# CARFFG System Development and Theoretical Background

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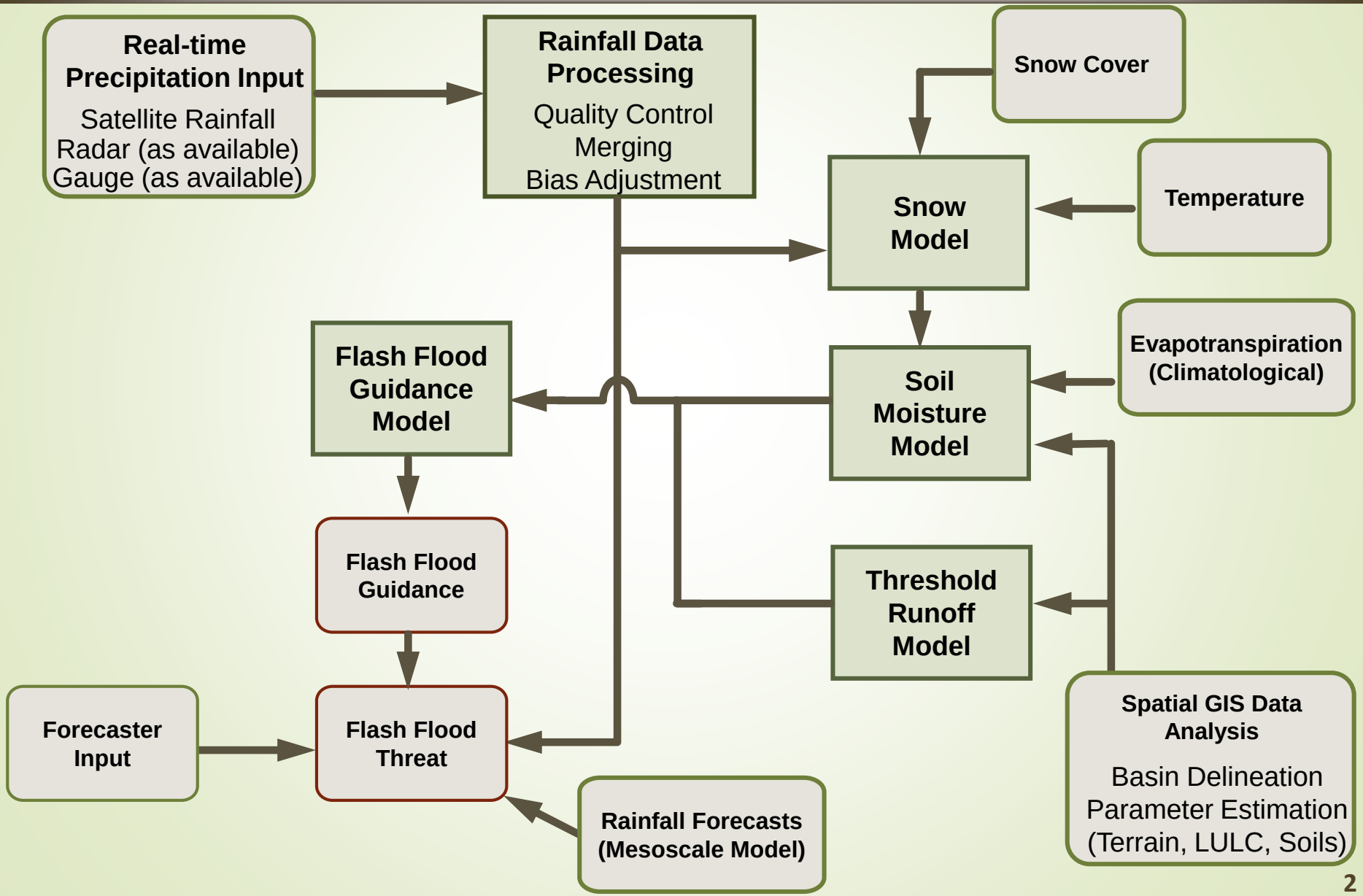
Hydrologic Research Center

CARFFG Steering Committee Meeting

15 SEPTEMBER 2015
Astana, KAZAKHSTAN

# Key Technical Components of the CARFFG System



# CARFFG System Development and Theoretical Background:

## 1. Spatial Analysis & Threshold Runoff

Hydrologic Research Center

CARFFG Steering Committee Meeting

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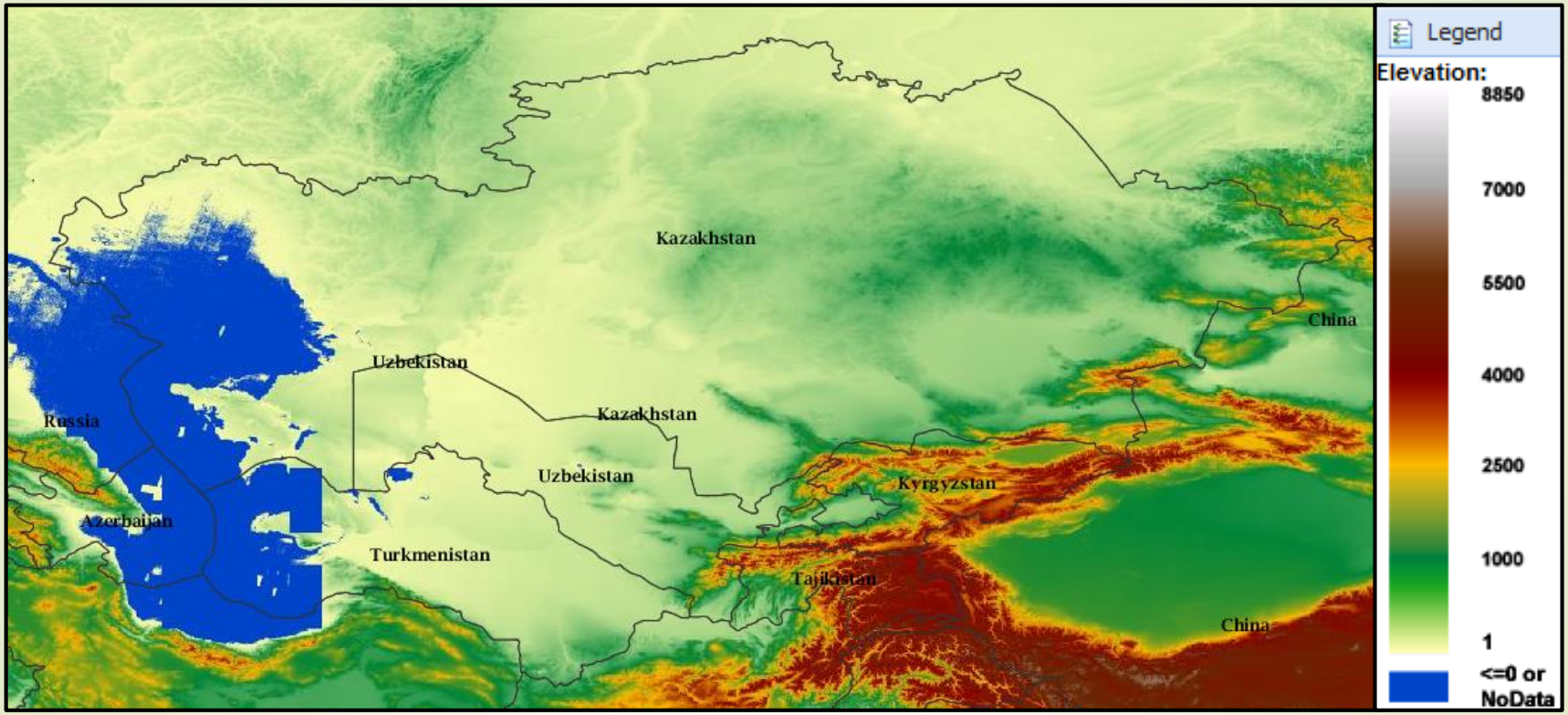
# Objective of This Presentation

- *Discuss process for delineation of flash flood-scale watersheds which are used for defining physical properties in CARFFG 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*

