SAsiaFFG System Development and Theoretical Background

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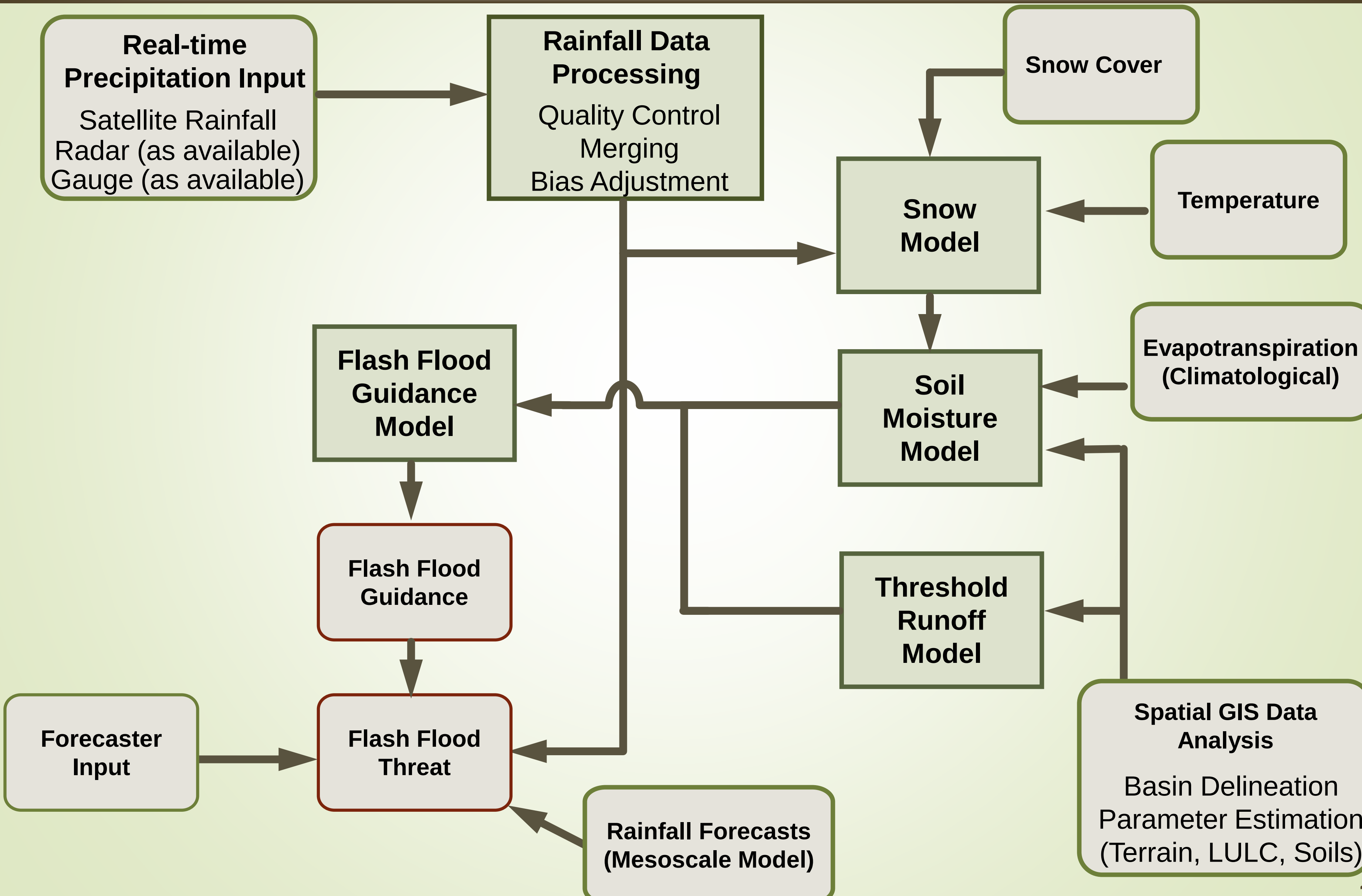
SAsiaFFG Steering Committee Meeting

27 APRIL 2016
New Delhi, INDIA

Key Technical Components of the SAsiaFFG System



SAsiaFFG System Development and Theoretical Background:

1. Spatial Analysis & Threshold Runoff

Hydrologic Research Center

SAsiaFFG Steering Committee Meeting

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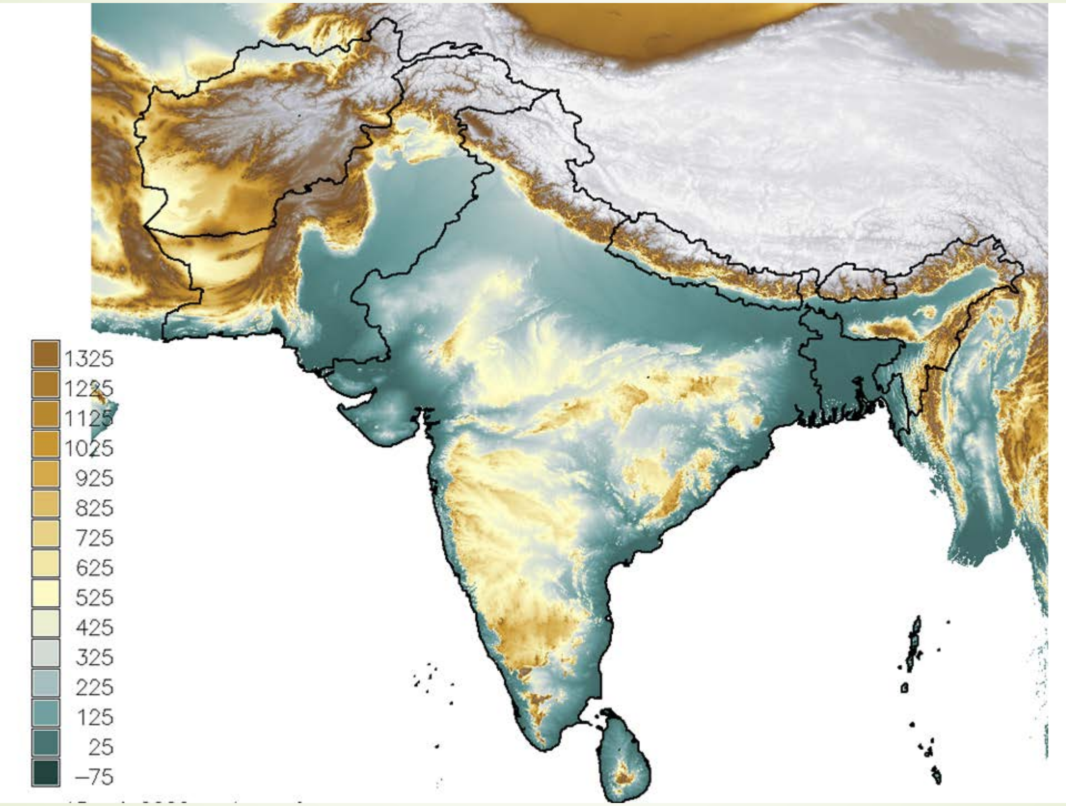
Objective of This Presentation

- *Discuss process for delineation of flash flood-scale watersheds which are used for defining physical properties in SAsiaFFG System:*
  - *model parameterization*
  - *model computations*
  - *product displays*

- *Briefly describe principles of Threshold Runoff estimation.*

Spatial Analysis to Delineate Small Flash Flood Watersheds

- *Use GIS processing of digital elevation data to define watersheds*



SRTM 90-m DEM

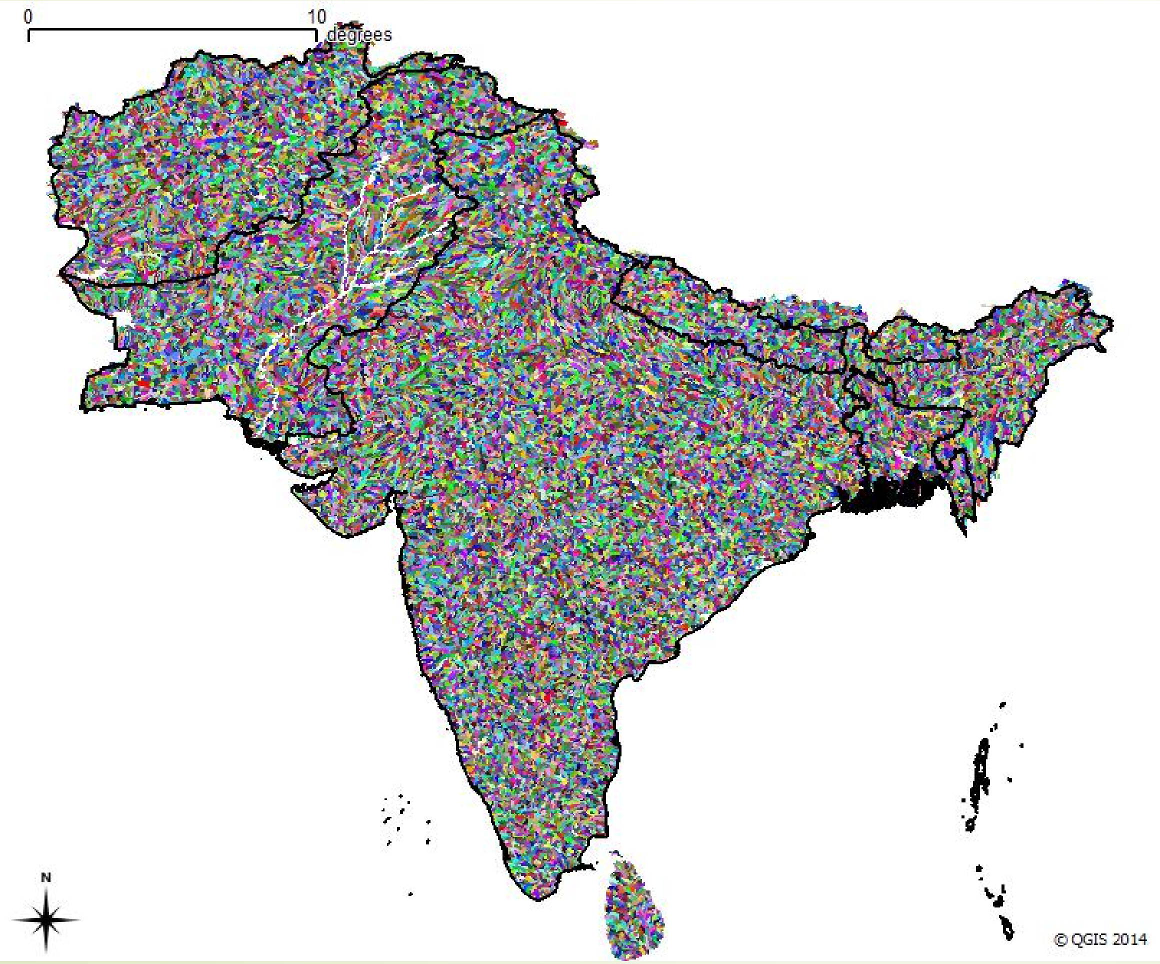
- *satellite-observed*
- *near global*
- *quality controlled*

GRASS GIS Software

- *Routine for automated delineation of stream network and watersheds*

Spatial Analysis to Delineate Small Flash Flood Watersheds

INITIAL DELINEATION RESULTS



Define small watersheds based on minimum headwater size

- *Our target: average local drainage area of 100-150 km^2.*
- *A total of ~42,000 basins defined*
- *Large lakes, rivers, and evaporative pans areas removed*

Output is digital stream network and watershed boundaries.

