>91</td>
<td>93</td>
</tr>
<tr>
<td>Residential Areas:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/8 Acre lots, about 65% impervious</td>
<td>77</td>
<td>85</td>
<td>90</td>
<td>92</td>
</tr>
<tr>
<td>1/4 Acre lots, about 38% impervious</td>
<td>61</td>
<td>75</td>
<td>83</td>
<td>87</td>
</tr>
<tr>
<td>1/2 Acre lots, about 25% impervious</td>
<td>54</td>
<td>70</td>
<td>80</td>
<td>85</td>
</tr>
<tr>
<td>1 Acre lots, about 20% impervious</td>
<td>51</td>
<td>68</td>
<td>79</td>
<td>84</td>
</tr>
</tbody>
</table>
## HSG Groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Infiltration Rate (mm/hr)</th>
<th>Soil Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>HIGH</td>
<td>&gt;25 Sand, Loamy Sand, or Sandy Loam</td>
</tr>
<tr>
<td>B</td>
<td>MODERATE</td>
<td>12.5-25 Silt Loam or Loam</td>
</tr>
<tr>
<td>C</td>
<td>LOW</td>
<td>2.5-12.5 Sandy Clay Loam</td>
</tr>
<tr>
<td>D</td>
<td>VERY LOW</td>
<td>&lt;2.5 Clay Loam, Silty Clay Loam, Sandy Clay, Silty Clay or Clay</td>
</tr>
</tbody>
</table>

## AMC Classes

<table>
<thead>
<tr>
<th>AMC-CLASS</th>
<th>AMC (mm)</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>&lt;35</td>
<td>Dry soil but not the wilting point</td>
</tr>
<tr>
<td>II</td>
<td>35-52.5</td>
<td>Average conditions</td>
</tr>
<tr>
<td>III</td>
<td>&gt;52.5</td>
<td>Saturated soils; heavy rainfall or light rain</td>
</tr>
</tbody>
</table>

## Curve Numbers for AMC I & III

\[
\begin{align*}
\text{CN I} & = \frac{(4.2 \times \text{CN II})}{(10 - 0.058 \times \text{CN II})} \\
\text{CN III} & = \frac{(23 \times \text{CN II})}{(10 + 0.13 \times \text{CN II})}
\end{align*}
\]

## Slope Correction

\[
\begin{align*}
\text{CN 2s} & = \frac{1}{3} (\text{CN 3} - \text{CN 2}) \left[1 - 2 \exp \left(-13.86 \times S\right)\right] + \text{CN 2} \\
\text{CN 1s} & = \frac{(4.2 \times \text{CN 2s})}{(10 - 0.058 \times \text{CN 2s})} \\
\text{CN 3s} & = \frac{(23 \times \text{CN 2s})}{(10 + 0.13 \times \text{CN 2s})}
\end{align*}
\]
Soil and Water Assessment Tool (SWAT)

An assembled hydrological model with combination of various process based models

SWAT structured with modelling environments
  • Hydrological Response Unit (HRU) level computations of surface runoff, Sub-surface runoff, Ground water flow, Evapotranspiration, Plan growth, sediment transport

SWAT consists of two broad components:
  • Simulation of the hydrological cycle with stream discharges as main output, sediment transportation & water quality on the surface, routing through sub-basins
  • Aggregated routing of the above to the basin outlet
Revised Universal Soil Loss Equation (RULSE, M-ULSE)
(Average annual soil erosion rate for the given land, soil and weather conditions)

Simulates soil water erosion process for the given rainfall erosivity (based on long-term rainfall data), soil type, land cover)

RULSE3D
**Hydrologic Models – Soil Loss / Erosion**

- **Water Erosion Prediction Project (WEPP)**
  (Average annual soil erosion rate for the given land, soil and weather conditions)

- Process based, overcomes the limitations of R & M-ULSE on runoff estimation, spatial locations of soil loss, effects of impoundments, successive events, transport and deposition

- WEPP is a continuous simulation, predicting soil loss, transport, deposition from overland flow on hill slopes, soil loss & sediment deposition from concentrated flow in small channels and sediment deposition in impoundments (Fares, 2008)

- Comprises erosion, climate, hydrology, plant growth and soils components
Hydrologic Models – Soil Moisture, Surface Runoff, ET

- Variable Infiltration Capacity Hydrological Model (VIC)
- Grid-wise water and energy balance
- Sub-grid heterogeneity of Land cover
- Soil depth-wise hydrological response
- Vegetation phenological changes
- Daily / sub-daily time step
- Profile soil moisture, Surface runoff, ET, Baseflow, ...
1. Basin Level Water Resources Assessment Using Space Inputs (annual/monthly time-step)
   - Joint pilot study with CWC in Godavari, Brahmini & Baitarani River Basins
   - Up scaled all 20 river basins: CWC will execute with the support of NRSC

2. Soil moisture simulation using process based hydrological model
   - Seasonal conditions
   - Short term forecast for water management interventions