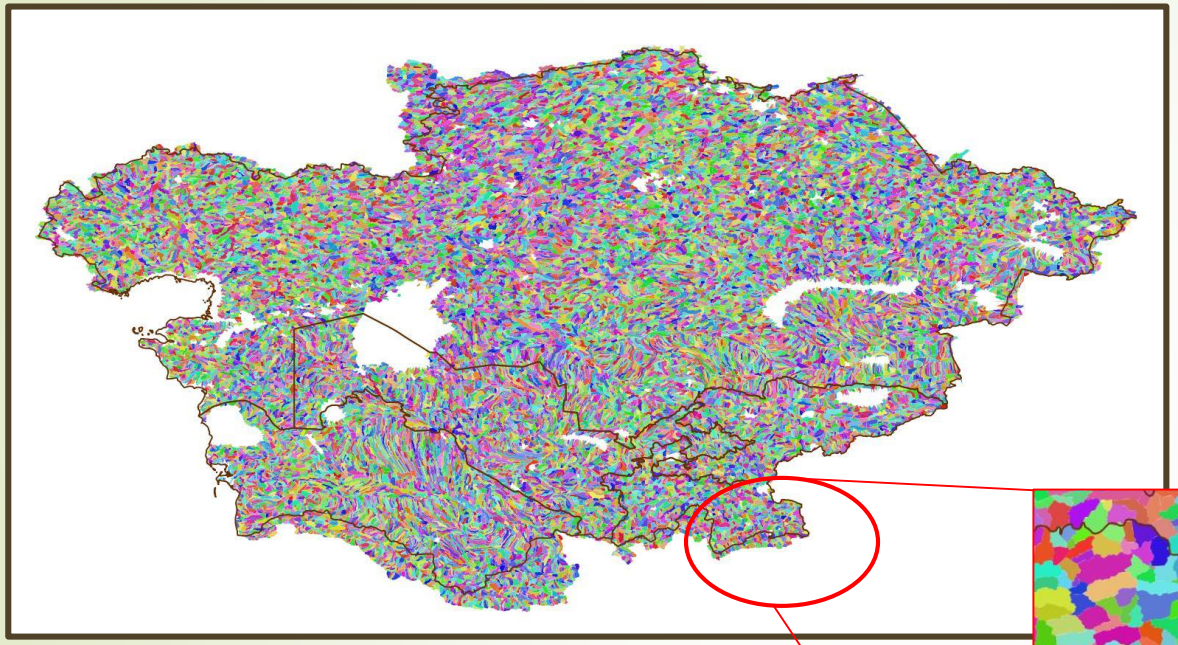
- *satellite-observed*
- *near global*
- *quality controlled*

*GRASS GIS Software*

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

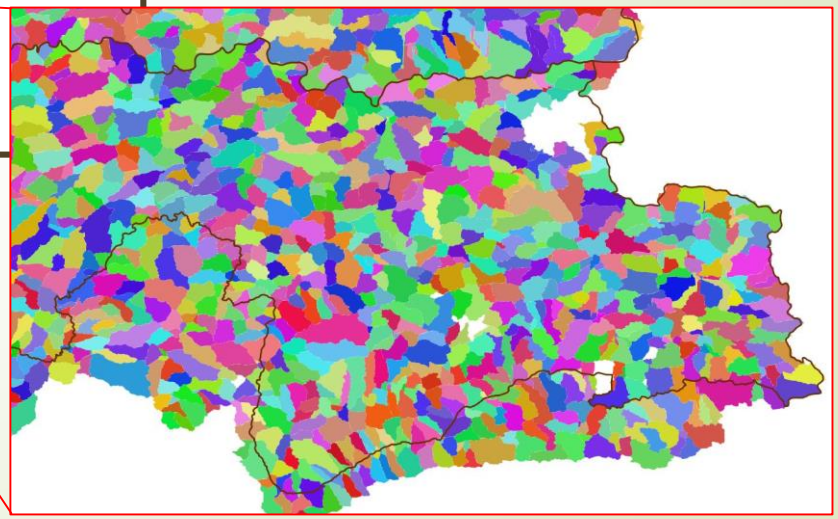
# Spatial Analysis to Delineate Small Flash Flood Watersheds

*INITIAL DELINEATION RESULTS*



*Define small watersheds based on minimum headwater size*

- *Our target: average local drainage area of 150 km$^2$.*
- *A total of 36185 basins defined*



- *Large lakes, rivers, and evaporative pans areas removed*

Output is digital stream network and watershed boundaries.