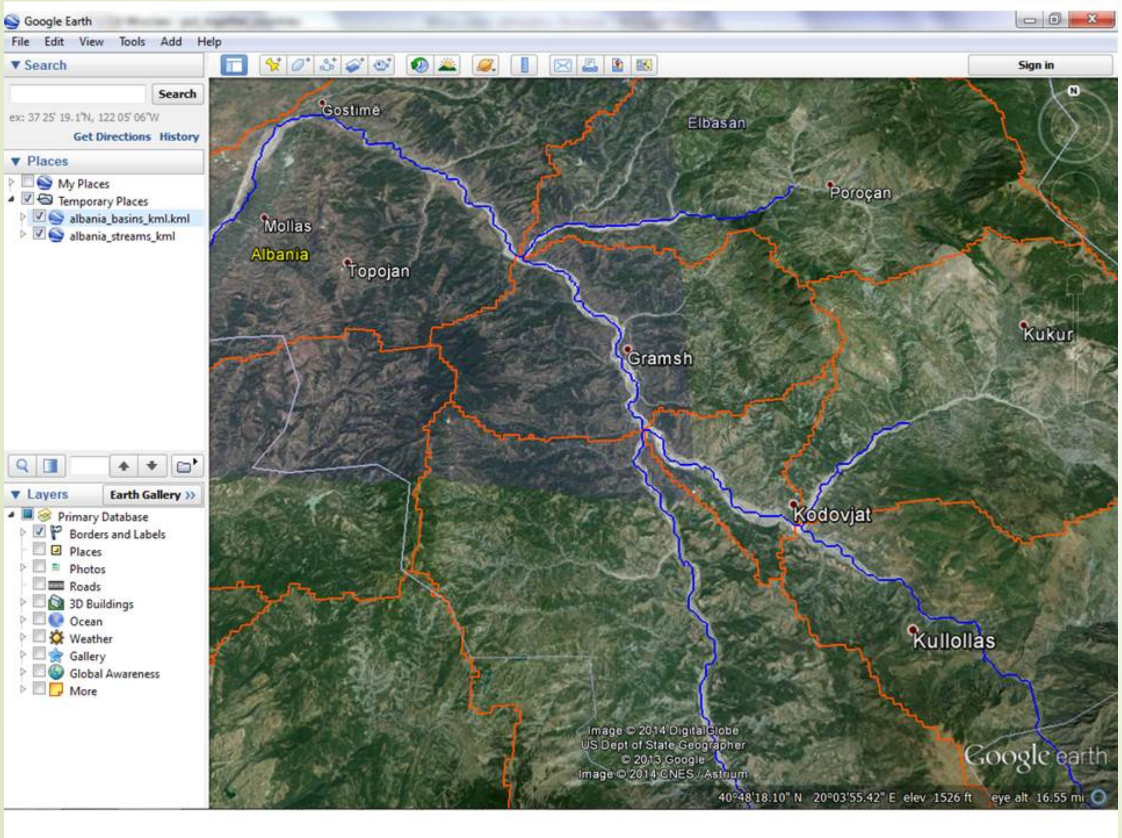
Validation of Delineation Results

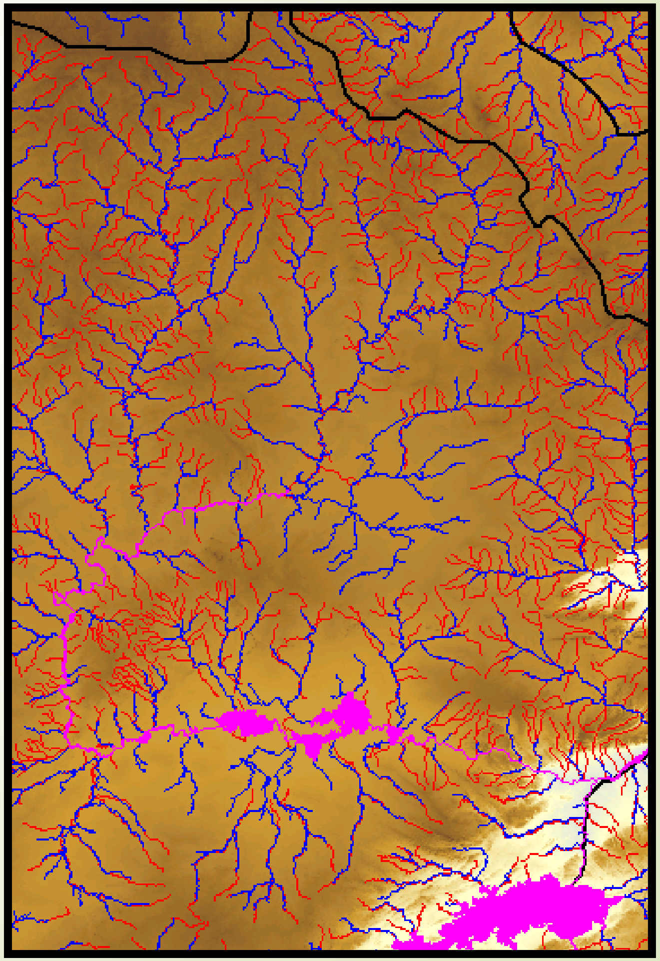
(a) HRC-internal review

comparison with Digital Chart of the World (DCW) stream database

comparison with GoogleEarth Satellite Imagery

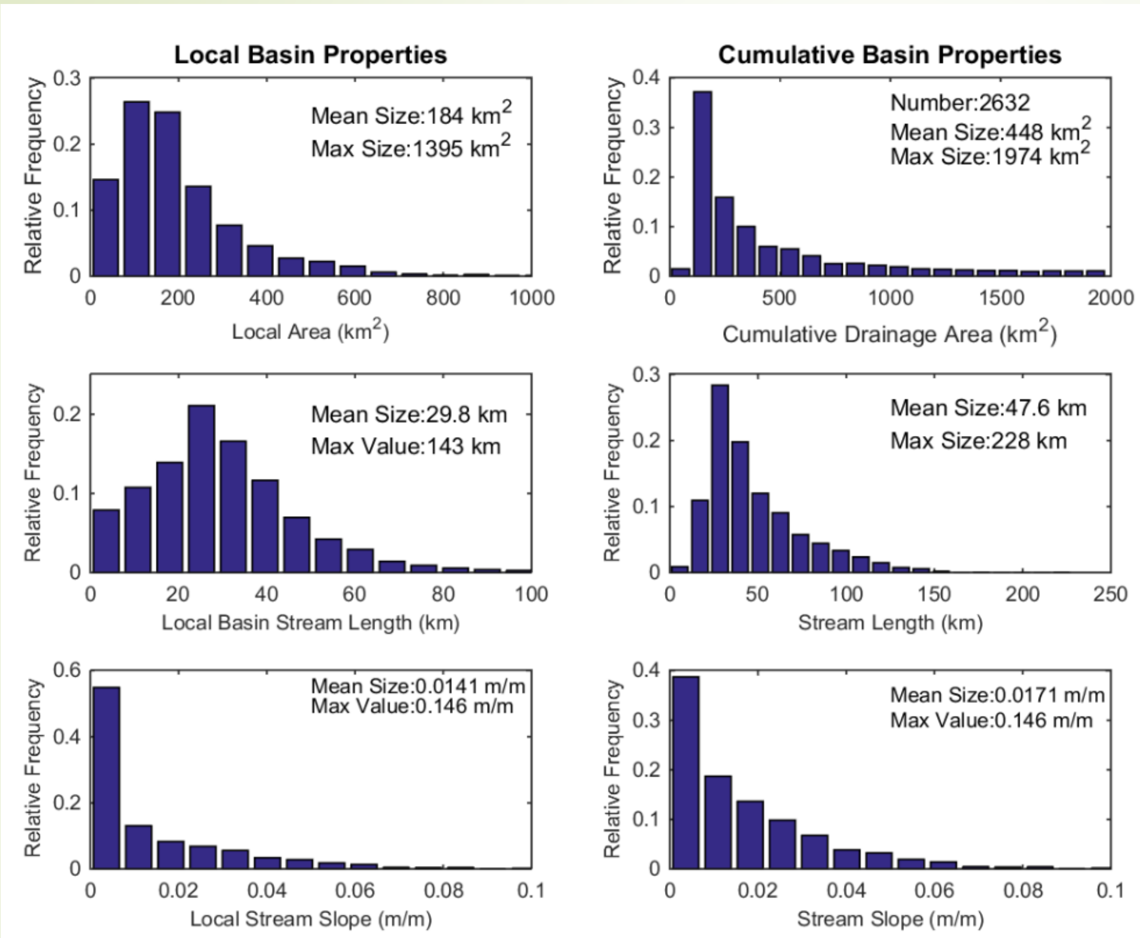
(b) Within-Country review and comments





Spatial Analysis for Small Watershed Properties

Delineation results used with GIS software to compute geometric properties (e.g., area, stream length, stream slope) of each small watershed.



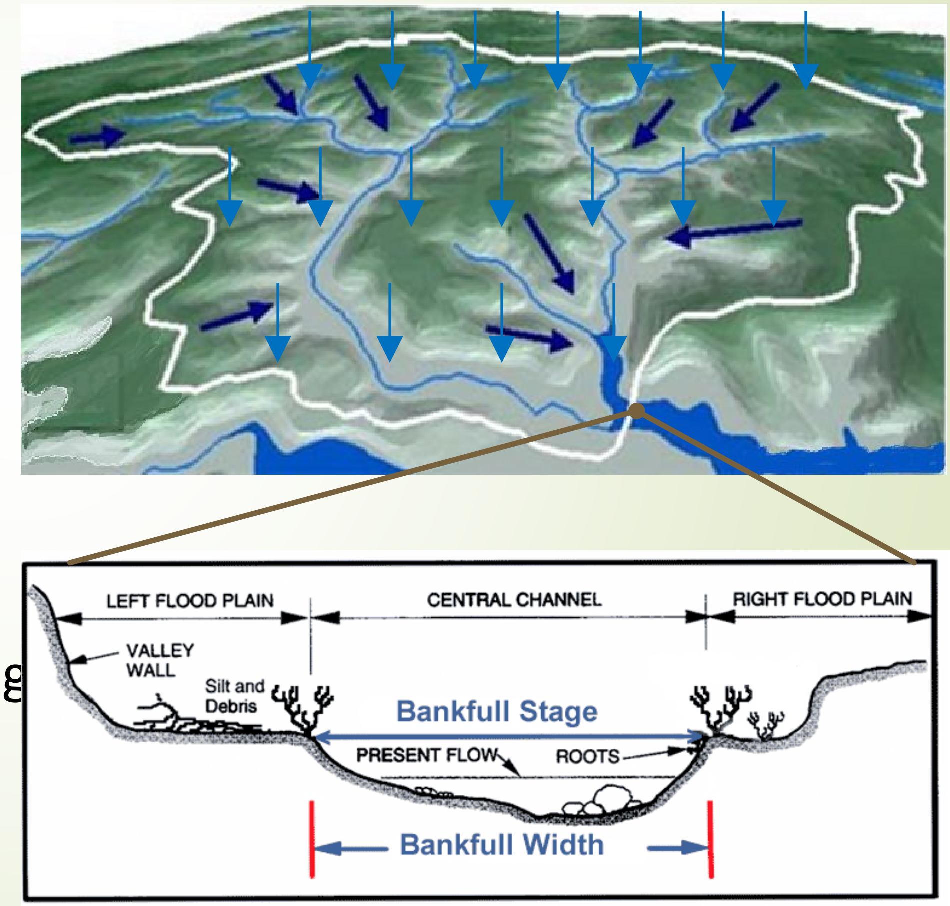
These watershed geometry properties are then used in the computation of *threshold runoff*, a characteristic parameter of FFG.

The watershed boundaries are also used to define average soils and land use properties to parameterize the hydrologic models, and to compute mean areal precipitation

Example from SEEFFG System

What can happen to rainfall once it falls on land surface?

- Infiltrate into the soil and fill soil moisture storage
- Runoff from land surface into channel and fill channel storage
- Be intercepted by vegetation and evaporate

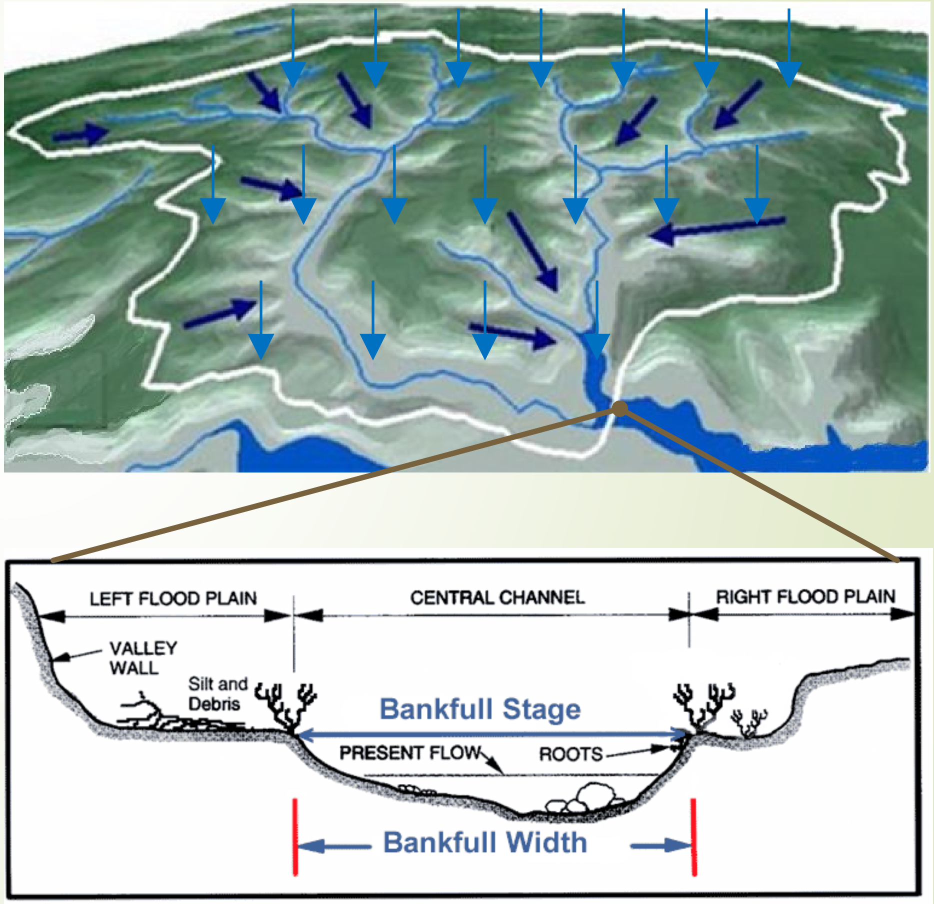


Threshold Runoff represents the amount of *rainfall* that goes to filling the channel capacity at the level of bankfull conditions.

Definition of Threshold Runoff

Threshold Runoff (TR) is defined as the amount of *effective rainfall* of a given duration falling over a watershed that is just enough to cause *bankfull* conditions at the outlet of the draining stream.

TR is a characteristic of the watershed (constant).



Flash flood guidance **(FFG)** is computed from TR by accounting for time-varying rainfall losses to soils and evapotranspiration.

Estimation of Threshold Runoff

Assuming *near-linear response* of watersheds to rainfall excess, threshold runoff may be calculated by equating:

(a) Peak watershed response, as determined by unit hydrograph theory (Geomorphologic Instantaneous Unit Hydrograph, GUIH);

TO

(b) Discharge at the watershed outlet associated with bankfull condition (Manning's steady flow formulation, Q_p)

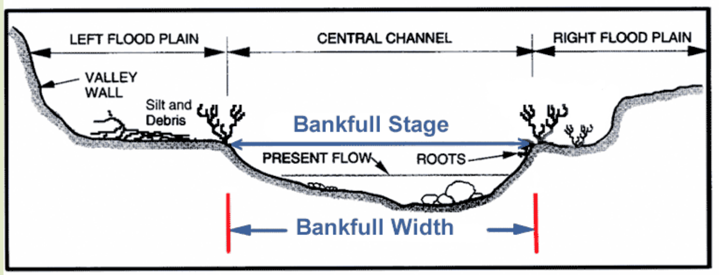
Carpenter et al, *J. Hydrology*, 1999

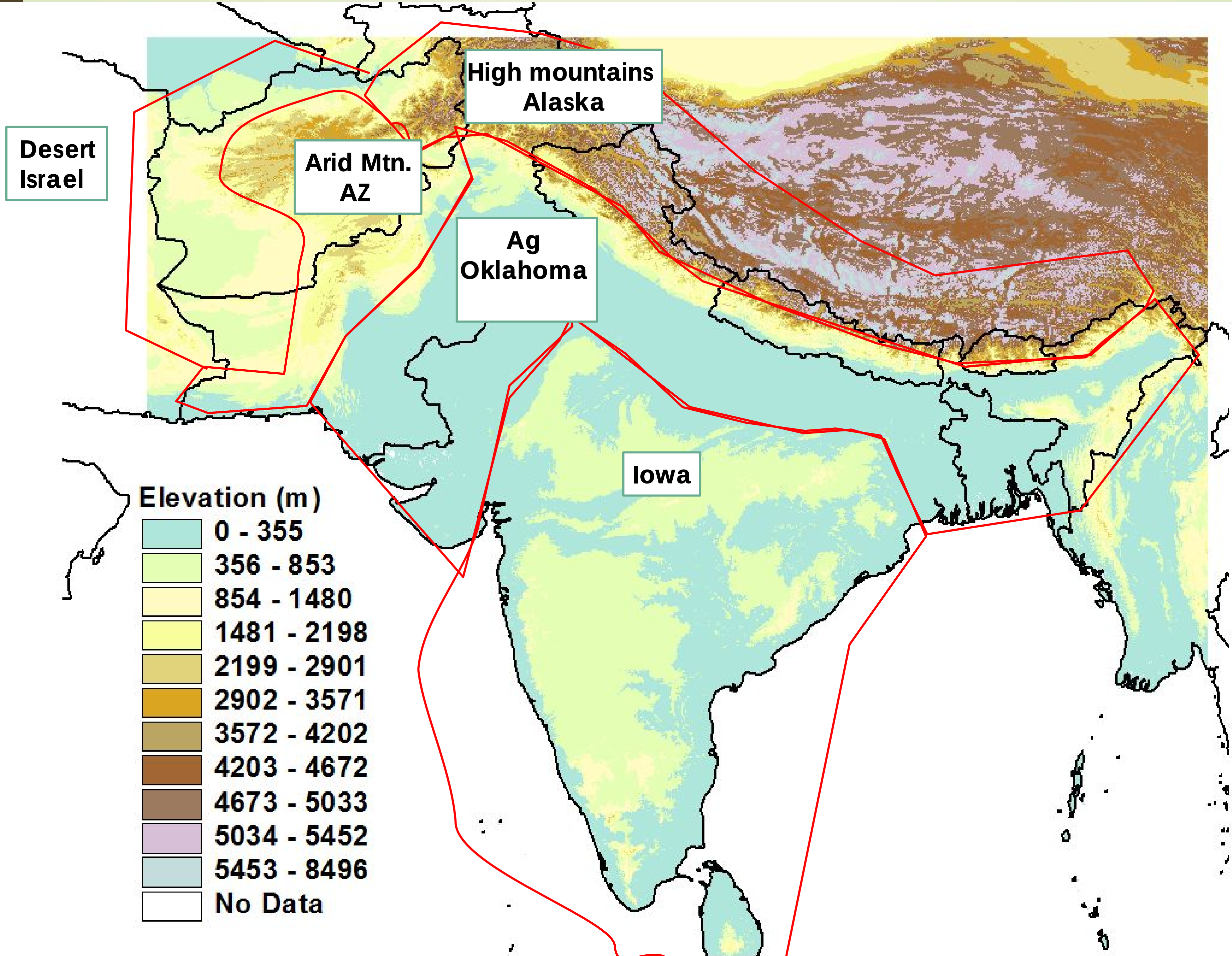
Threshold Runoff, $R = f(A, L, B_b, D_b, S_c)$

Estimation of Threshold Runoff

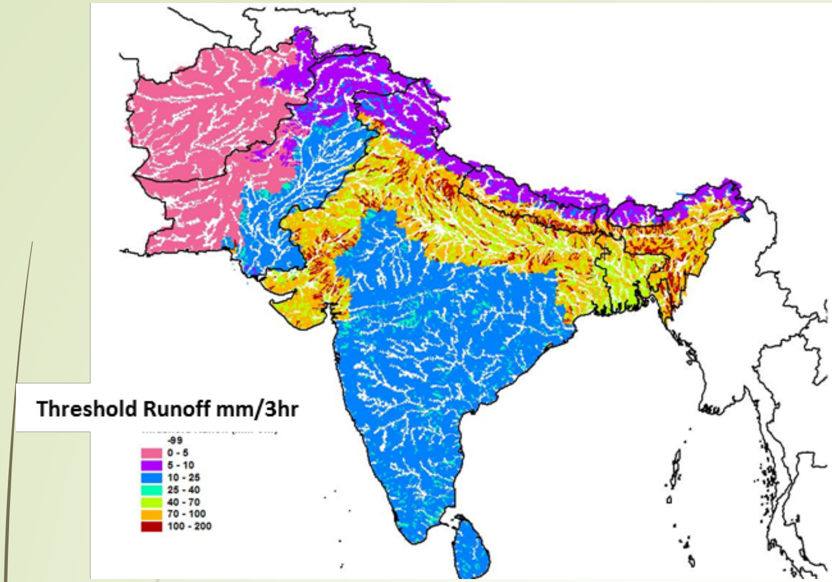
$R = f(A, L, B_b, D_b, S_c)$

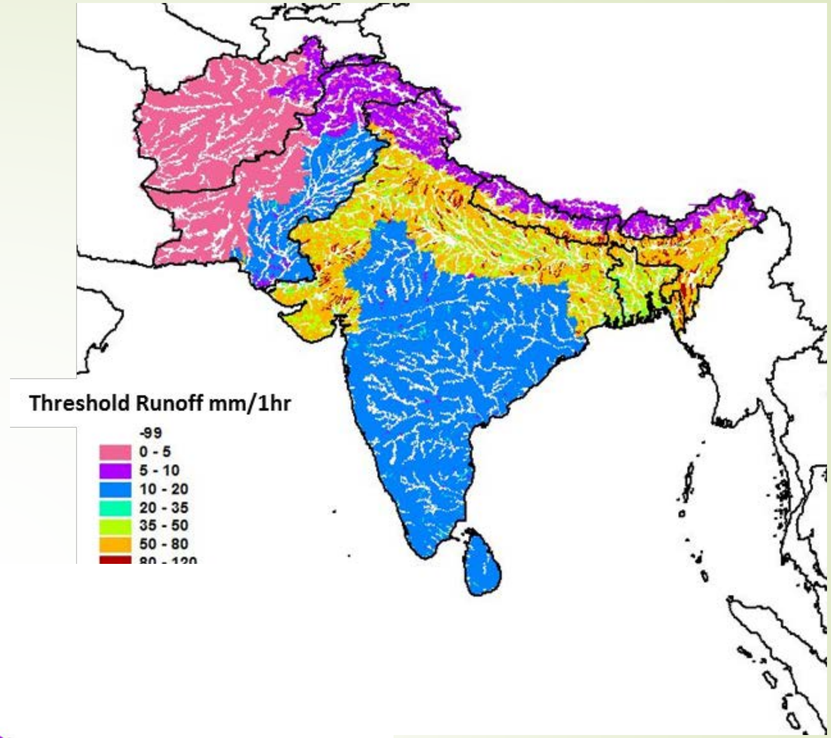
- *Non-linear* expression in R
- Watershed-scale geometry properties (A, L) from spatial GIS analysis
- Channel *cross-sectional* properties (B_b, D_b) estimated from regional relationships with watershed scale properties.
  - Typically, relationships derived from country-provided channel cross-sectional survey information for small streams (limited number of locations).