3. Flood early warning systems
   - Flood hydrographs
   - Spatial inundation simulation
   - Inputs for flood damage assessment
Reassessment of Water Resources of India using Space Inputs

NRSC & CWC Joint Study
Currently used water resources potential estimates are old (CWC: 1988 & 1993; NCIWRD:1999; Lumped, Basin scale)

Significant change in land use / land cover; demographic utilization (Sectoral water utilization and its temporal changes)

CWC (1993) Procedure needs water use data, which is not available

Precipitation (or rainfall), as the primary resource for assessment (Precipitation (and not river flow/ aquifer recharge) constitutes the primary resource for assessment)

Compute the runoff using process based models (Water balance approach, Hydrology Models)

Take advantage of new technology tools (satellite derived spatial data bases, high density field observations, GIS,)

Adopt distributed modelling approaches (Assessment of water resources at basin/sub-basin scale at required time-step and frequency)

Address the impact of climate change (Impact of climate change on resource and use; development and analysis of scenarios to evaluate water policies)
key aspects ...

- Water balance approach
- Precipitation, the start point of water budgeting
- Integration of multi-variant terrain parameters in GIS (prevailing land use / land cover, elevation, soil, ... )
- Spatial interpolation/extrapolation of meteorological data (rainfall, hydro-met data, groundwater data, ... )
- Hydrological Response Unit (HRU) level water budgeting
- Monthly time-step, with carry over effect
- Calibration and validation with observed runoff (CWC recorded, ... )
- Basin/sub-basin water resources availability and sectoral utilization

Pilot Study - Godavari & Brahmani-Baitarni River basins
approach ...

GIS Analysis

Land use

Basin / Sub-basin

Soil

Point Hydro-Met data

Gridded Hydro-met Data

Hydrological Response Unit

Water Balance Computation

Water Balance Model (TM, SWAT, ...)

DEM
Water balance computation at HRU Level

Water Balance Model (TM, SWAT, ...)

Precipitation

- Agriculture Consumptive Use
- Other Land Use Consumptive Use
- Kharif Double cropped
- Forest Misc. Vegetation Bare Soil Open Water

Runoff

- Demographic Consumptive Use
- Annual Ground Water Flux
- Annual Surface Water Flux

Runoff Validation with CWC G&D observation data

Paddy / Others

Irrigated command area Boundaries

Land use / Land cover

Domestic Industrial

CWC Records

Administrative Boundaries

Demographic Data

WHO / CPSP / CWC Norms
Pilot Studies - Re-Assessment of Country’s Water Resources Potential Using Space Inputs

- Geo-spatial data based hydrological modeling approach demonstrated through pilot studies (Godavari and Brahmani & Baitarani)

- MoWR Expert Committee reviewed Pilot Studies and Recommended for upscaling to entire Country to obtain latest update

- CWC through its regional Basin Organizations to carryout the study

- ISRO to provide capacity building through Training and Hand holding

Major Benefits

- Latest update on country’s water resources potential

- Impact of land use/land cover changes on water resources availability

- Standard Framework for periodic re-assessment and assessment under future climate scenarios
Estimated Irrigation Water Use in Krishna Basin

KRISHNA BASIN (CA=259439 Sq.km)

<table>
<thead>
<tr>
<th>WATER YEARS</th>
<th>Irrigation Water Use (BCM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-05</td>
<td>50</td>
</tr>
<tr>
<td>2005-06</td>
<td>60</td>
</tr>
<tr>
<td>2006-07</td>
<td>70</td>
</tr>
<tr>
<td>2007-08</td>
<td>65</td>
</tr>
<tr>
<td>2008-09</td>
<td>65</td>
</tr>
<tr>
<td>2009-10</td>
<td>65</td>
</tr>
<tr>
<td>2010-11</td>
<td>65</td>
</tr>
<tr>
<td>2011-12</td>
<td>80</td>
</tr>
<tr>
<td>2012-13</td>
<td>70</td>
</tr>
<tr>
<td>2013-14</td>
<td>65</td>
</tr>
<tr>
<td>2014-15</td>
<td>85</td>
</tr>
</tbody>
</table>
Soil Moisture Simulation for Agricultural Water Management

Hydrological Modeling Framework

- Variable Infiltration Capacity Hydrological Model
  - Open source; Grid-wise water and energy balance
  - Sub-grid heterogeneity of Land cover
  - Soil depth-wise hydrological response
  - Vegetation phenological changes
  - Daily / sub-daily time step

- 3 min (~ 5.5km) Grid-wise data base

Geo-spatial data

- Terrain - Topographic, Soil (NBSSLUP), LULC (NRC-250k), LAI, Albedo
- Meteorological - Rainfall, Temperature, ... (IMD & CPC)
- Hydrological - River discharge, Reservoir Storage/Releases, GW levels, ...
Near Surface Soil Moisture