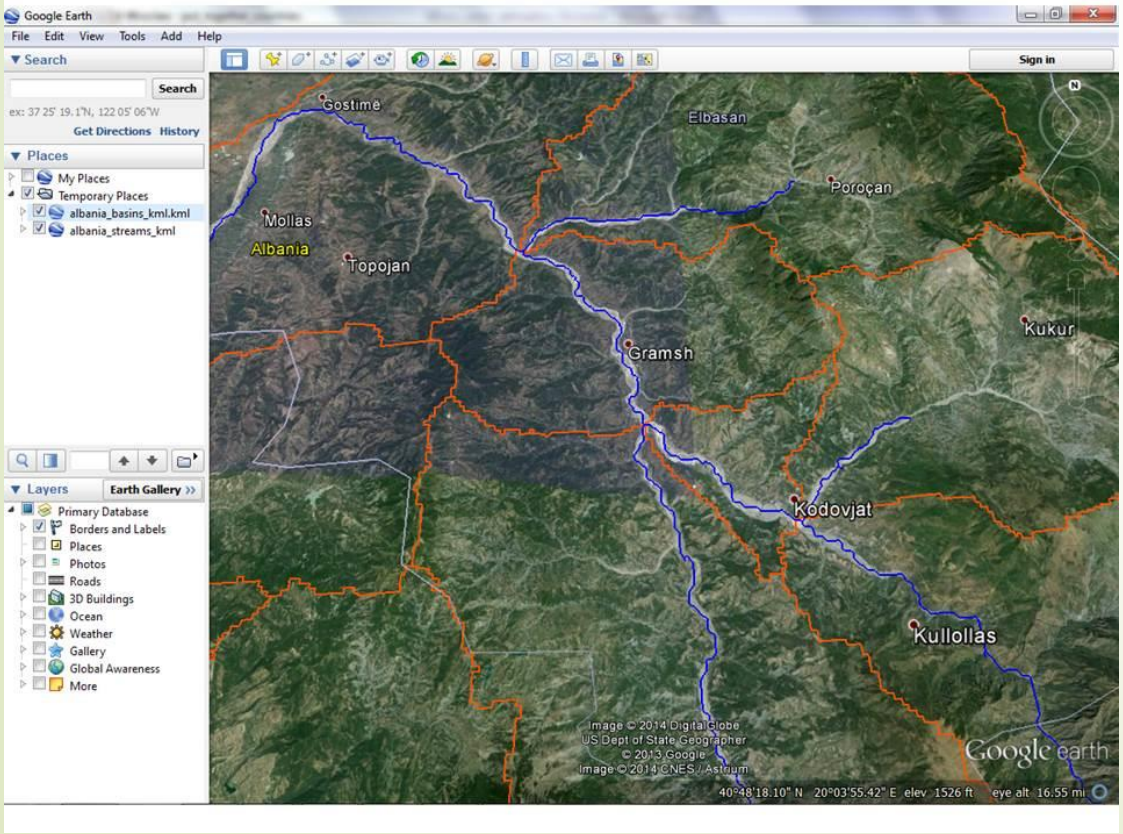
# Validation of Delineation Results

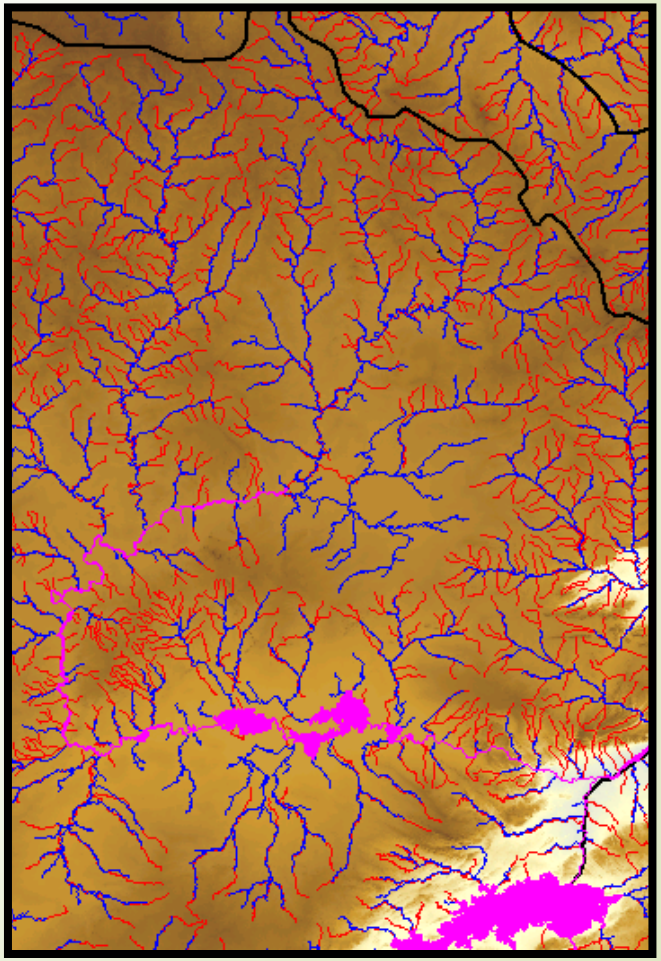
(a) HRC-internal review

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

comparison with GoogleEarth Satellite Imagery

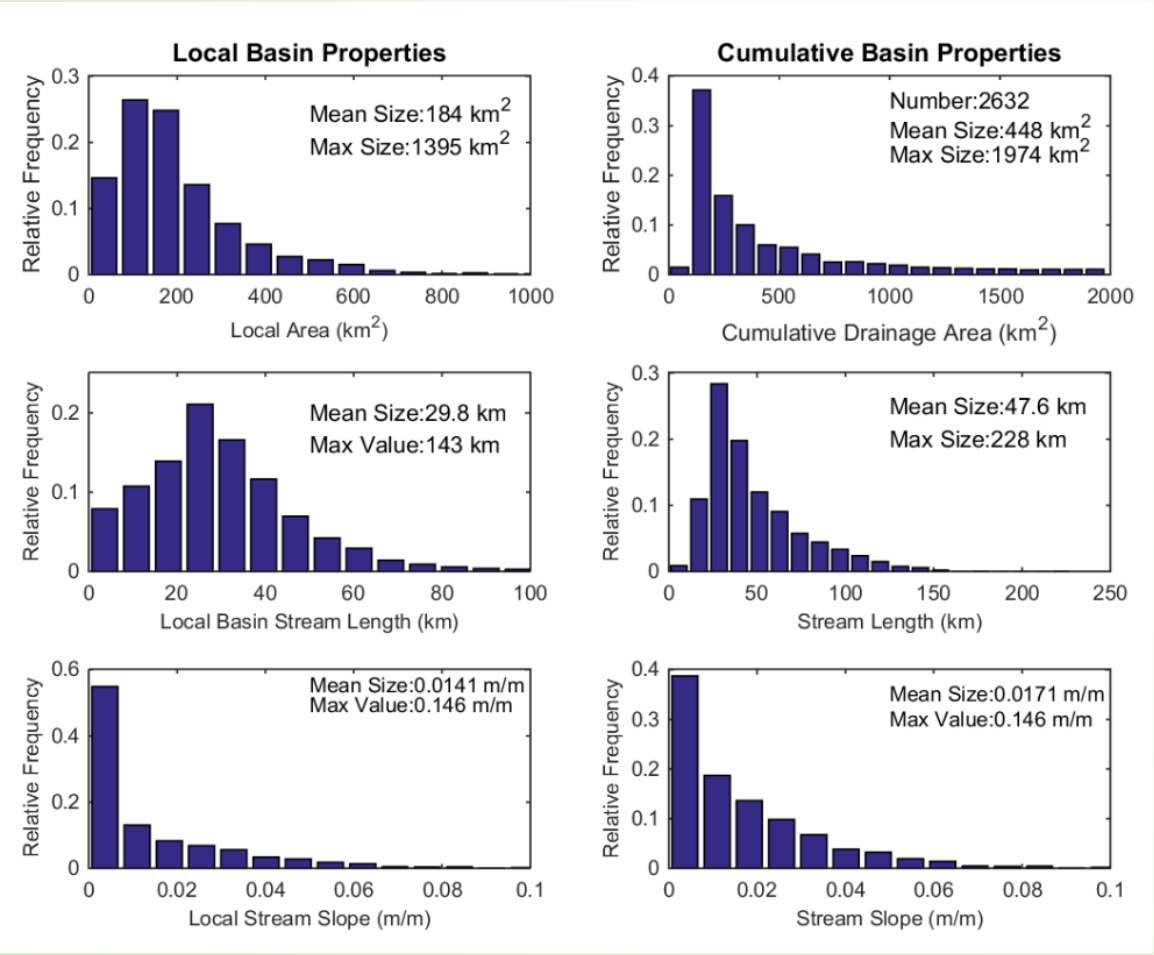
(b) Within-Country review and comments



# 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.*




*Example from SEEFFG System*

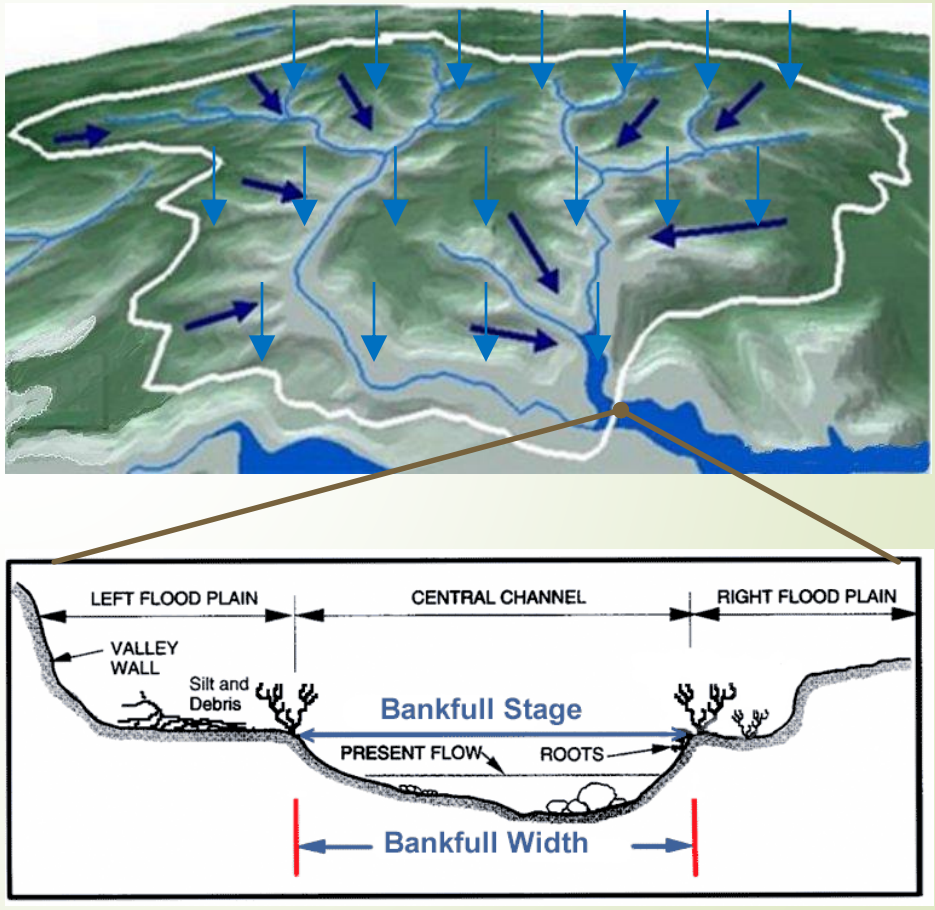
These watershed geometry properties are then used in the computation of *threshold runoff*, a characteristic parameter of FFG.

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

# 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 *rainfall* that goes to filling the channel capacity at the level of bankfull conditions.

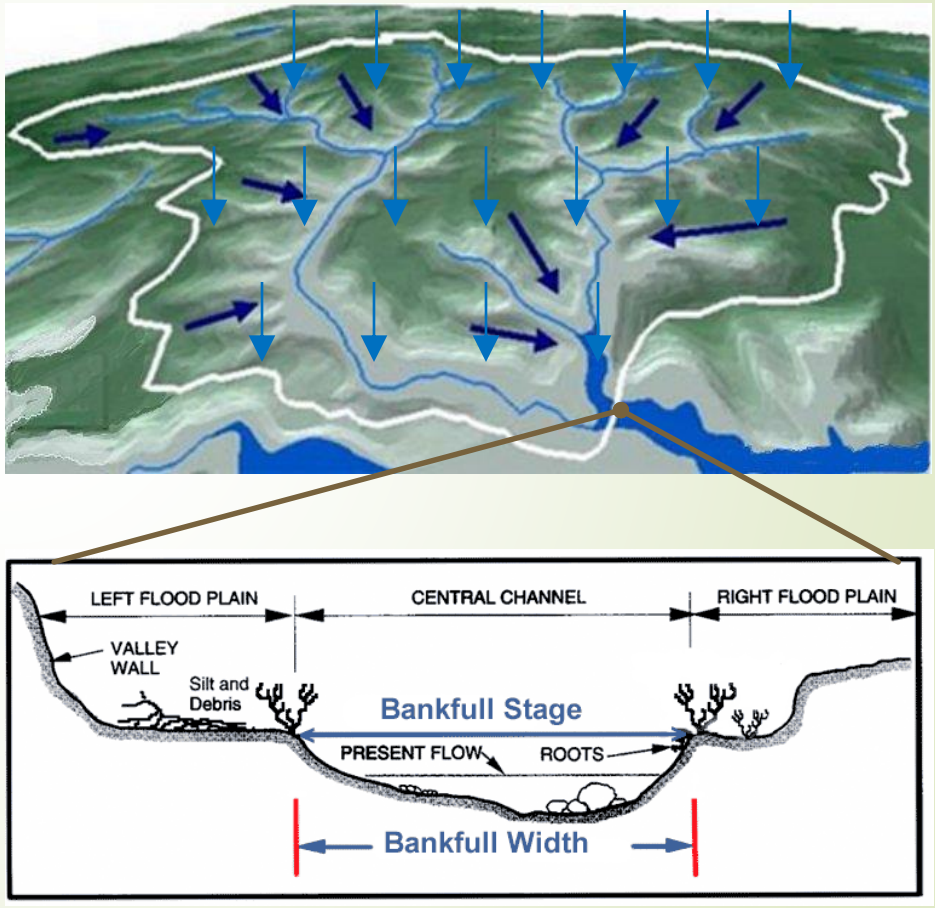


# Definition of Threshold Runoff

**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 characteristics 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 *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, $Q_p$)