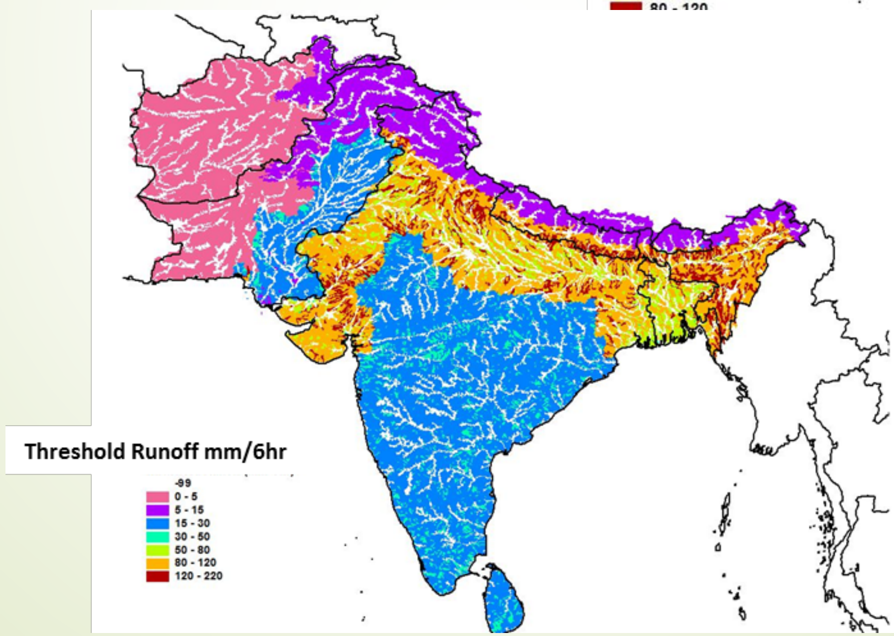




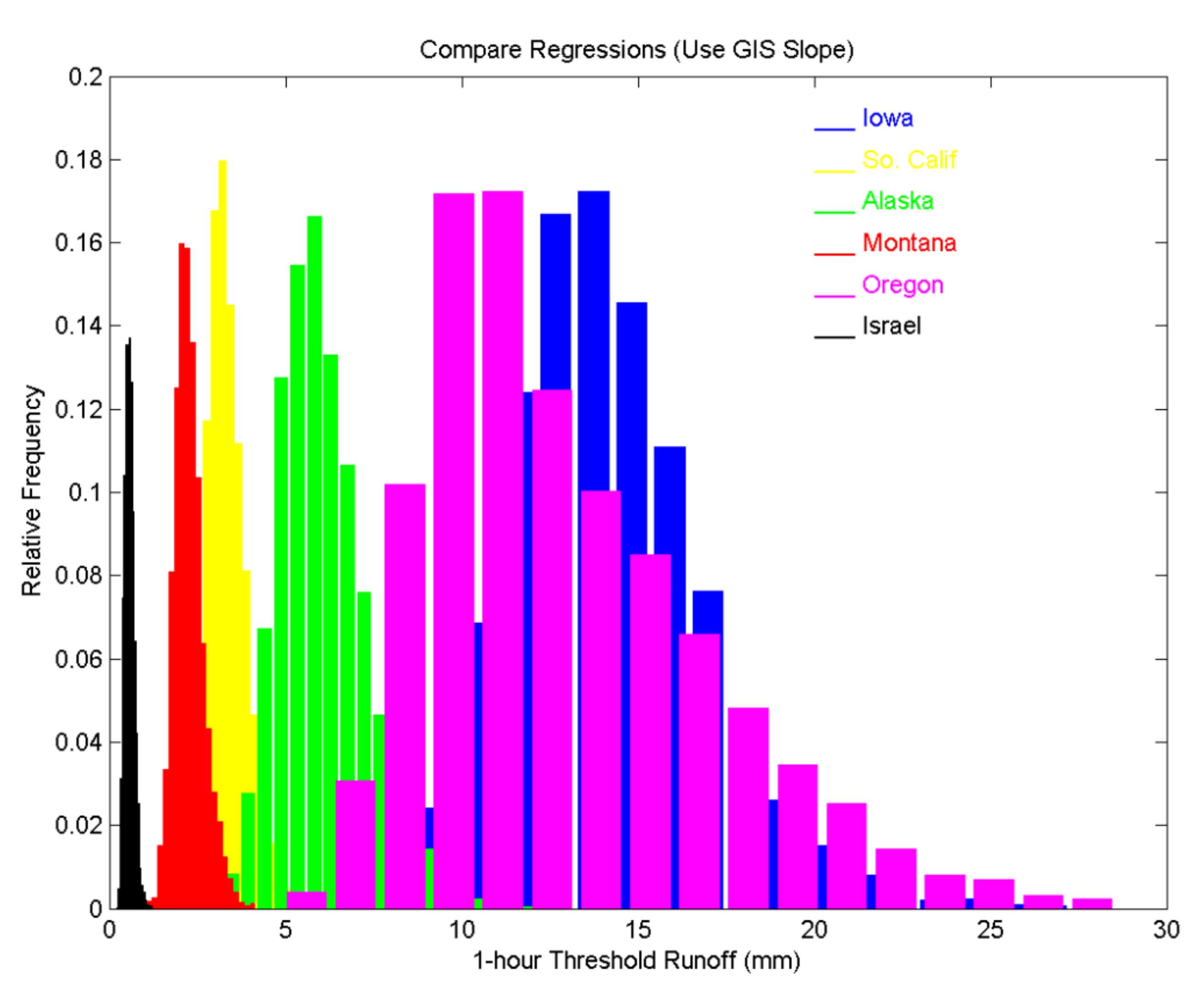
High mountains
Alaska
Desert
Israel
Arid Mtn.
AZ
Ag
Oklahoma
Iowa
Elevation (m)
0 - 355
356 - 853
854 - 1480
1481 - 2198
2199 - 2901
2902 - 3571
3572 - 4202
4203 - 4672
4673 - 5033
5034 - 5452
5453 - 8496
No Data


Threshold Runoff mm/3hr
-99
0 - 5
5 - 10
10 - 25
25 - 40
40 - 70
70 - 100
100 - 200

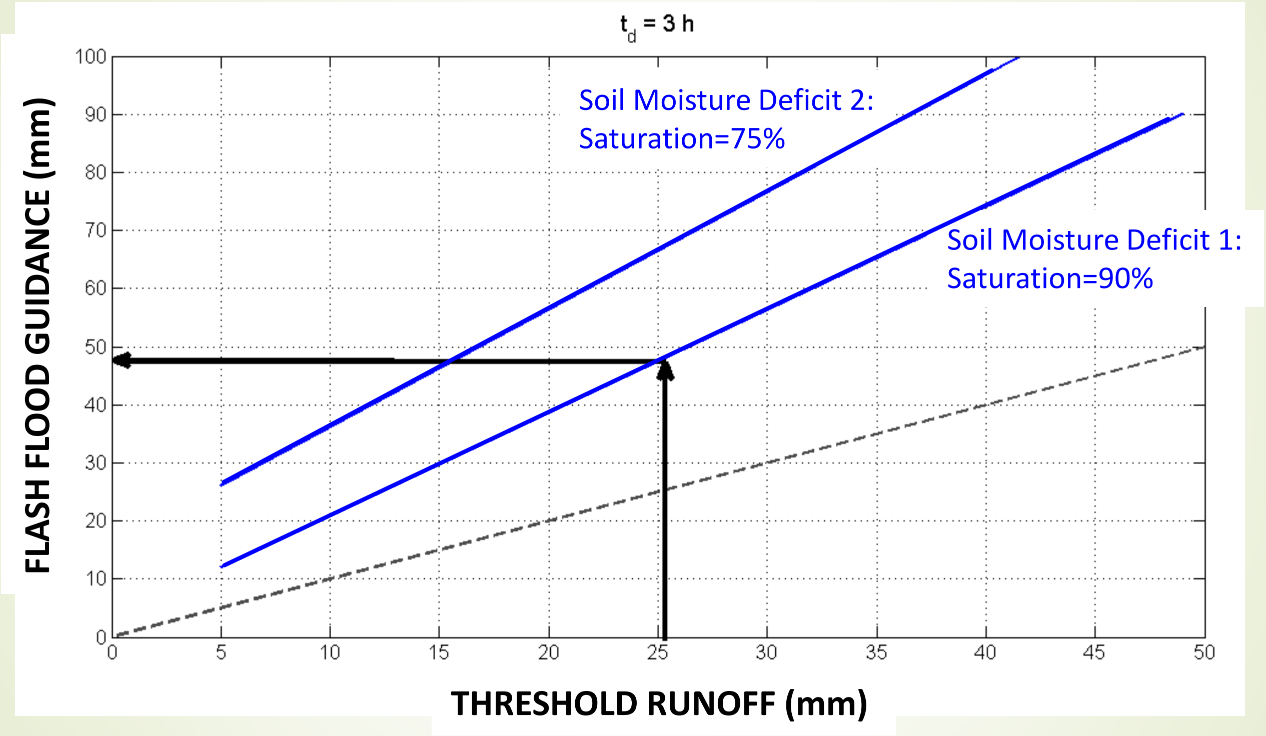

Threshold Runoff mm/1hr
-99
0 - 5
5 - 10
10 - 20
20 - 35
35 - 50
50 - 80
80 - 120


Threshold Runoff mm/6hr
-99
0 - 5
5 - 15
15 - 30
30 - 50
50 - 80
80 - 120
120 - 220

Estimation of Threshold Runoff



Relationship between Threshold Runoff and FFG



*Threshold Runoff is a **one-time** calculation for a given watershed (a characteristic of the watershed), whereas FFG is computed on a **real-time** basis considering up-to-date soil water content conditions. Soil water content greatly influences FFG.*

Summary

- Initial Delineation of flash flood watersheds for SAsiaFFG based on GIS processing of 90-m SRTM DEM.
- ***Threshold Runoff*** (TR) is defined in a physically-based manner using hydrologic principles.
- TR employs *bankfull discharge* as flow associated with flooding conditions, and *geomorphologic unit hyd*rograph to obtain characteristic peak catchment response to uniform rainfall of given duration.
- TR formulated in terms of catchment properties (A,L), and cross-sectional dimension (B_b, D_b), which are estimated based on regional relationship with catchment properties.
- TR related to FFG by accounting for losses to soil and evaporation through hydrologic modeling of each watershed.

SAsiaFFG System Development and Theoretical Background:

2. Soil Moisture, Snow, & FFG Modeling

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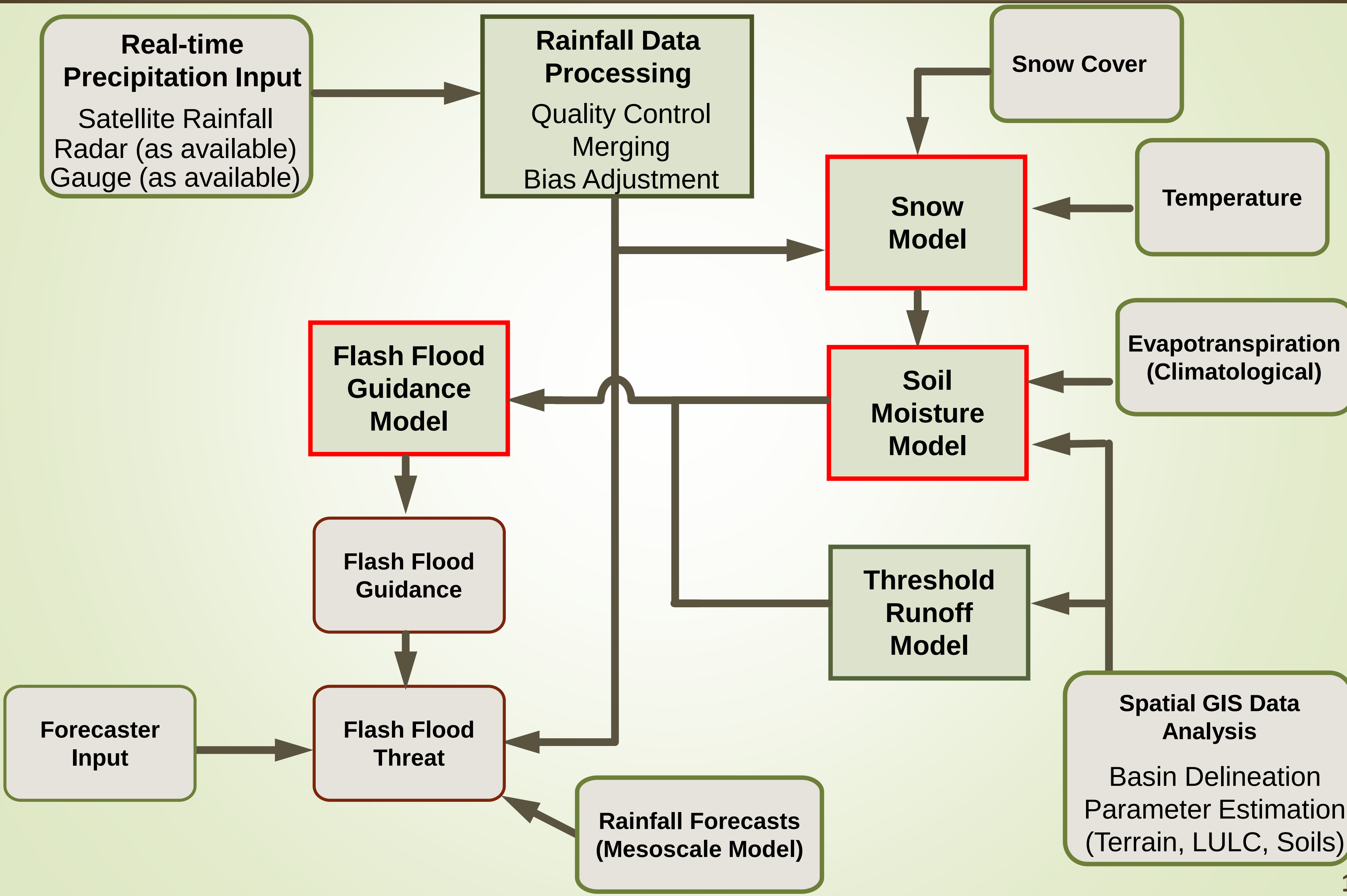
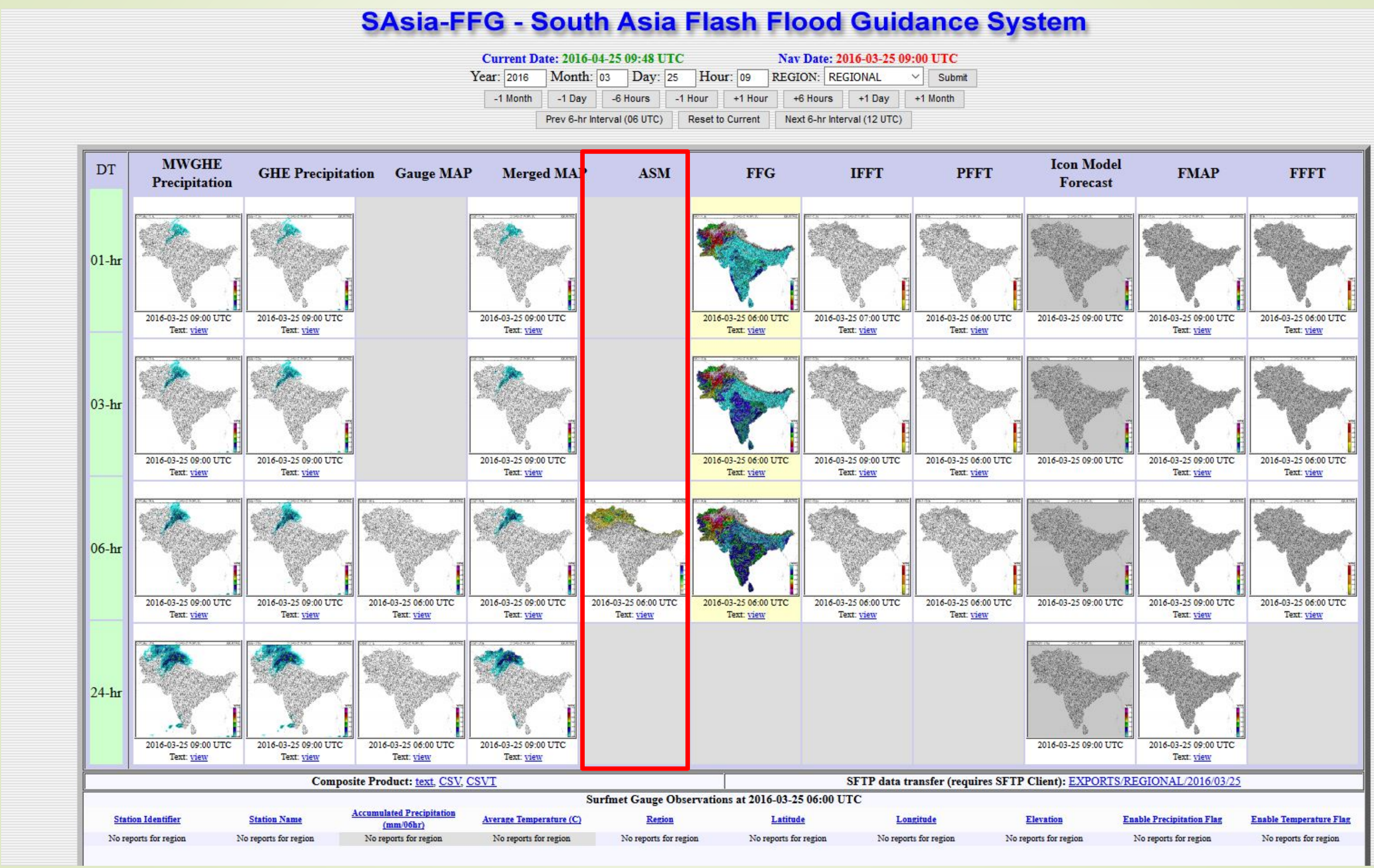
Key Technical Components of the SAsiaFFG System