30 cm depth Soil Moisture

Legend information:
- Soil Moisture in %
- High
- Low

Colours:
- 0-20
- 20-40
- > 40
Soil Moisture Deficit Index (SMDI) = \( \sum_{i=1}^{n} SMI \)

SMI = AWC/WHC, for 0 < SMI < 0.5
= 1, for SMI > 0.5

Where, n = no of days in the season

SMI: Soil Moisture Index
SMDI: Soil Moisture Deficit Index
AWC: Available Water Content
WHC: Water Holding Capacity
Soil Moisture Deficit Index (SMDI)

Andra Pradesh State

2002

2008

2014

2016

June to September

0

122
Soil Moisture Deficit Index (SMDI)

Andra Pradesh State

No. of days with AWC > 50% WHC

<table>
<thead>
<tr>
<th>No. of days with AWC &gt; 50% WHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>1-30</td>
</tr>
<tr>
<td>31-60</td>
</tr>
<tr>
<td>61-92</td>
</tr>
<tr>
<td>93-122</td>
</tr>
</tbody>
</table>

2002

2008

2014

2016
Weekly Moisture Adequacy Index – 2017 (AET/PET)

<table>
<thead>
<tr>
<th>Time</th>
<th>Weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>W23 (4th June - 10th June)</td>
</tr>
<tr>
<td>2</td>
<td>W24 (11th June - 17th June)</td>
</tr>
<tr>
<td>3</td>
<td>W25 (18th June - 24th June)</td>
</tr>
<tr>
<td>4</td>
<td>W26 (25th June - 01st July)</td>
</tr>
<tr>
<td>5</td>
<td>W27 (2nd July - 08th July)</td>
</tr>
<tr>
<td>6</td>
<td>W28 (9th July - 15th July)</td>
</tr>
<tr>
<td>7</td>
<td>W29 (16th July - 22nd July)</td>
</tr>
<tr>
<td>8</td>
<td>W30 (23rd July - 29th July)</td>
</tr>
<tr>
<td>9</td>
<td>W31 (30th July - 5th Aug)</td>
</tr>
<tr>
<td>10</td>
<td>W32 (6th Aug - 12th Aug)</td>
</tr>
<tr>
<td>11</td>
<td>W33 (13th Aug - 19th Aug)</td>
</tr>
<tr>
<td>12</td>
<td>W34 (20th Aug - 26th Aug)</td>
</tr>
<tr>
<td>13</td>
<td>W35 (27th Aug - 2nd Sep)</td>
</tr>
<tr>
<td>14</td>
<td>W36 (3rd Sep - 9th Sep)</td>
</tr>
<tr>
<td>15</td>
<td>W37 (10th Sep - 16th Sep)</td>
</tr>
<tr>
<td>16</td>
<td>W38 (17th Sep - 23rd Sep)</td>
</tr>
<tr>
<td>17</td>
<td>W39 (24th Sep - 30th Sep)</td>
</tr>
<tr>
<td>18</td>
<td>W40 (1st Oct - 7th Oct)</td>
</tr>
</tbody>
</table>
Hydrological modelling framework has been established for the Mahanadi and Brahmani & Baitarani catchments for the period 1976 to 2013.

- **SWAT** (Soil & Water Assessment Tool)
- Open source hydrological model, semi-distributed, continuous time-step
- Considers land management practices on water, sediment, and agricultural chemical yields at watershed scale
Hydrological Modeling Framework - Sediment and Nutrients

- Soil and Water Assessment Tool (SWAT)
  - Sub-basin scale
  - Monthly time step
  - SCS based Runoff
  - USLE for sediment transport

Sub-Basins

LULC

Soil

Monthly Discharge

Sediment Concentration

Nutrient Loading
Inputs for Irrigation Scheduling
Near-real Time inputs

Prior to irrigation

19 Dec 2003

Irrigation supply initiated

03 Jan 2004

Irrigation supply extended

12 Jan 2004

Onset & extension of irrigation service as captured by multi-date AWiFS data

FCC – GRN SWIR NIR
Progression of Rabi Season Crop Area

As captured by multi-date AWiFS data

Incremental area
Cumulative area

Prior to Irrigation
Irrigation Supplies Initiated
Field Preparation/ Rice Transplantation

Rice Transplantation / Spectral Emergence / Active Tillering

Spectral Emergence / Active Tillering / Heading
Variability in Rice Transplantation period and Irrigation Water Requirement

Attabira Branch Canal

Rice Transplantation
- Early
- Normal
- Late

River / Stream Canal

M. c.u.m

0 5 10 15 20 25 30 35 40
Jan-1 Jan-2 Feb-1 Feb-2 Mar-1 Mar-2 Apr-1 Apr-2 May-1

Actual req. Supplies
Comparison between actual requirement and supplies
Andhra Pradesh State

Seasonal Runoff Potential (June to October)

50% Runoff Percentile

60% Runoff Percentile

75% Runoff Percentile
Thank you