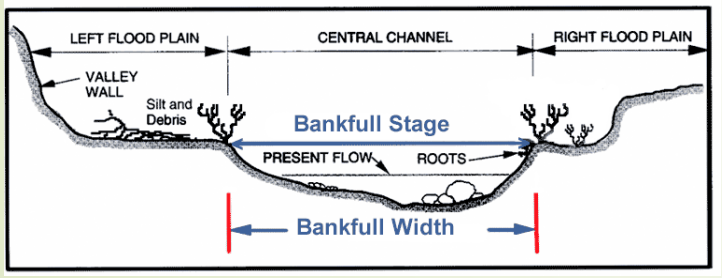
**Carpenter et al, *J. Hydrology*, 1999**

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

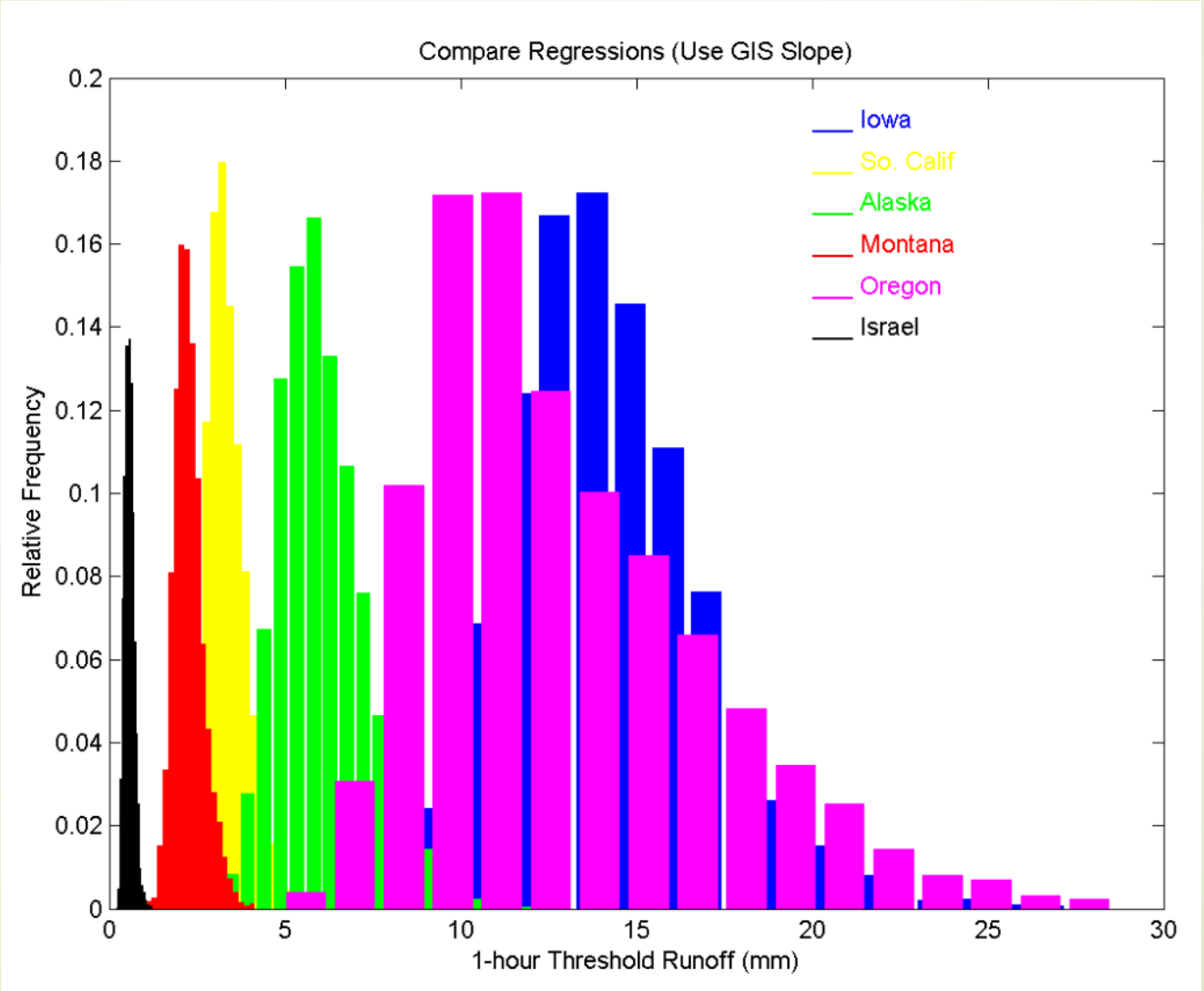
# Estimation of Threshold Runoff

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

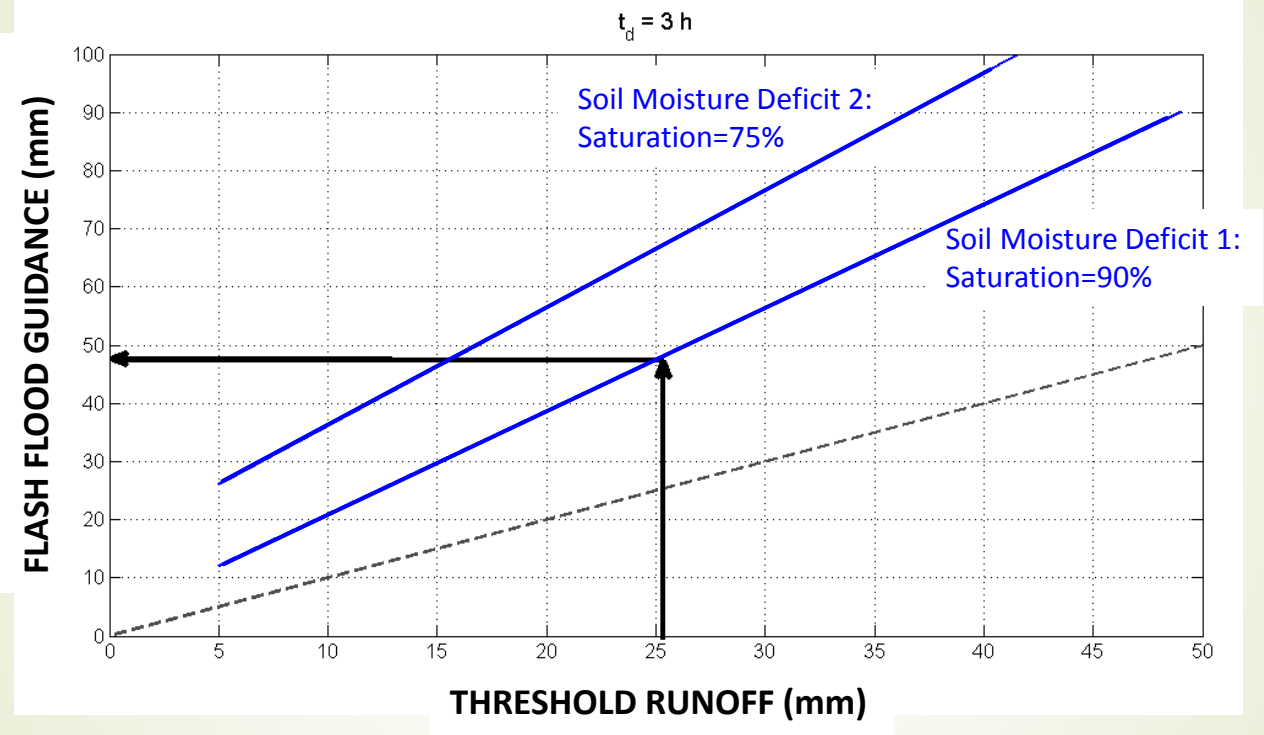
- *Non-linear* expression in R
- Watershed-scale geometry properties (A, L) from spatial GIS analysis
- Channel *cross-sectional* properties ($B_b$, $D_b$) estimated from regional relationships with watershed scale properties.
  - Typically, relationships derived from country-provided channel cross-sectional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