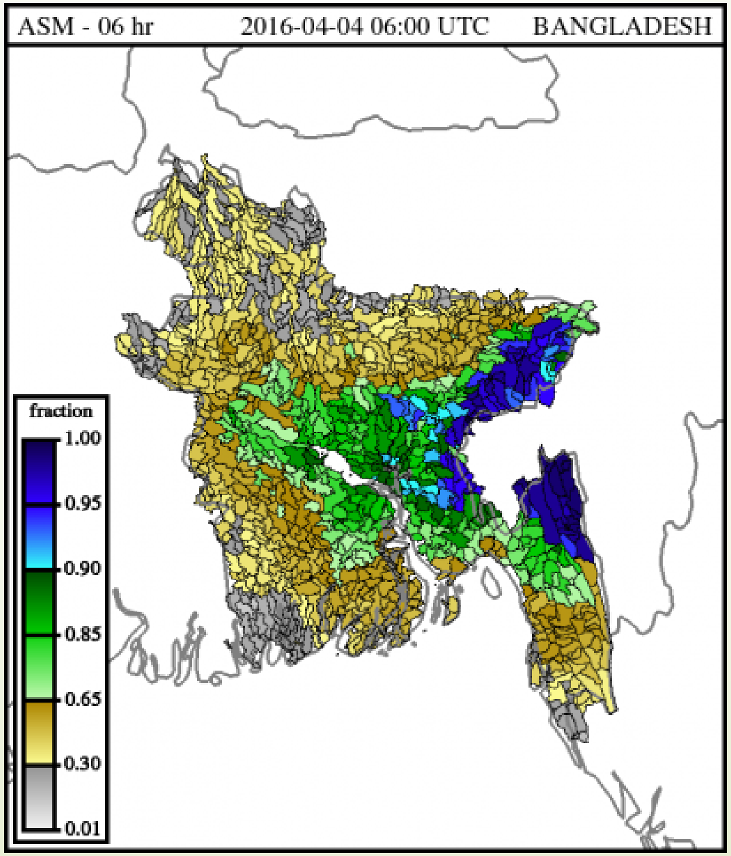


ASM – Average Soil Moisture



ASM Product

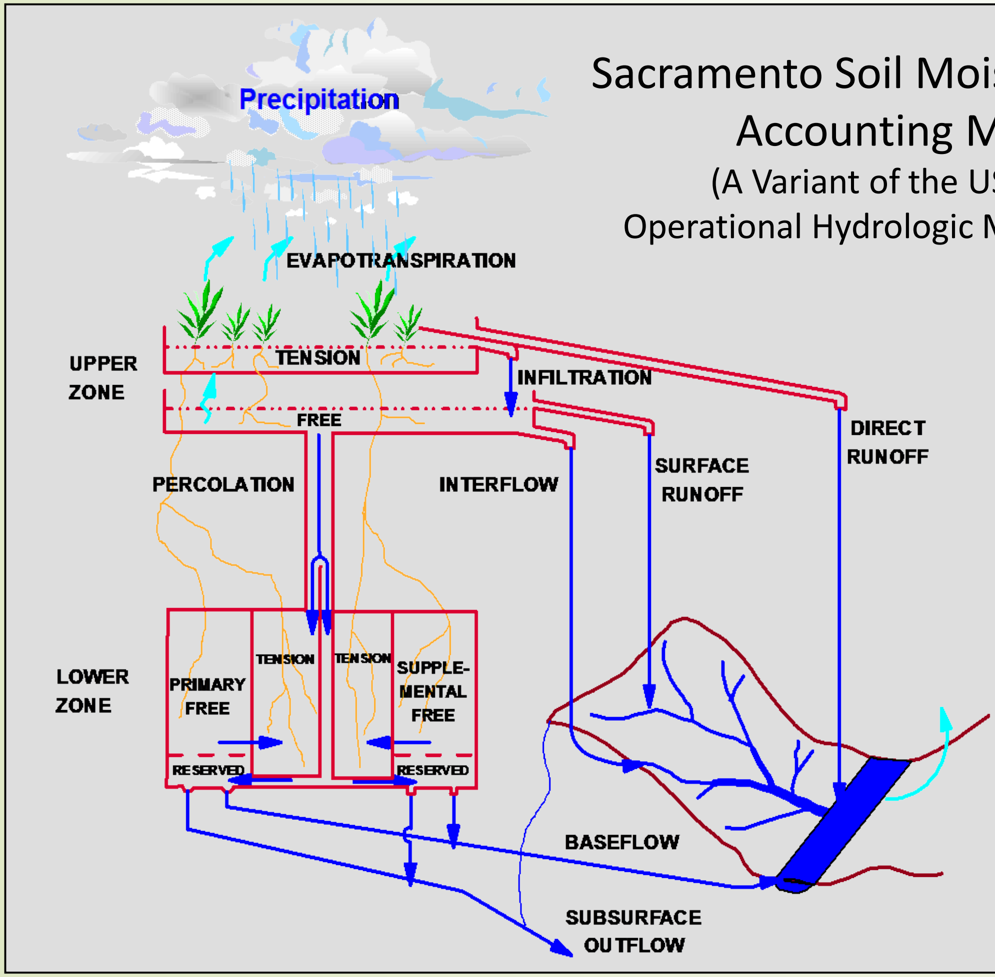
Average Soil Moisture (ASM) product provides an estimate of current soil water in the upper soil depth, expressed as a fraction of saturation. ASM reflects history of prior precipitation. The upper soil water depth is most indicative for flash flood production.



Soil Water Content Modeling for FFG Systems

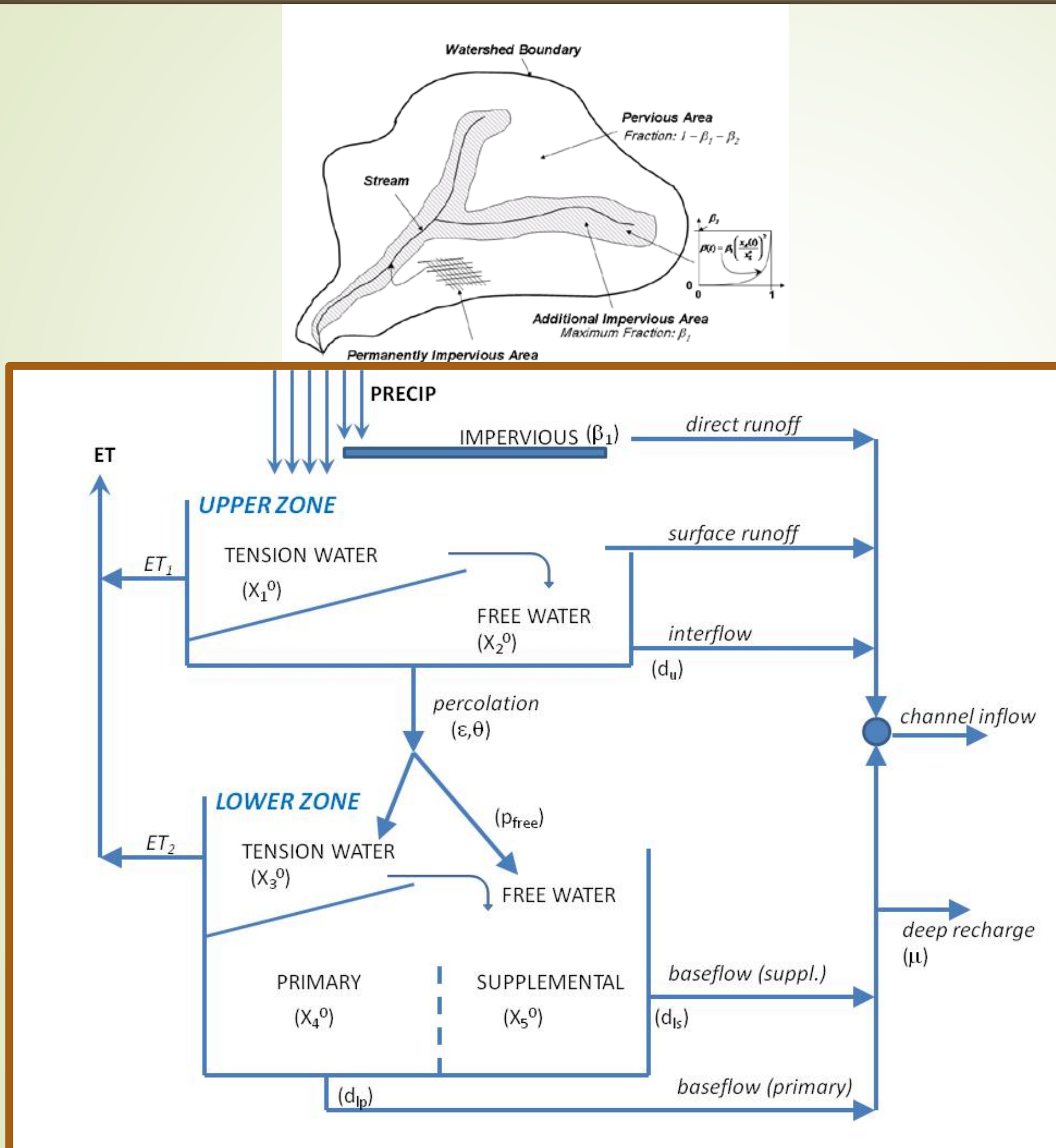
Soil Water Index Model represents : - Saturation excess runoff
- Infiltration excess runoff
- Combined runoff

Sacramento Soil Moisture Accounting Model
(A Variant of the US NWS Operational Hydrologic Model)



- *Soil Water = depth integrated soil moisture*
- *A process-based conceptual model*
  - *Simplified description of physical processes*
  - *Mass balance: two soil layers as a series of connected reservoirs*
- *Areal lumped model at basin scale*
  - *Mean areal fluxes*
  - *Time invariant parameters*

Schematic of SAC-SMA Model Structure



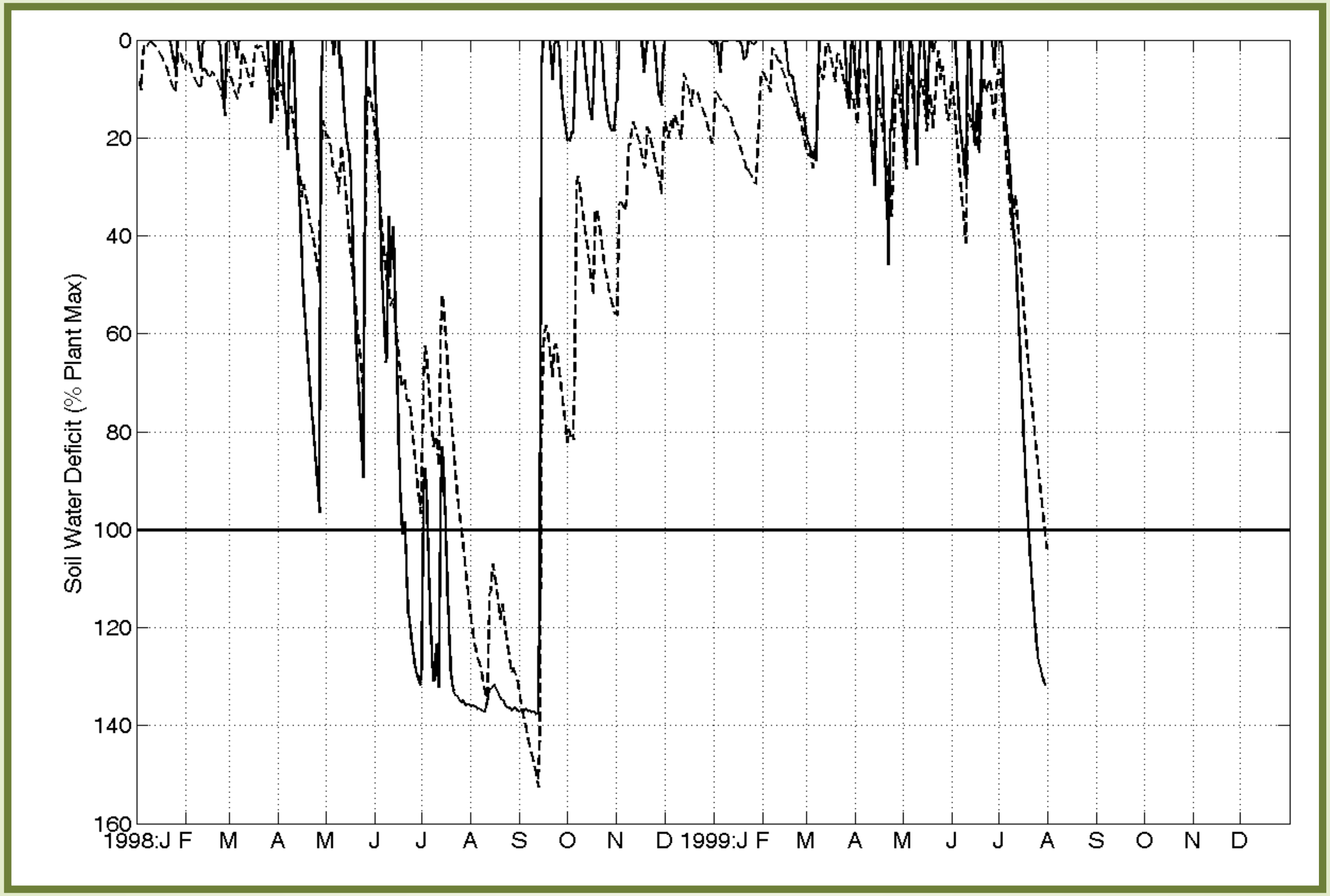
INPUT:
- Precipitation (or Rain + Snow-Melt)
- Potential Evapotranspiration (Demand)

RUNOFF COMPONENTS:
- Direct RO
- Surface RO
- Interflow
- Baseflow

PARAMETERIZATION:
- 15 model parameters

On-Site Validation of Soil Water Modeling

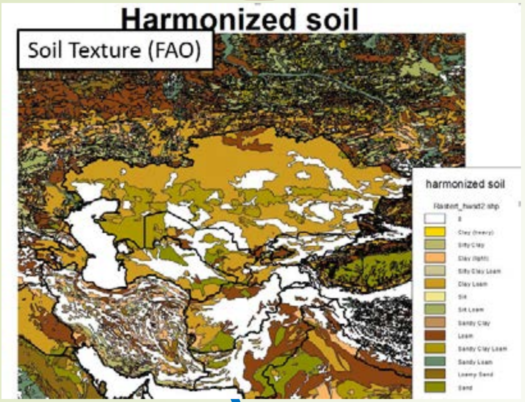
Simulation for Illinois River Basin in Oklahoma, U.S.A