# 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 CARFFG 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.

# CARFFG System Development and Theoretical Background:

## 2. Soil Moisture, Snow, & FFG Modeling

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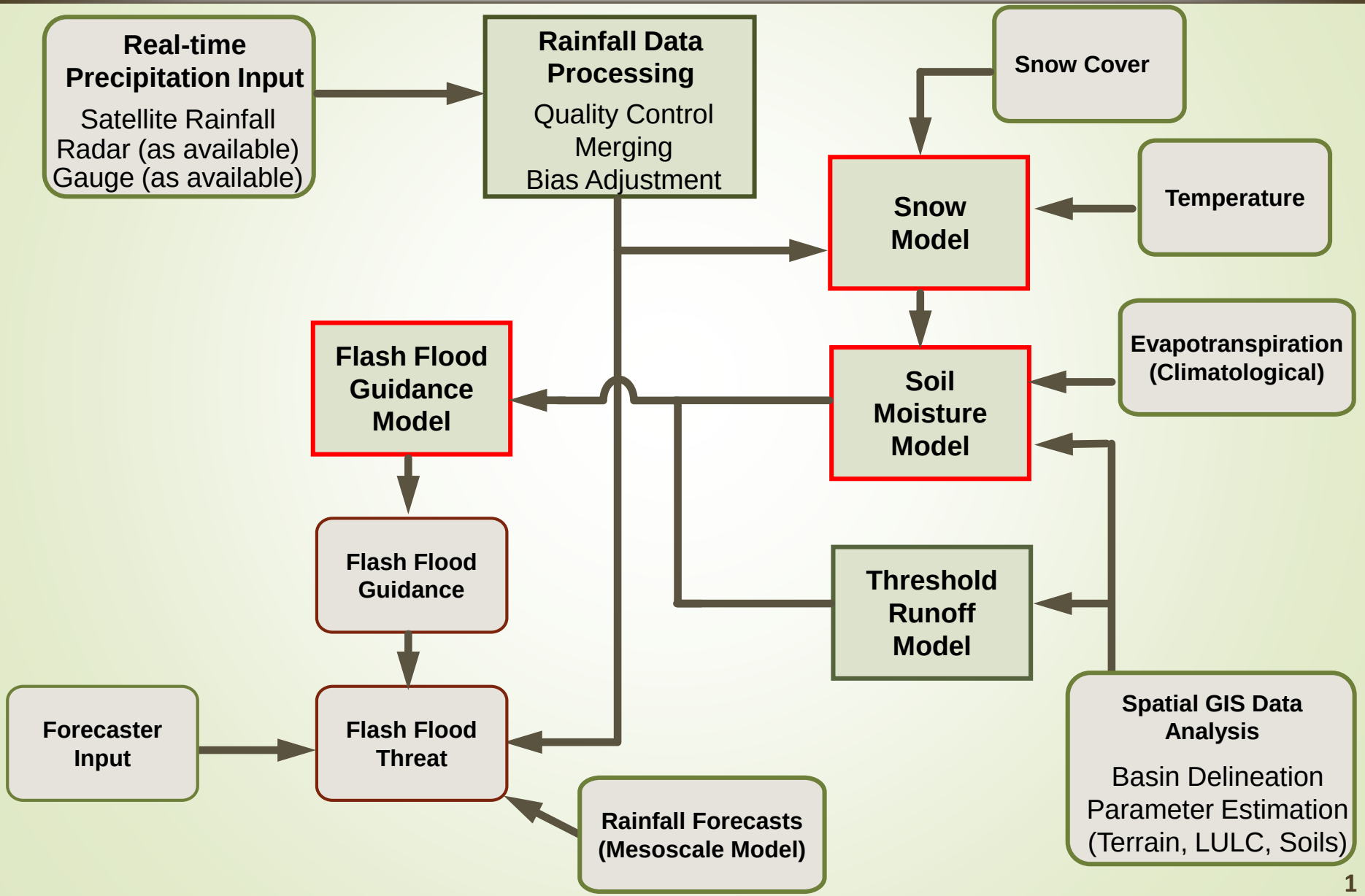
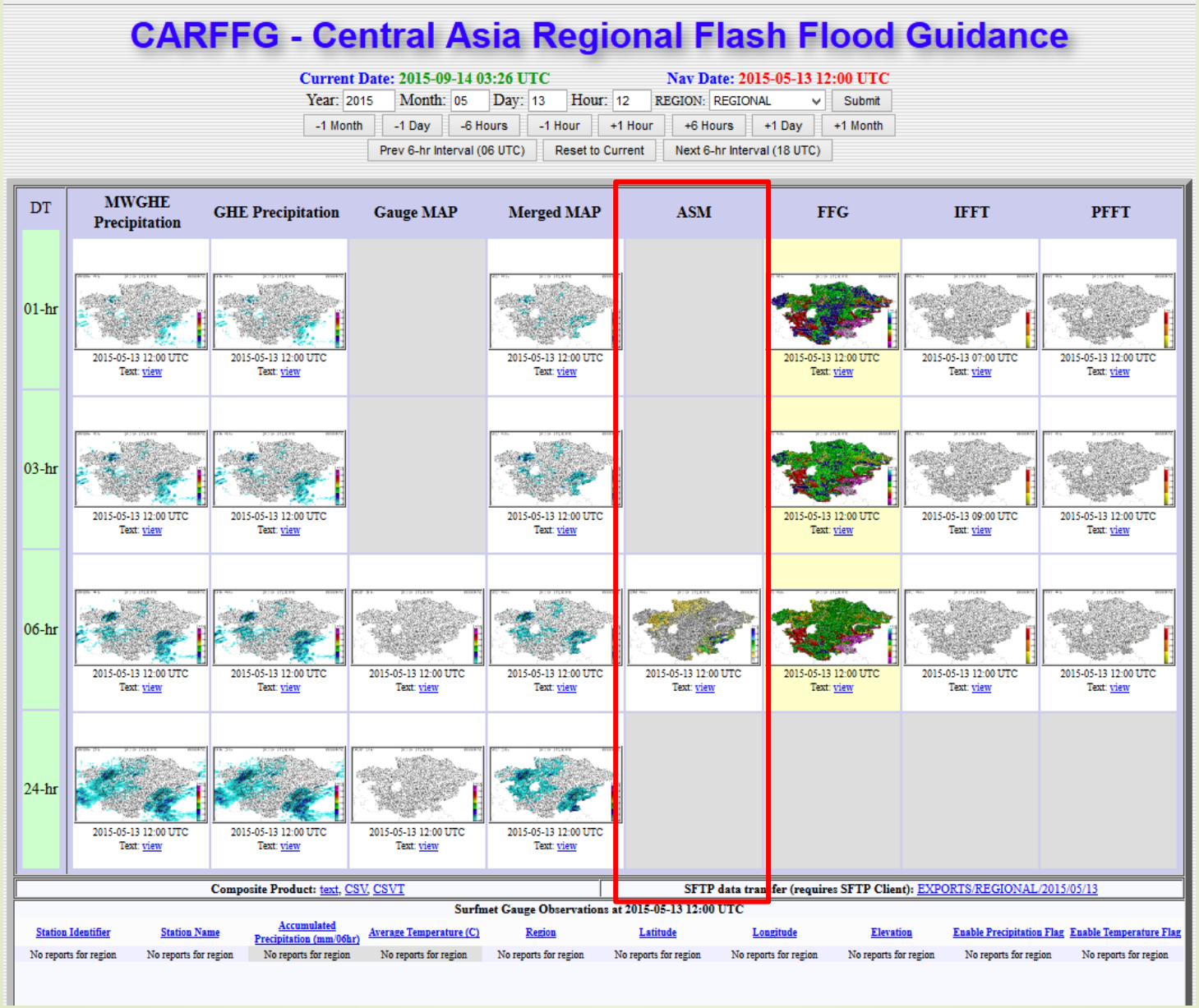
# Key Technical Components of the CARFFG System

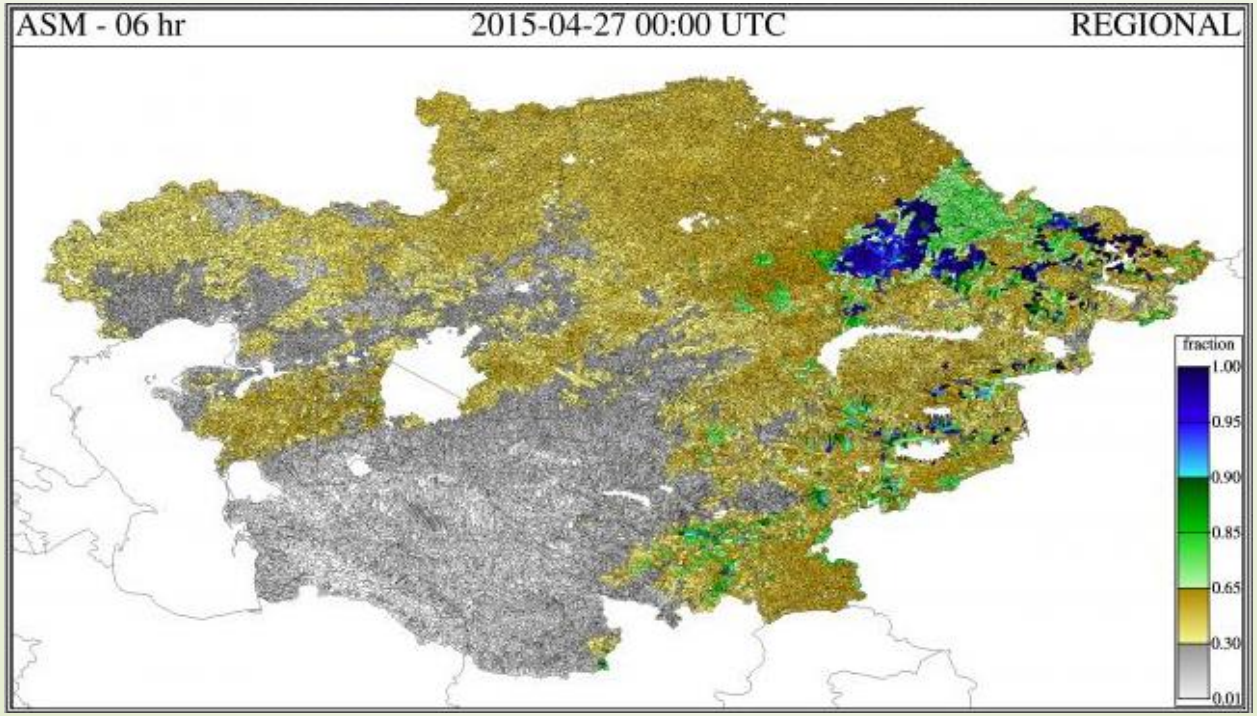


# ASM – Average Soil Moisture



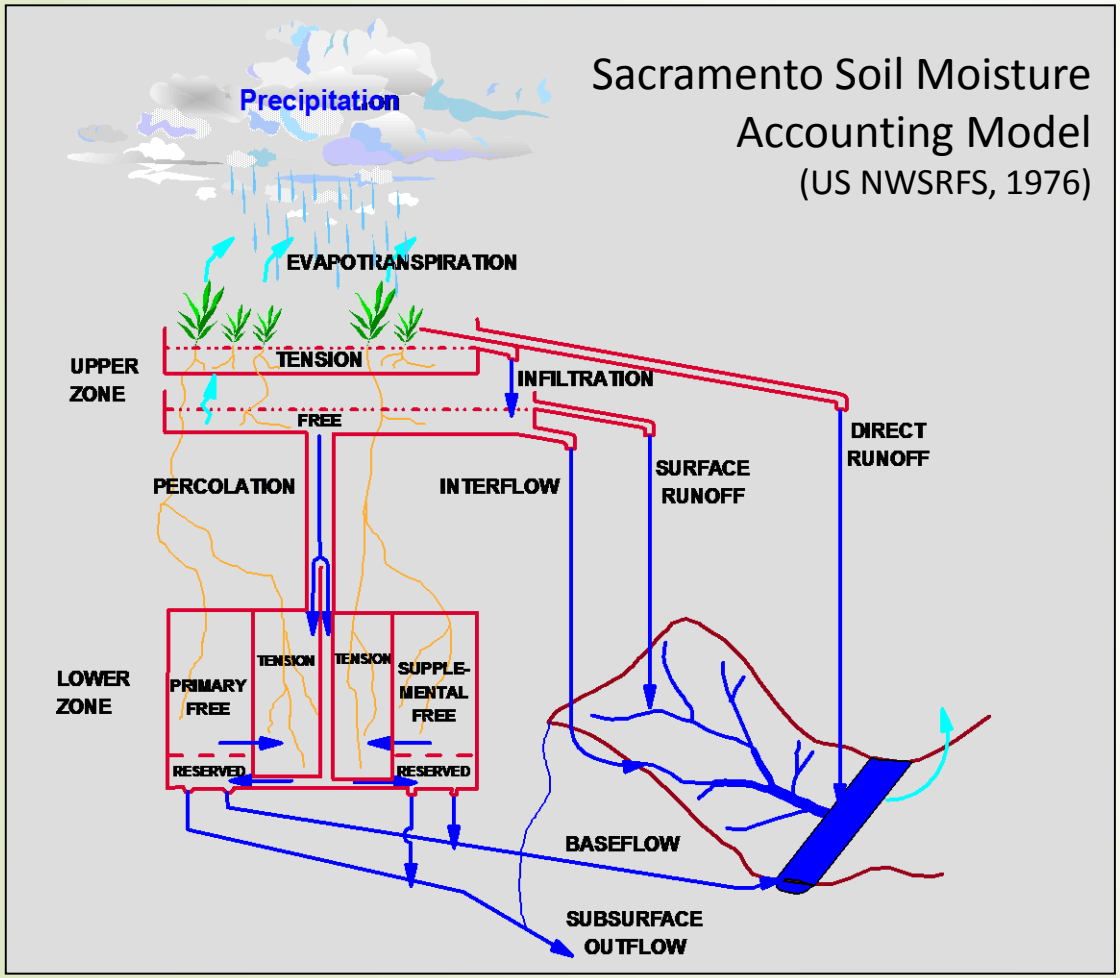
# ASM Product

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 depth is most indicative for flash flood production.



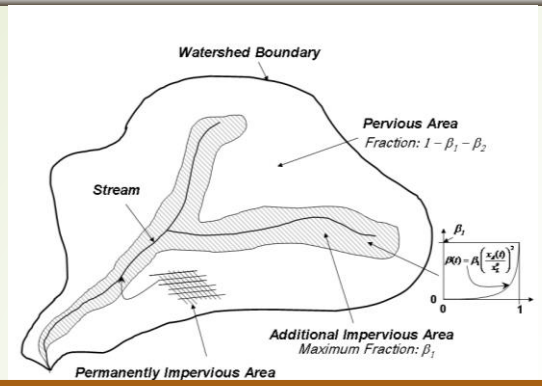
# Soil Water Content Modeling for FFG Systems

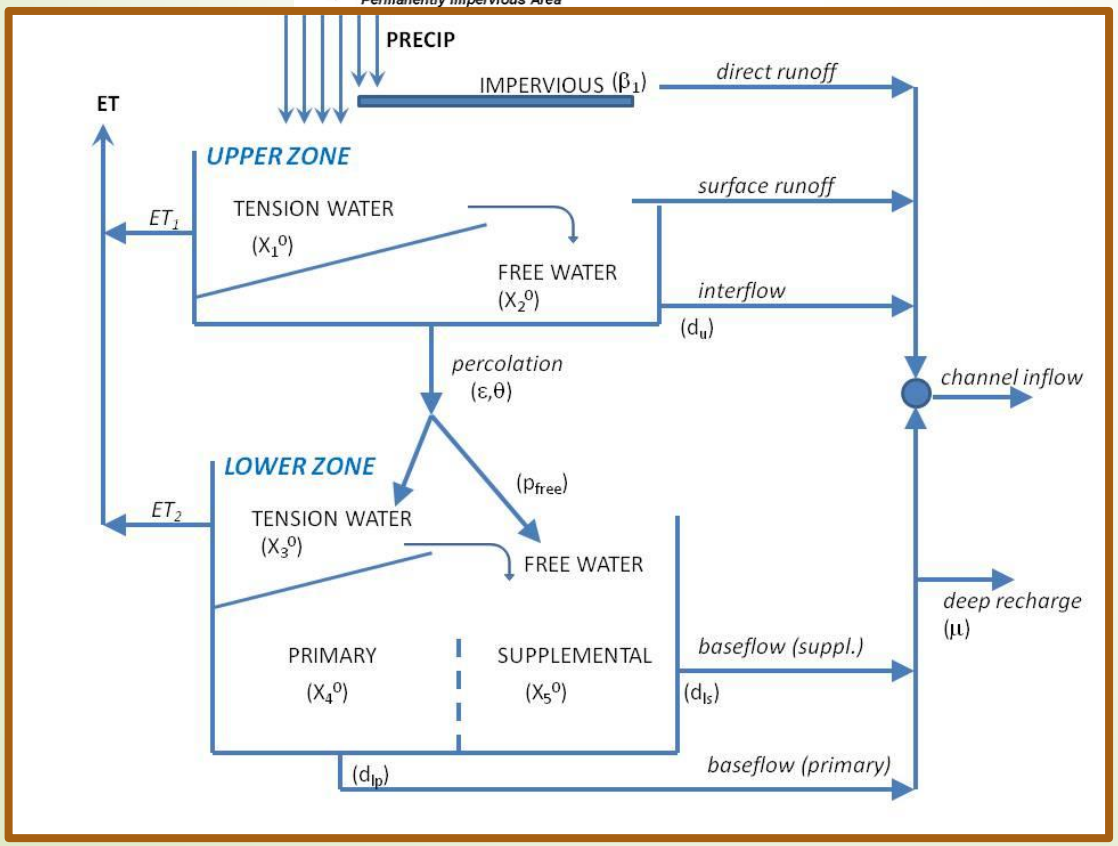
Soil Water Index Model represents : - Saturation excess runoff
- Infiltration excess runoff
- Combined runoff