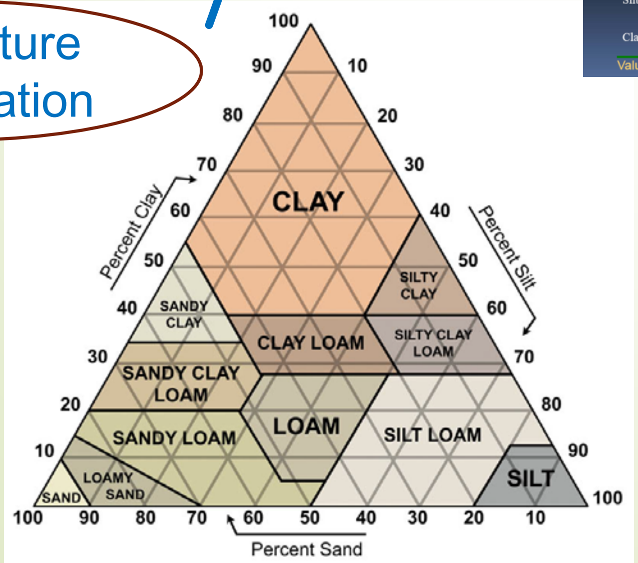
Reasonably good reproduction of depth integrated soil water deficit

A priori Parameter Estimation

Soil Texture (from surveys)



Soil Texture Classification



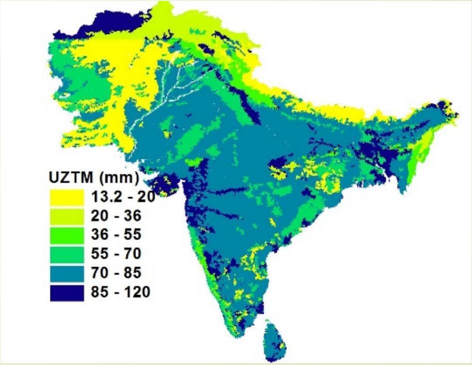
Soil Hydraulic Properties (θwlt, θfld, porosity,Ks)

Soil Texture and Hydraulic Properties

Soil Class	$\theta_s(m^3/m^3)$	$\theta_f(m^3/m^3)$	$\theta_m(m^3/m^3)$	$K_s(m/h)$	α	$\sigma_{Ks}(m/h)$
Sand	0.34	0.09	0.015	0.168	2.79	0.062
Loamy Sand	0.42	0.16	0.05	0.050	4.26	0.082
Sandy Loam	0.43	0.21	0.07	0.019	4.74	0.119
Loam	0.44	0.25	0.095	0.012	5.25	0.108
Silty Loam	0.48	0.29	0.11	0.010	5.33	0.090
Sandy Clay Loam	0.40	0.24	0.11	0.016	6.77	0.088
Clay Loam	0.47	0.32	0.17	0.009	8.17	0.099
Silty Clay Loam	0.46	0.33	0.19	0.007	8.72	0.103
Sandy Clay	0.41	0.29	0.18	0.026	10.73	0.054
Silty Clay	0.47	0.35	0.21	0.005	10.39	0.124
Clay	0.47	0.36	0.24	0.004	11.55	0.106

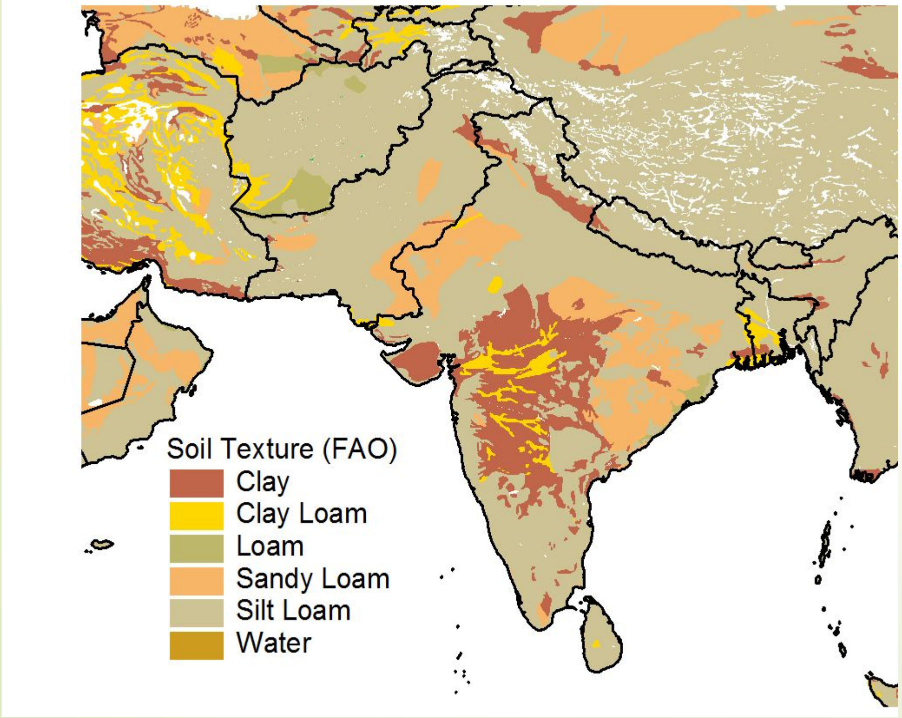
Values are from Cosby et al. 1984

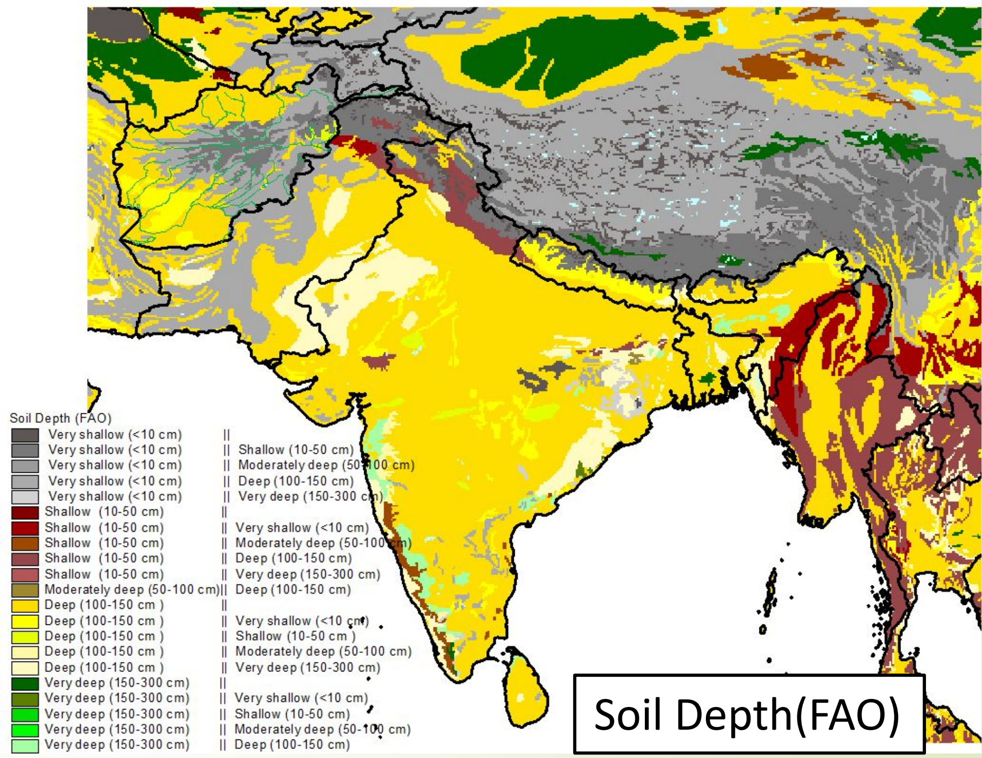
Model Parameters



SAsiaFFG Soil Information: FAO Database

Soil Texture (FAO)

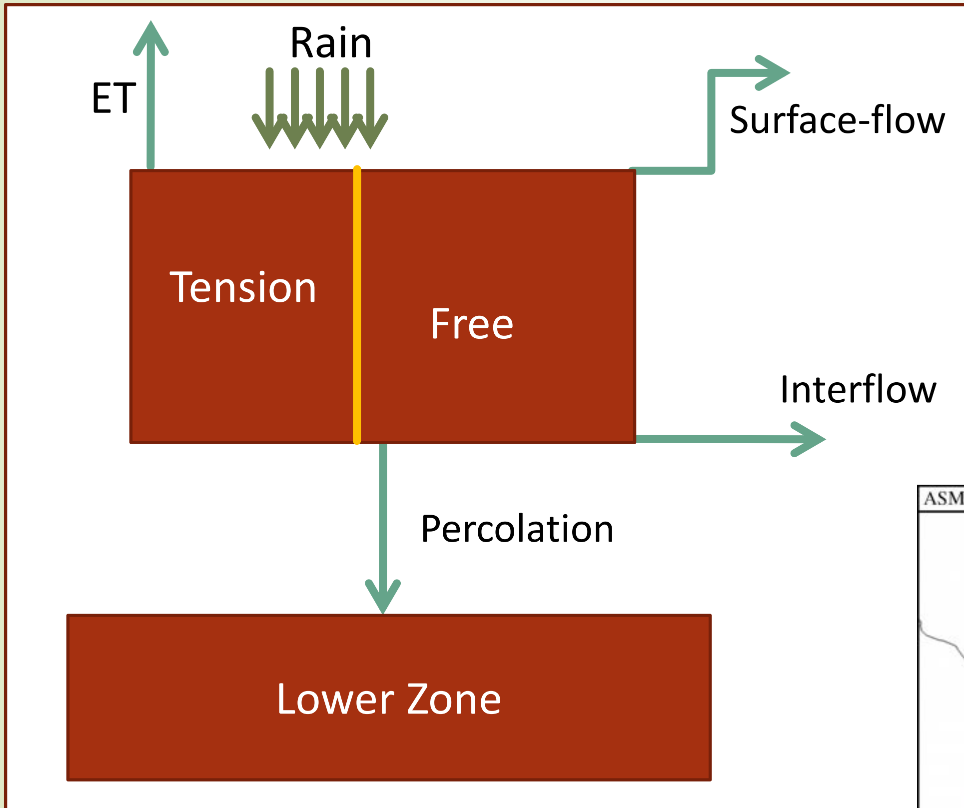




Soil Depth(FAO)

Flash Flood Sensitive Parameters

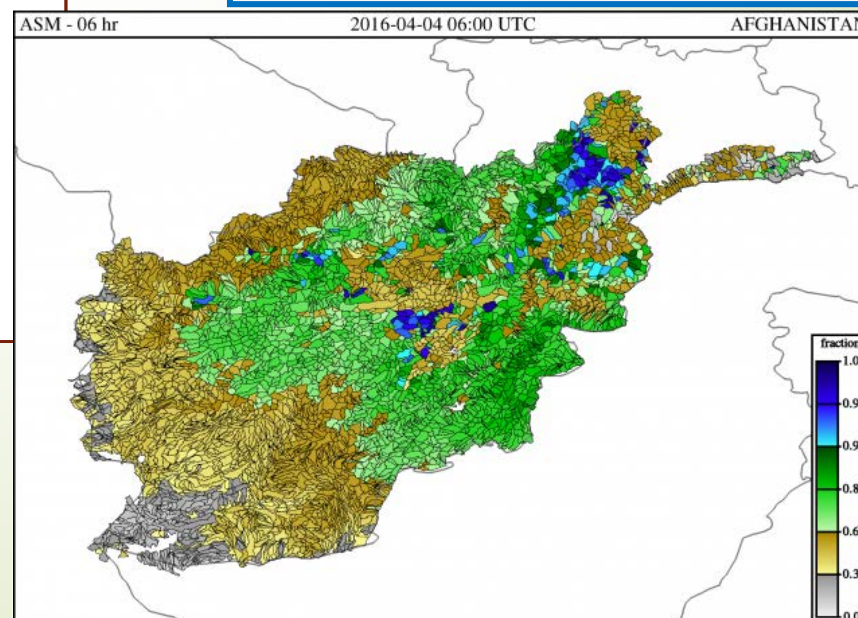
Fast Response components are greatest concern for flash flooding.



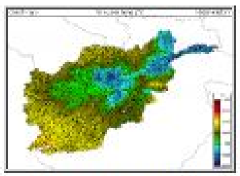
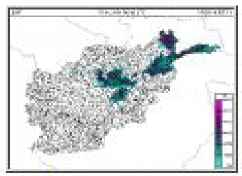
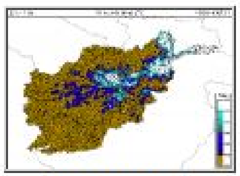
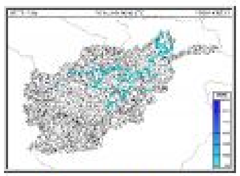
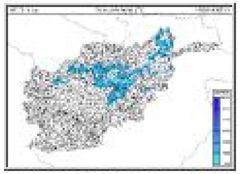
- Define soil moisture product based on Upper Zone:

XTo – upper zone tension capacity
XT – upper zone tension content
XFo – upper zone free capacity
XF – upper zone free content

$ASM=(XT+XF)/(XT_o+XF_o)$



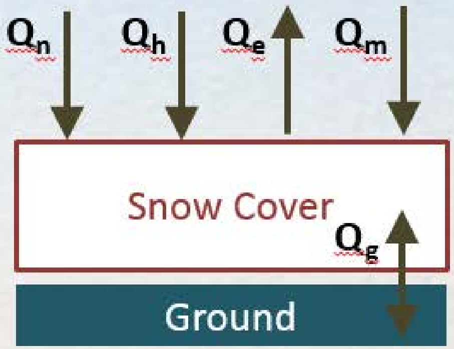
Snow Modeling

Snowpack Products				
DT	Gauge MAT	Latest IMS SCA	SWE	Melt
06-hr	 2016-04-04 06:00 UTC Text: view		 2016-04-04 06:00 UTC Text: view	
24-hr		 2016-04-04 00:00 UTC Text: view		 2016-04-04 06:00 UTC Text: view
4-day				 2016-04-04 06:00 UTC Text: view

For regions with significant snow cover, a snow model is employed to account for snow storage and snow melt impact on soil moisture.

Snow Modeling

- Energy Balance for Snow Cover



$$Q_n + Q_e + Q_h + Q_g + Q_m = \Delta Q$$

where Q_n = net radiation (solar – longwave) $= f\,(Q_{sw}, Q_{lw}, A, T_o)$

Q_e = latent heat transfer $= f\,(e_o, u_a)$

Q_h = sensible heat transfer $= f\,(T_o, T_a, u_a)$

Q_g = heat transfer at snow-soil interface $= f\,(T_g, T_s)$

Q_m = heat transfer by mass changes (e.g. advected by rain) $= f\,(p)$

ΔQ = change in heat storage of snow cover

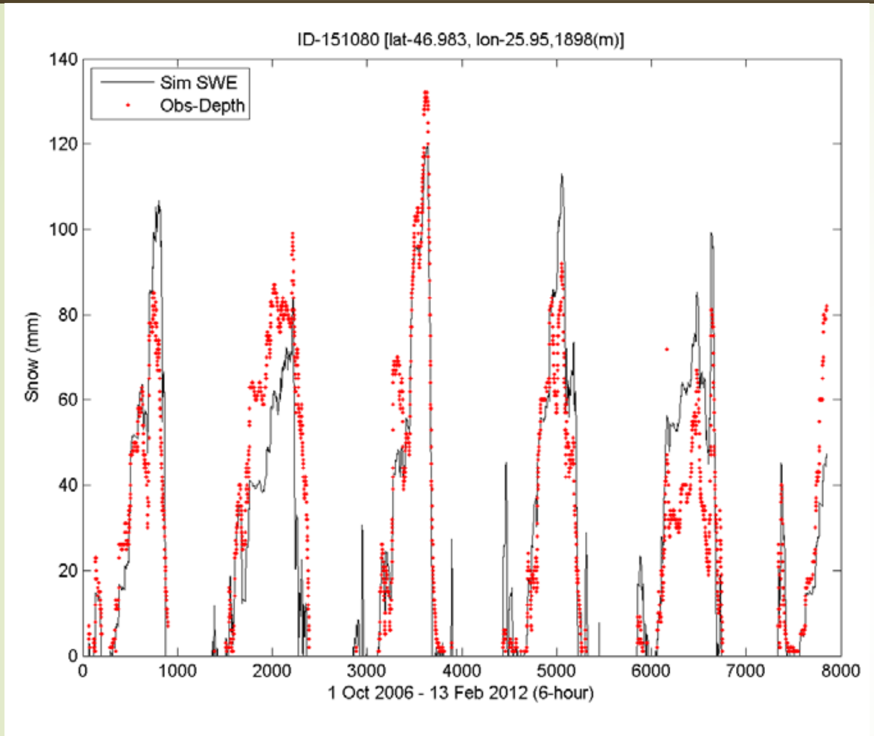
Energy Balance solution is data intensive!