- *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:

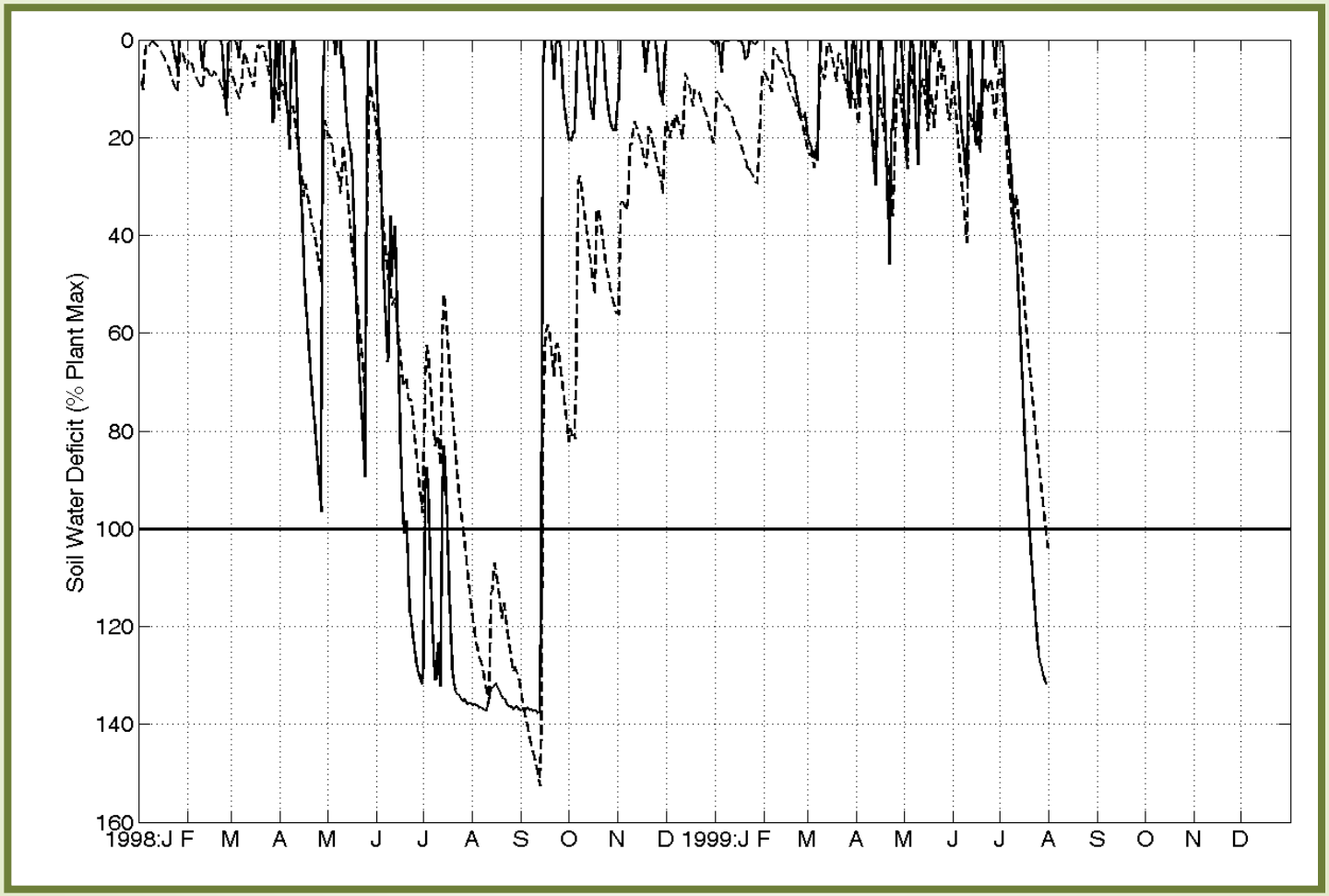
- Direct RO
- Surface RO
- Interflow
- Baseflow

PARAMETERIZATION:

- 15 model parameters

# On-Site Validation of Soil Water Modeling

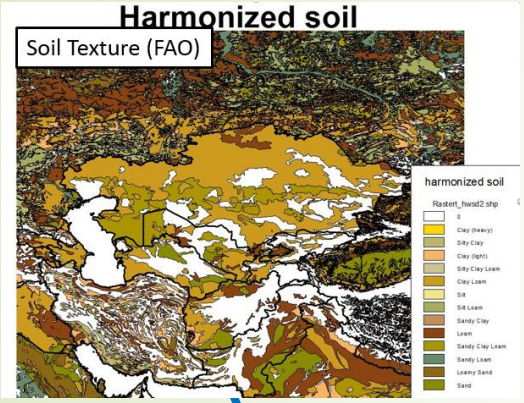
Simulation for Illinois River Basin in Oklahoma, U.S.A




*Reasonably good reproduction of depth integrated soil water deficit*

# A priori Parameter Estimation

Soil Texture (from surveys)



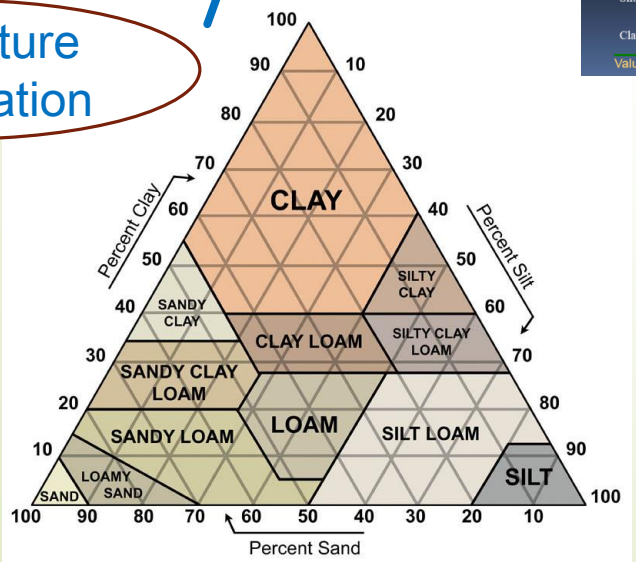

Soil Hydraulic Properties (θwlt, θfld, porosity,Ks)

Soil Texture and Hydraulic Properties

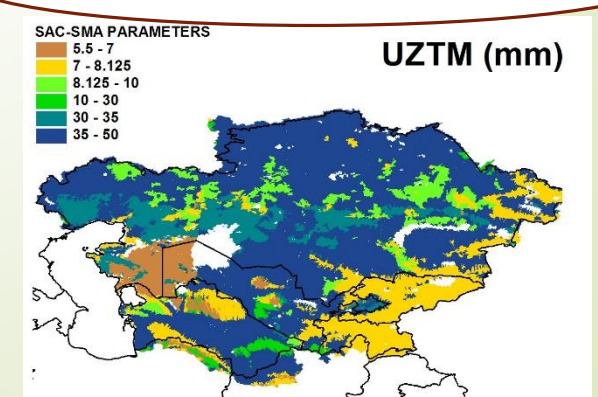
| Soil Class | $\theta_s(m^3/m^3)$ | $\theta_f(m^3/m^3)$ | $\theta_w(m^3/m^3)$ | $K_s(m/h)$ | $\alpha$ | $\sigma_{Ks}(m/h)$ |
|---|---|---|---|---|---|---|
| Sand | 0.34 | 0.09 | 0.015 | 0.168 | 2.79 | 0.062 |
| Loamy Sand | 0.42 | 0.16 | 0.05 | 0.050 | 4.26 | 0.082 |
| Sandy Loam | 0.43 | 0.21 | 0.07 | 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