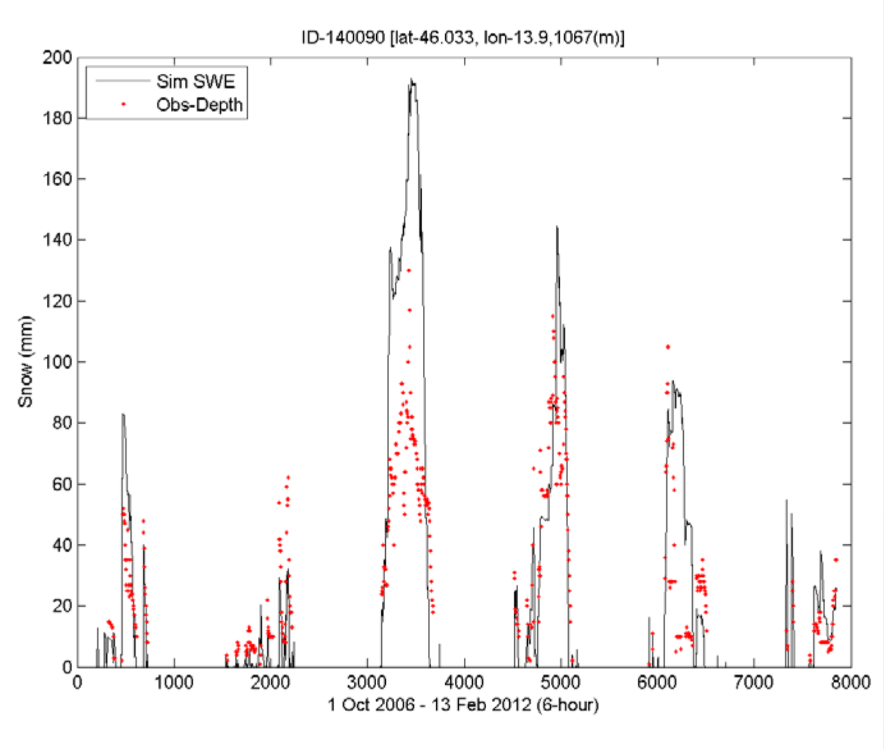
Snow Model – SNOW 17

- Snow Accumulation and Ablation Model (SNOW-17) of the U.S. NWS (Anderson, 1973)
- Designed to use readily available operational data
- A conceptual areal lumped energy and mass balance model
- *Air Temperature* used as an index for pack energy and division of precipitation as rain or snow
- Considers: melt during no rain; melt during rain; no melt
- Model states track: snow water equivalent (SWE), heat deficit, pack temperature, liquid content.
- Single vertical layer
- Three modules:
  - Melt during rain
  - Melt during no rain
  - Heat accounting during no melt

Describe the snow cover extent using the Snow Depletion Curve

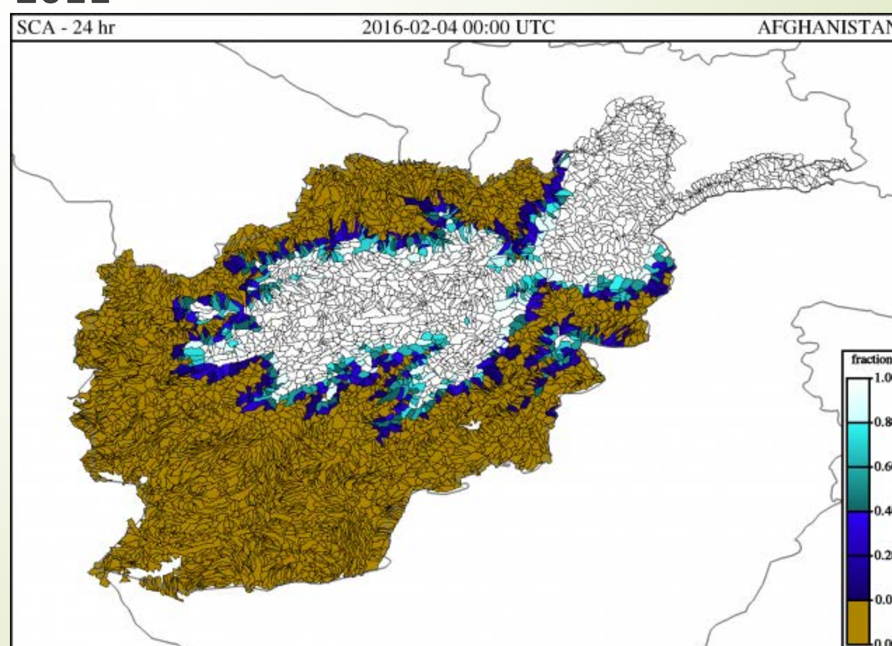
Comparison of modeled SWE with Observed Snow Depth





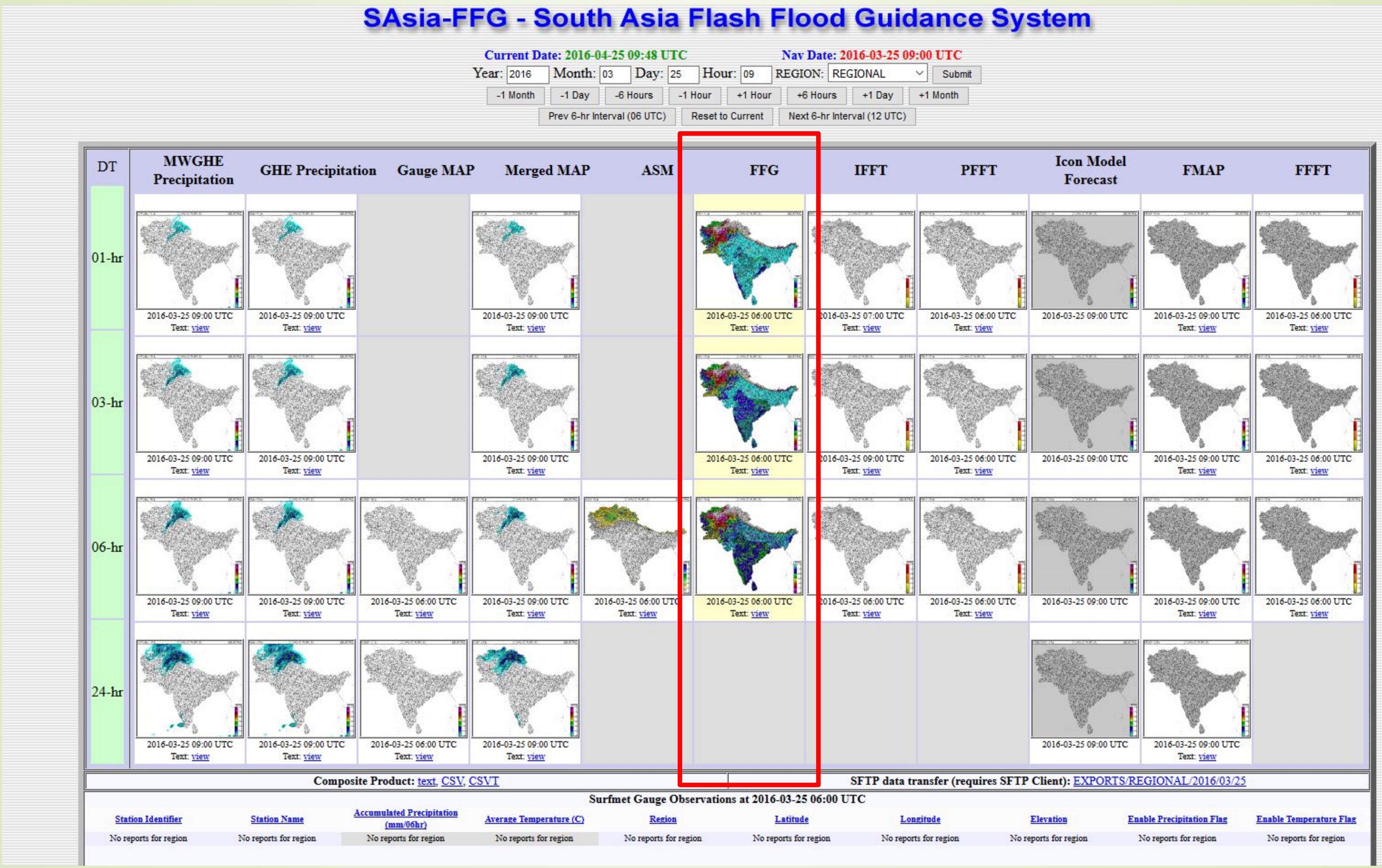
Satellite Snow Covered Area

- Interactive Multisensor Snow and Ice Mapping System (IMS), made available through National Snow and Ice Data Center, NOAA.
  http://nsidc.org/data/docs/noaa/g02156_ims_snow_ice_analysis/index.html
- Daily snow cover based on summary of multiple satellites at 4km x 4km resolution.
  - Geostationary & Polar orbiter satellites
  - Assisted by modeling , climatological maps, and personnel expertise
- Generally available within 1 day (often within several hours) after date of observation
- 4km product is Operational since 2006-2011



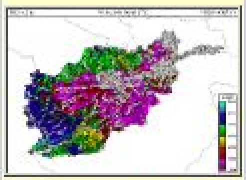
In CARFFG, presented as fraction of snow cover in each basin.
- *Apportion rain for uncovered areas*
- *Soil-snow interface leakage for snow covered areas*

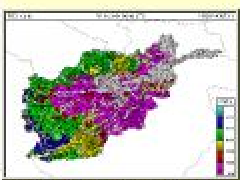
Flash Flood Guidance - FFG



Flash Flood Guidance


2016-04-04 06:00 UTC
Text: view


2016-04-04 06:00 UTC
Text: view

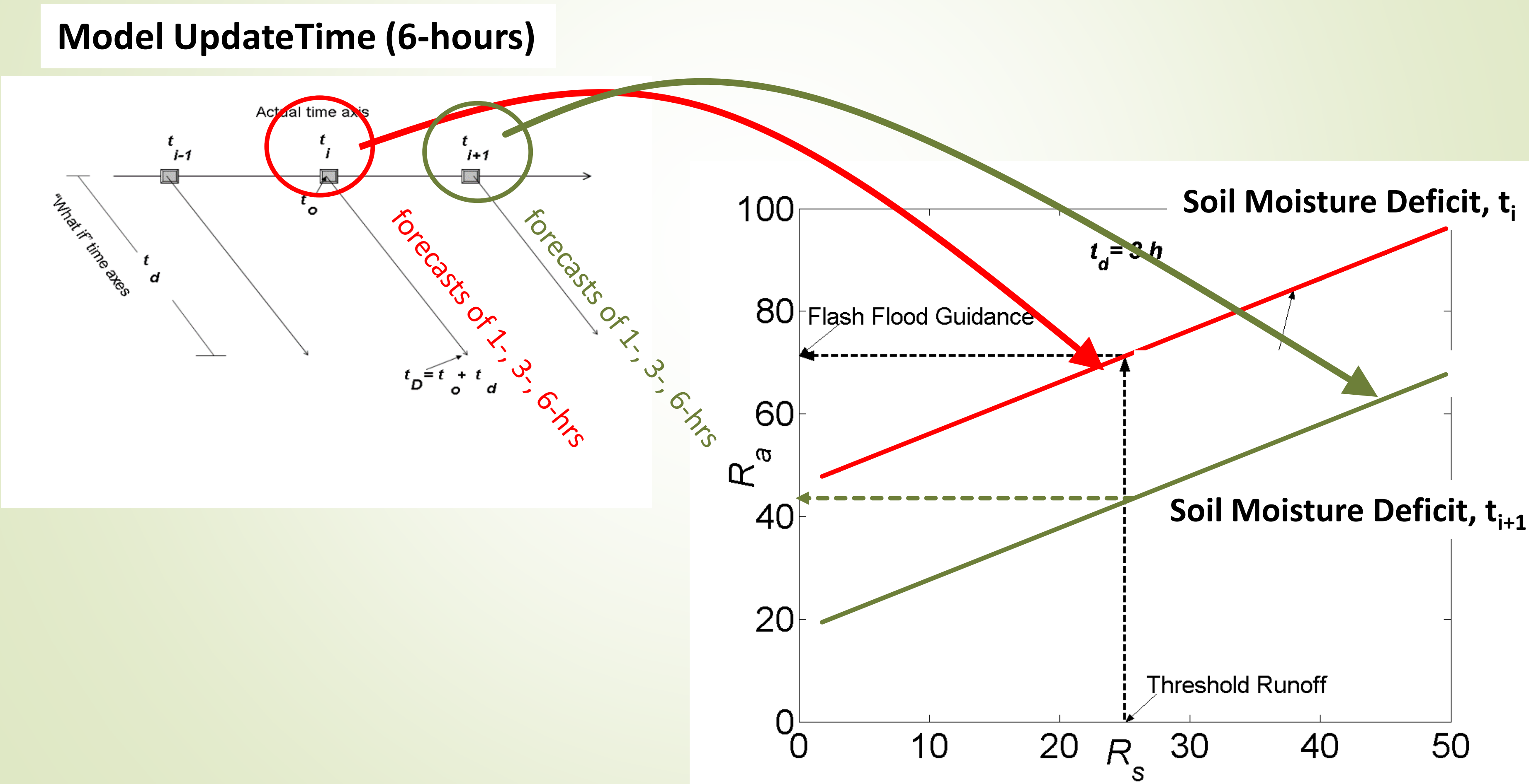

2016-04-04 06:00 UTC
Text: view

Flash Flood Guidance (FFG) is an estimate of the amount of rainfall of a given duration over a given small watershed which is enough to produce bankfull flow in the stream channel at the outlet of the watershed.

FFG integrates information from threshold runoff, soil water content, and current precipitation.

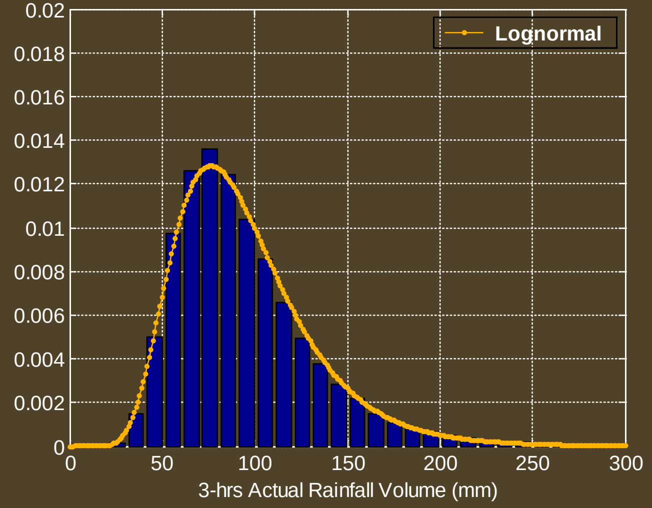
FFG is updated every six-hour in CARFFG System.

Relationship b/t Threshold Runoff, Soil Moisture, & FFG

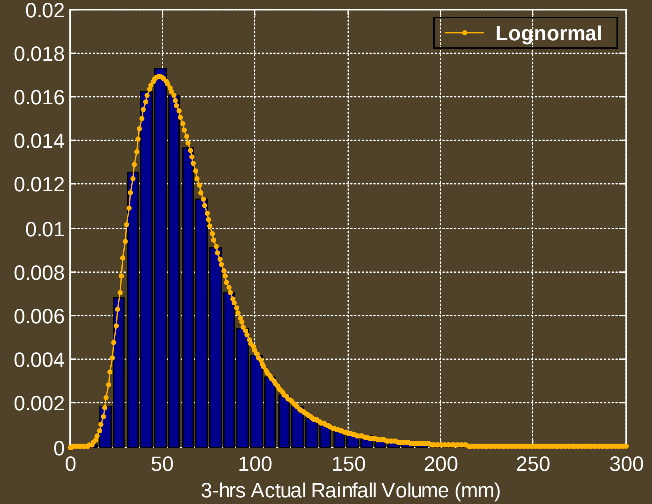


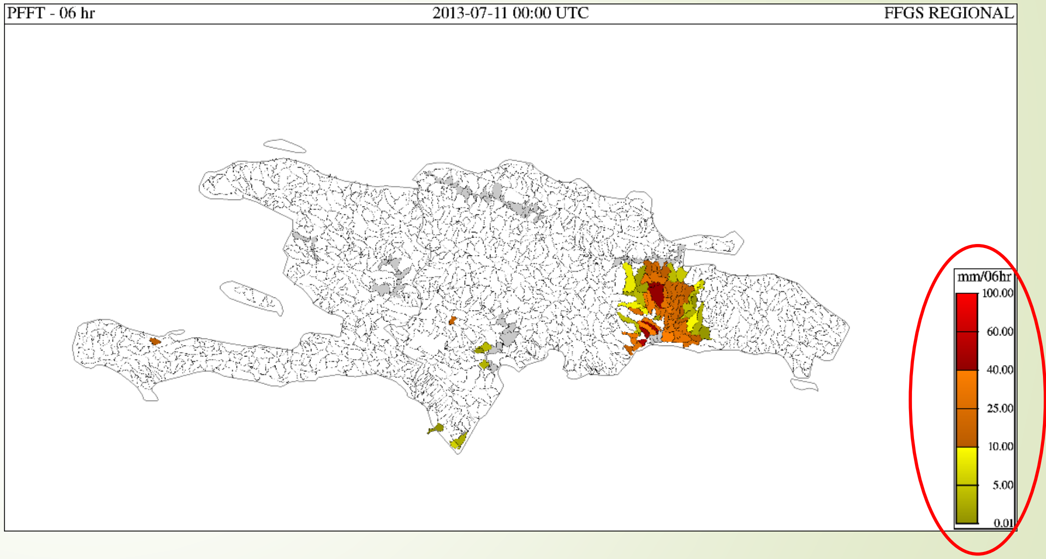
Uncertainty in FFG

Dry Conditions



WetConditions





Summary

- SAsiaFFG system includes hydrologic modeling components for (a) soil water content, (b) snow, and (c) flash flood guidance.
- The soil water index model is based on the Sacramento Soil Moisture Accounting (SAC-SMA) model, which is a physically based conceptual model.
- The SNOW-17 model is a temperature index model for snow accumulation and ablation. Satellite estimates of snow cover (from IMS) are ingest into the system to compute snow cover, snow water equivalent, and snow melt.
- FFG integrates current precipitation, threshold runoff, and soil water deficit for each basin to estimate additional rainfall of a given duration necessary to reach bankfull conditions at the outlet of the basin.

SAsiaFFG System Development and Theoretical Background:

3. Satellite Precipitation & Bias Adjustment

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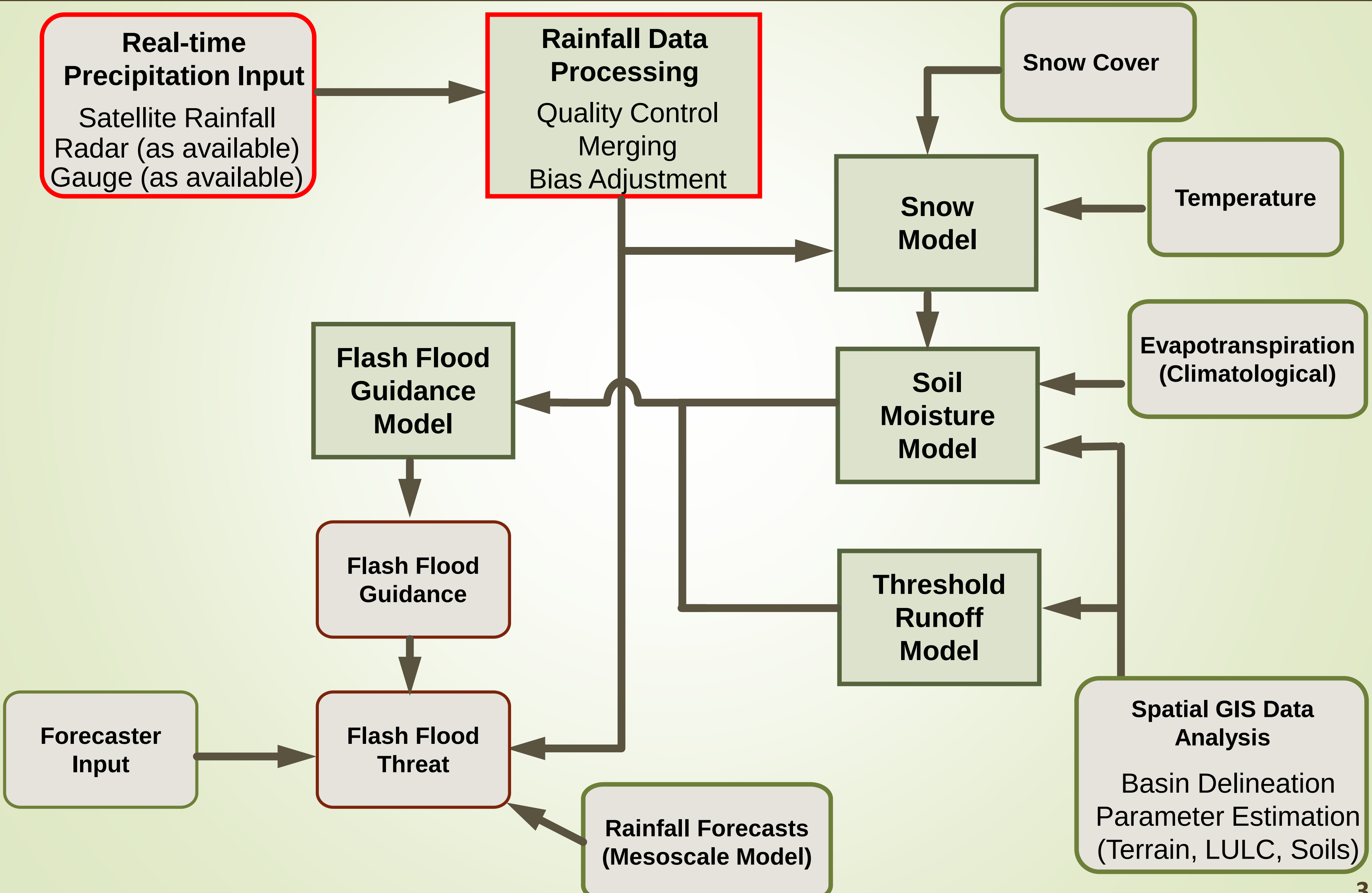
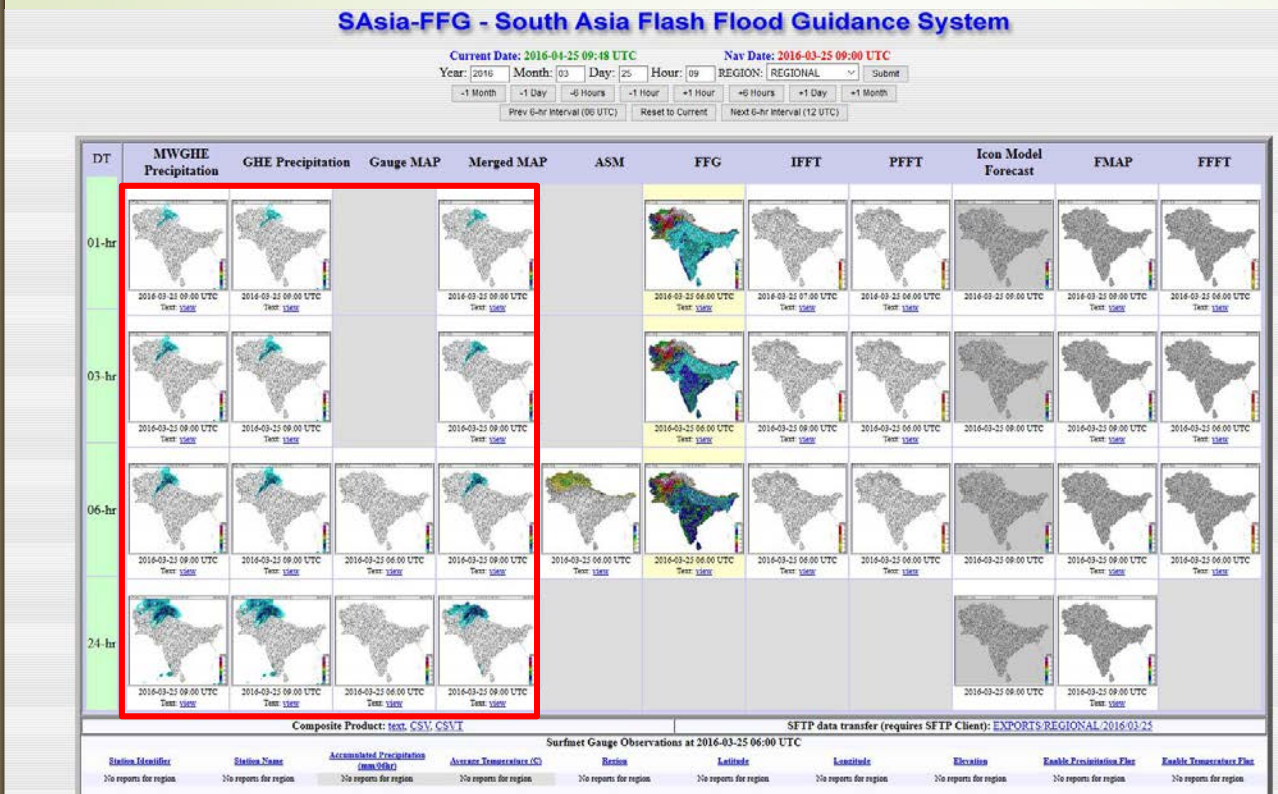
27 APRIL 2016

Key Technical Components of the CARFFG System



Satellite Precipitation Estimation

Satellite Precipitation estimates provide critical information in regions with sparse coverage by traditional gauge or radar networks.



In this presentation:

- Describe satellite products
- Introduce procedures to handle bias in precipitation estimates

Global HydroEstimator (GHE)

Rainfall rate based on Cloud Top Brightness Temperature (indirect measurement)

InfraRed–based (10.7μm)

Produced by NOAA/NESDIS

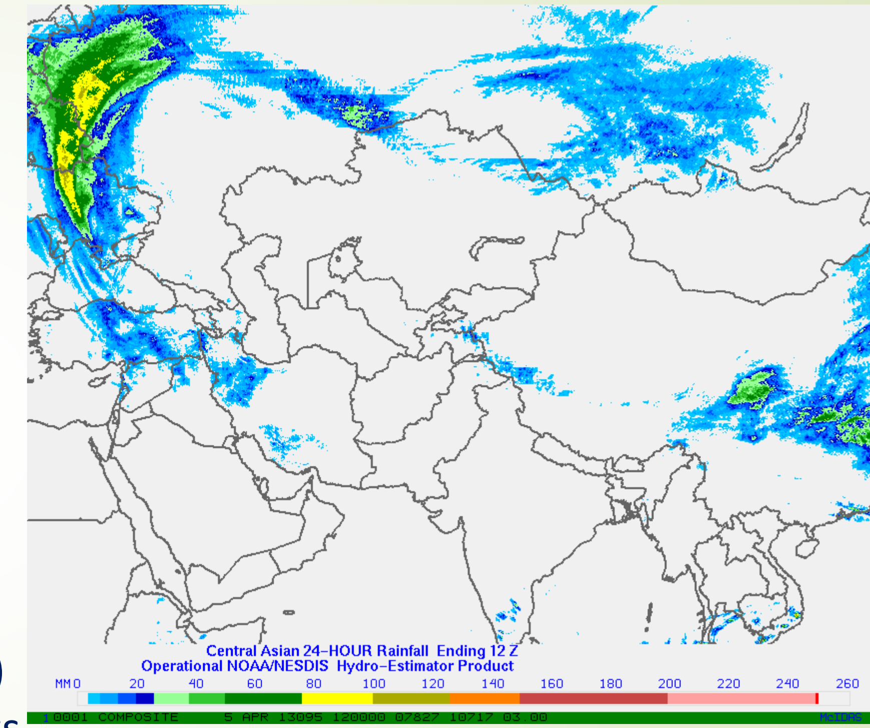
Research/development on HE since 1970s

Short latency (<30-min in operations)

~4km resolution

Enhanced for:

1. Atmospheric moisture effects
2. Orography (upslope/downslope)
3. Convective Eqlb. Level (warm-top convection)
4. Local pixel Temp. difference with surroundings
5. Convective core / no-core region

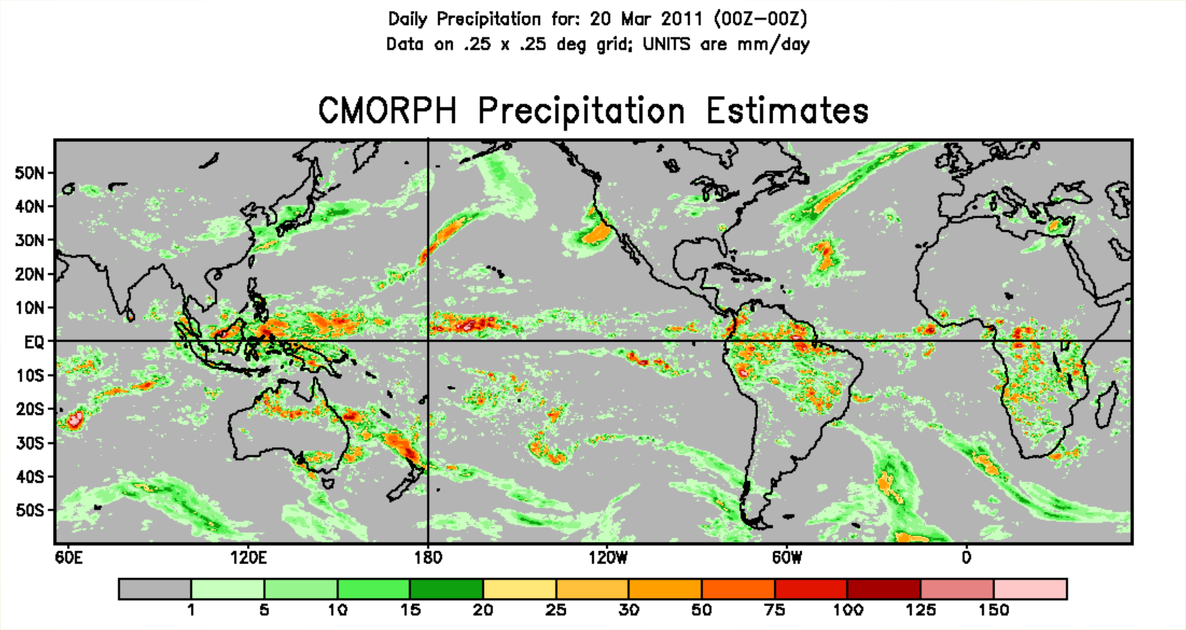


NOAA/NESDIS H-E
24 Hour Rain Accum
05-Apr-2013

Microwave Estimate: CMORPH

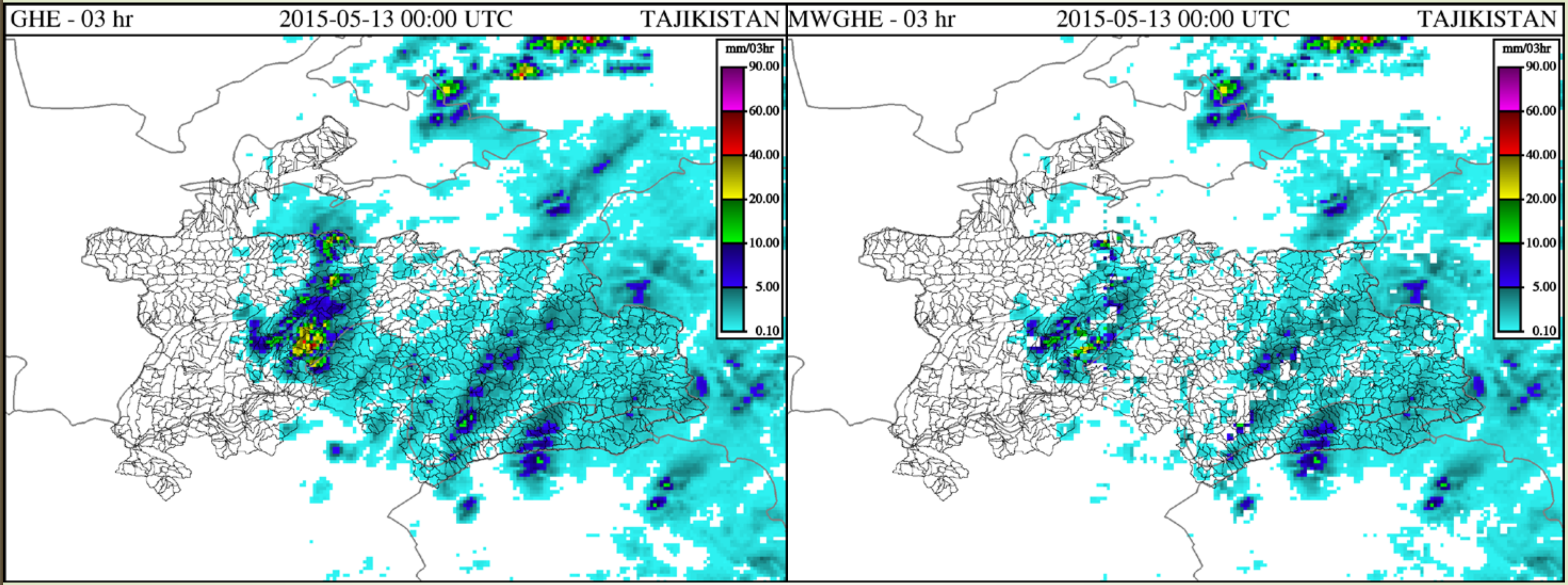
CMORPH

Based on measurements of microwave scattering from raindrops
MW–based
Produced by NOAA/CPC
18-26 hour latency in operations
~ 8km resolution

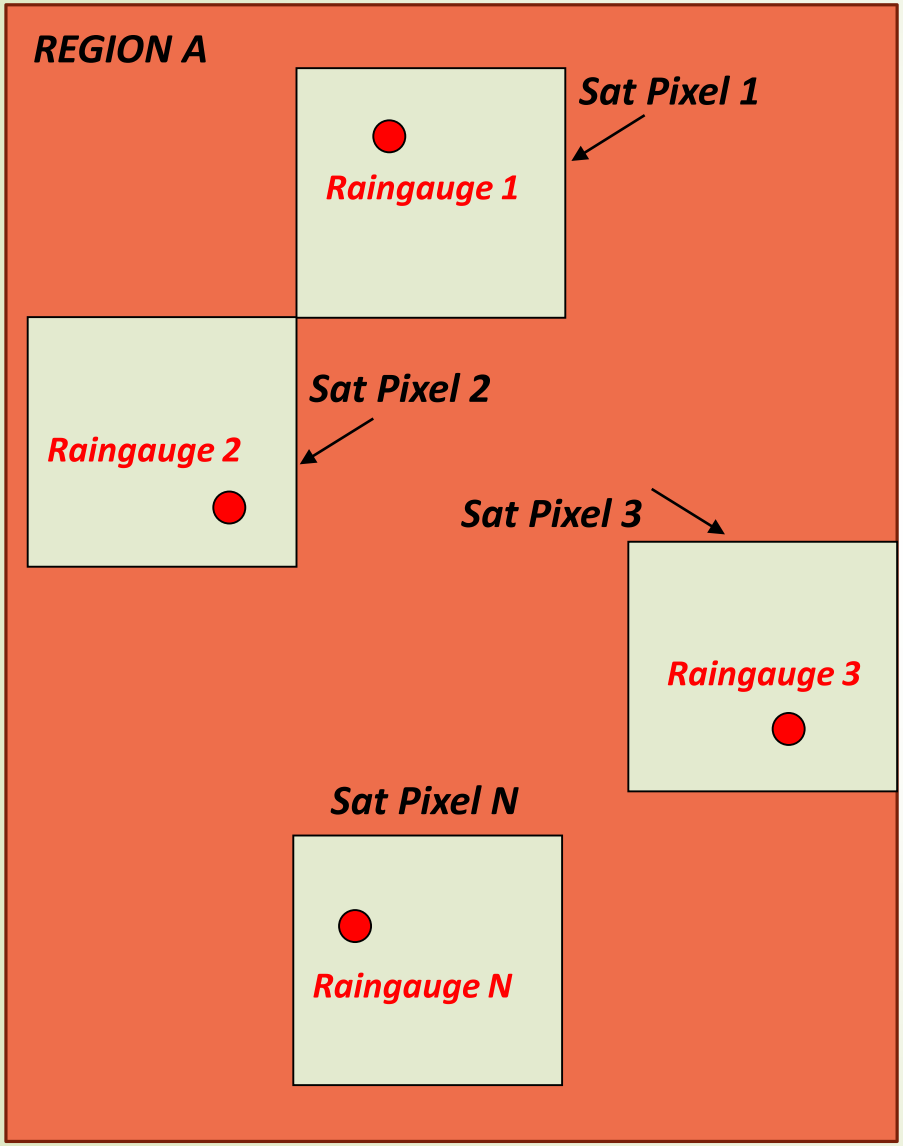


FFGS Product combines IR-based GHE with MW-based CMORPH: MWGHE

Example from CARFFG



Satellite Precipitation Bias Adjustment



Log Bias:

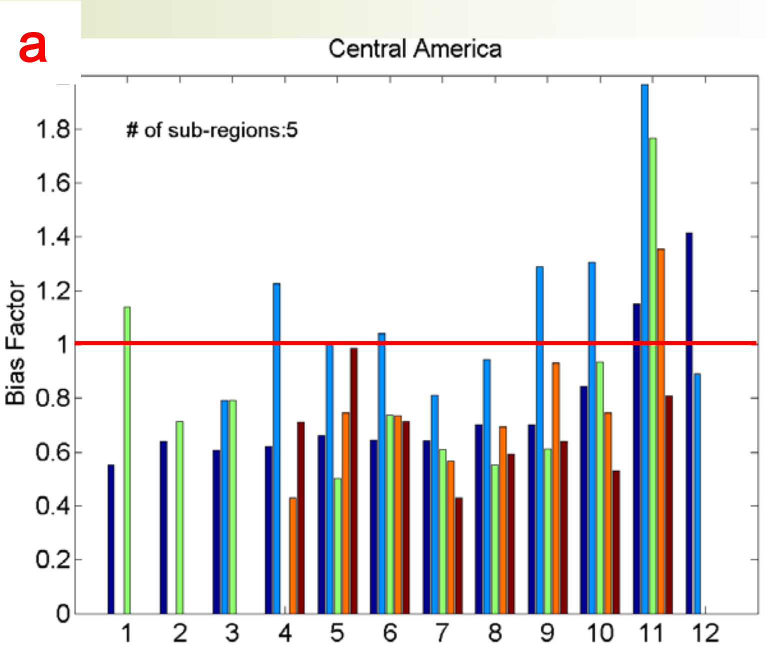
$$\beta_t = \ln\left\{\frac{\sum_{j=1}^{N_G} R_G(j,t)/NG}{\sum_{j=1}^{N_G} R_{SAT}(j,t)/NG}\right\}$$

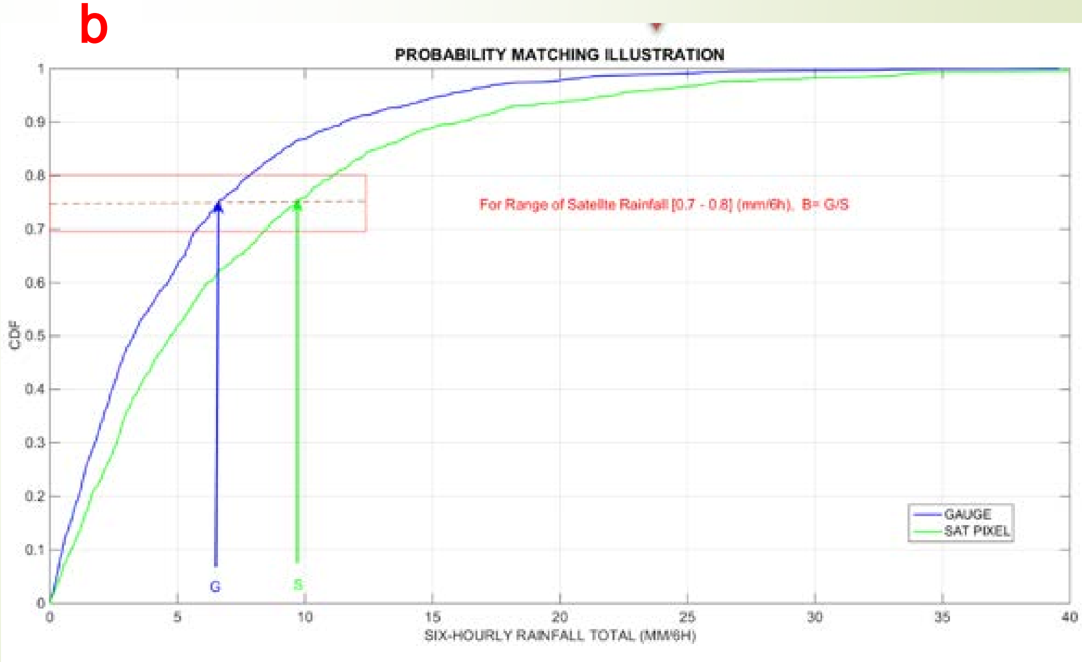
This is foundation of both the real-time and climatological bias adjustment.

Climatological Bias Adjustment

Goal is to determine long-term bias in satellite precipitation within a given region using historical records

- Uses historical data for regions of uniform hydro-climatology, terrain, and gauge density
- Usually done for given month or season (depending on historical record)
- Results in a “bias factor” that can be applied to satellite estimates for each region & month
- May be computed based on (a) mean values or (b) probability matching





Dynamic Bias Adjustment Basics

Employs Kalman Filter with Stochastic Approximations

$$\beta_t = \ln\left\{\frac{\sum_{j=1}^{N_G} R_G(j,t)}{\sum_{j=1}^{N_G} R_{SAT}(j,t)}\right\}$$

$$\beta_{t+1} = \beta_t + w_{t+1}$$

- Uses available real-time gauge precipitation to compute current bias with conditions for:
  - Minimum # pairs of consecutive values
  - Minimum # pairs with rain
  - Conditional Mean > Threshold (mm/h) for both satellite and gauge)

Prediction/Update cycle assimilates observations and tracks variance of Errors

Prediction:

$$\hat{\beta}_{t+1}^{-} = \hat{\beta}_t^{+}$$

$$P_{t+1}^{-} = P_t^{+} + Q_{t+1}$$

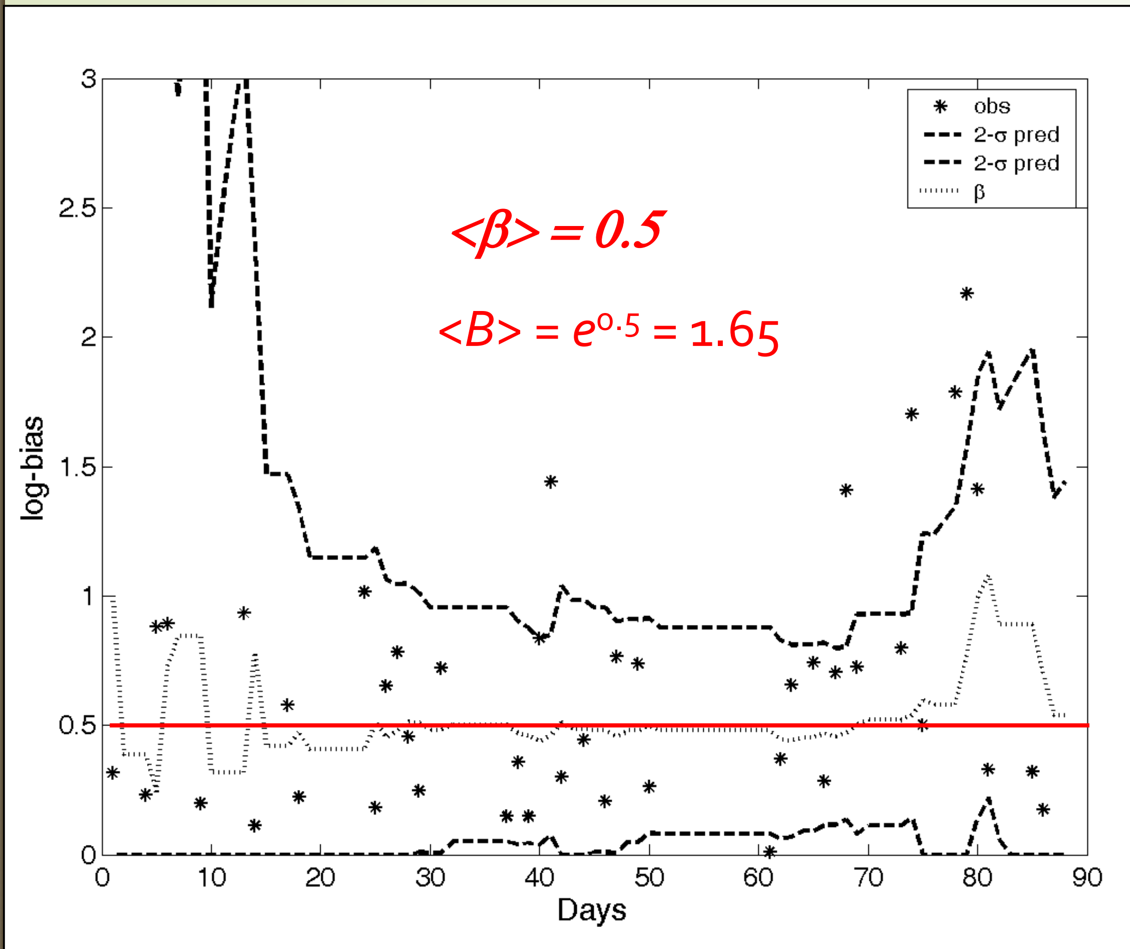
Stochastic Approximations Algorithm

Updating:

$$\hat{\beta}_{t+1}^{+} = \hat{\beta}_{t+1}^{-} + K_{t+1}(z_{t+1} - \hat{\beta}_{t+1}^{-})$$

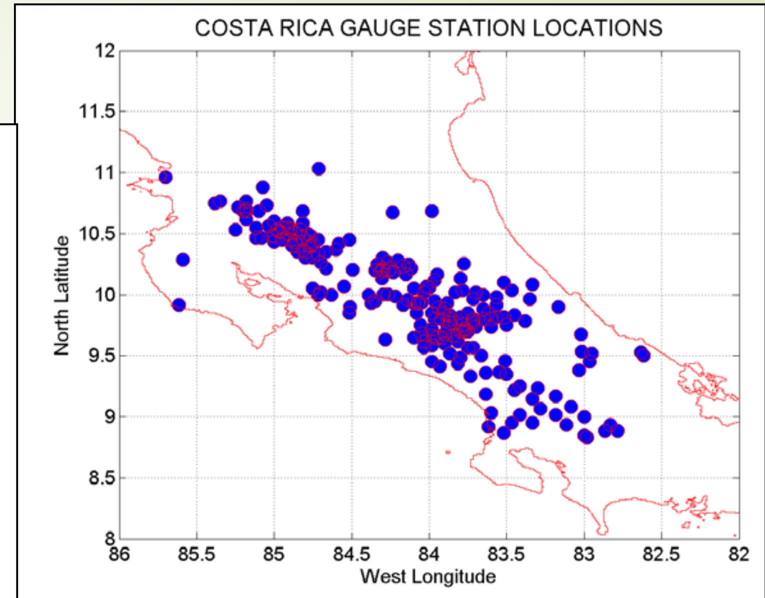
Kalman Gain

An Example From Costa Rica, Central America



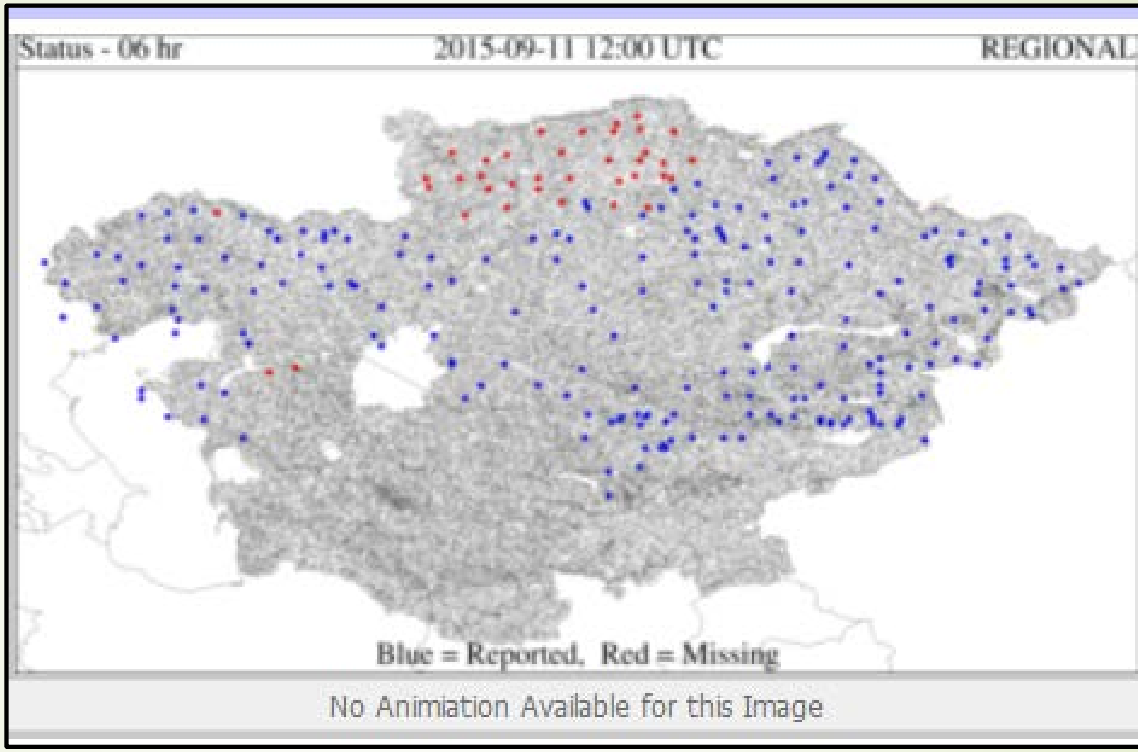
$<\beta> = 0.5$

$<B> = e^{0.5} = 1.65$



Real-Time Gauge Data

FROM CARFFG System “DASHBOARD”



FROM CARFFG System “PRODUCT CONSOLE”

Composite Product: text, CSV, CSVT | SFTP data transfer (requires SFTP Client): EXPORTS/REGIONAL/2015/09/12

Surfmet Gauge Observations at 2015-09-12 12:00 UTC

Station Identifier	Station Name	Accumulated Precipitation (mm/06hr)	Average Temperature (C)	Region	Latitude	Longitude	Elevation	Enable Precipitation Flag	Enable Temperature Flag
28676	PETROPAVLOVSK	0.00	9.45	KAZAKHSTAN	54.8	69.1	100	Enabled	Enabled
28678	MAMLUTKA	0.00	11.50	KAZAKHSTAN	54.5	68.3	136	Enabled	Enabled
28764	PRESNOGORKOVKA	0.00	9.35	KAZAKHSTAN	54.2	65.4	160	Enabled	Enabled
28766	BLAGOVESHCHENKA	0.00	8.95	KAZAKHSTAN	54.2	67	150	Enabled	Enabled
28775	YAVLENKA	0.00	9.20	KAZAKHSTAN	54.2	68.2	113	Enabled	Enabled
28776	SMIRNOVO	0.00	9.10	KAZAKHSTAN	54.3	69.2	138	Enabled	Enabled
28785	VOZVYSHENKA	Reported Missing	9.80	KAZAKHSTAN	54.2	70.5	125	Enabled	Enabled
28843	KARABALYK	0.00	11.30	KAZAKHSTAN	53.4	62	177	Enabled	Enabled