Soil Texture Classification

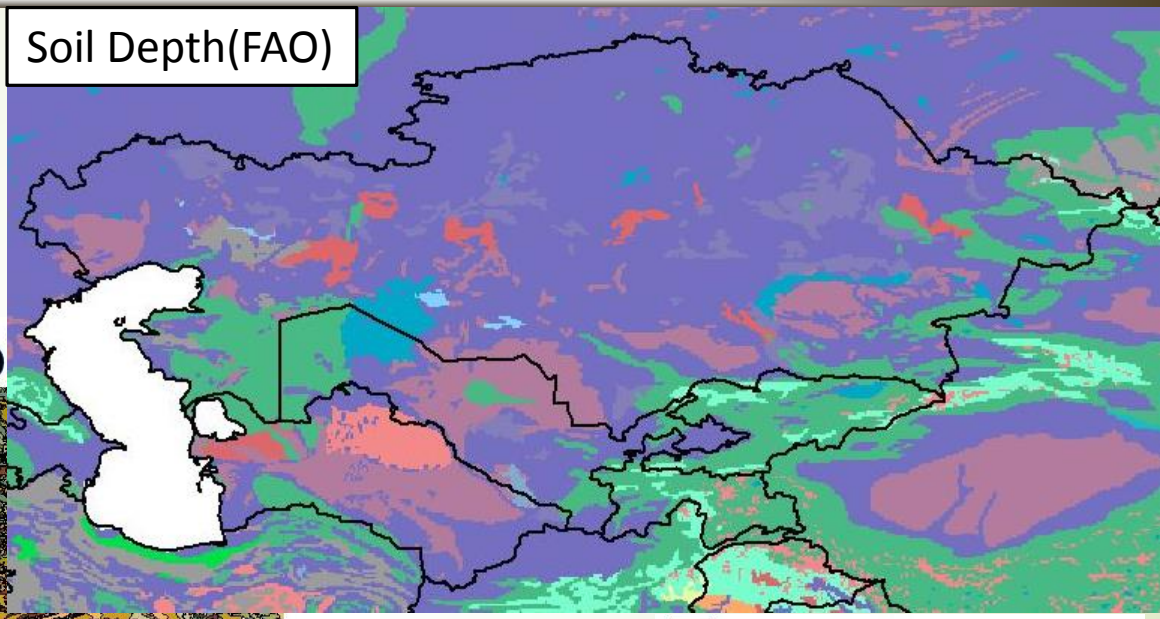



Model Parameters



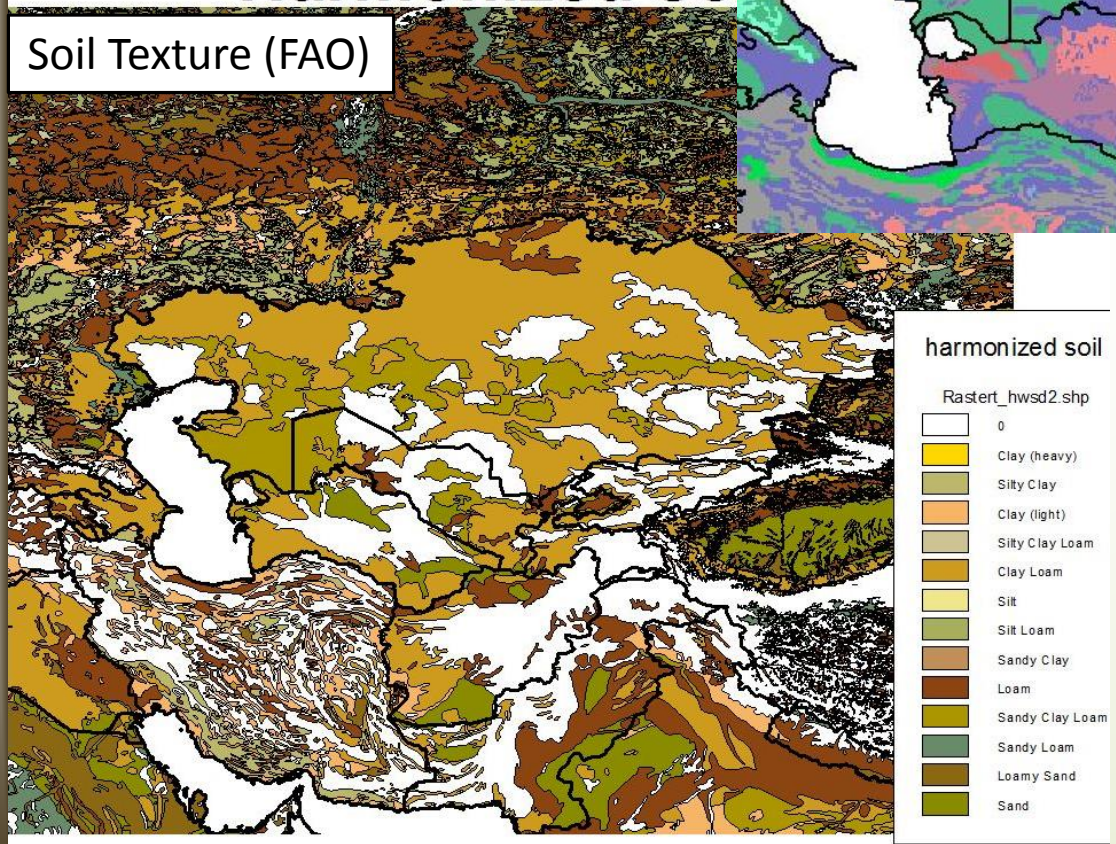
# CARFFG Soil Information: FAO Database

Soil Depth(FAO)



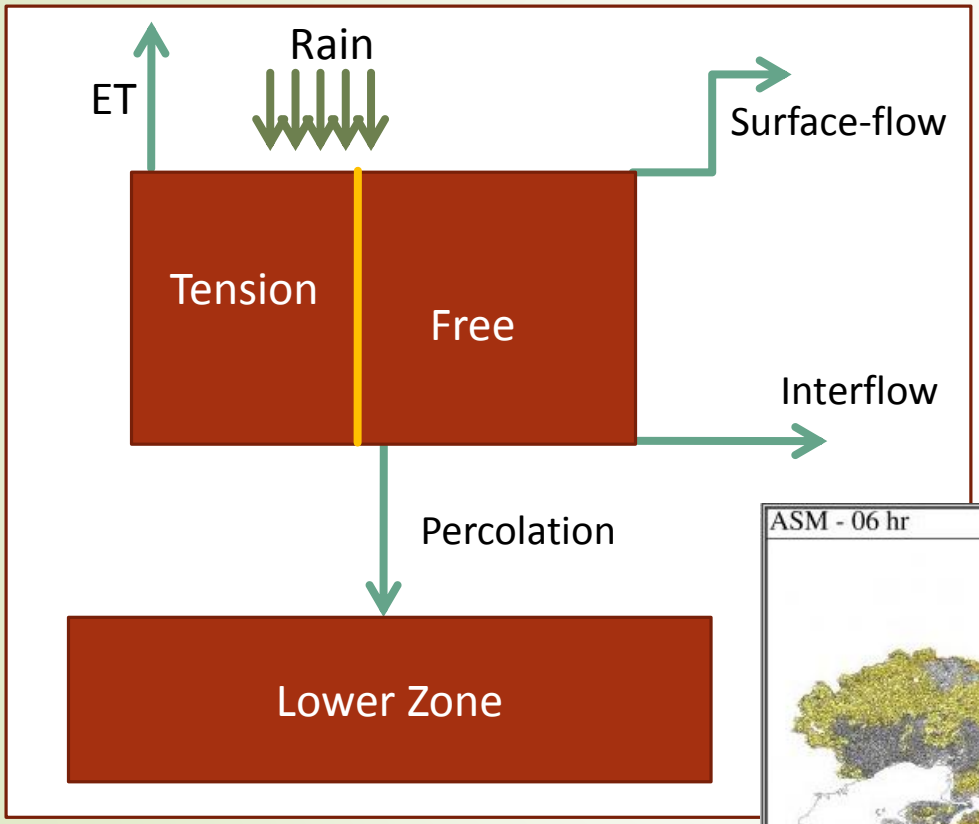
Harmonized so

Soil Texture (FAO)




# Flash Flood Sensitive Parameters

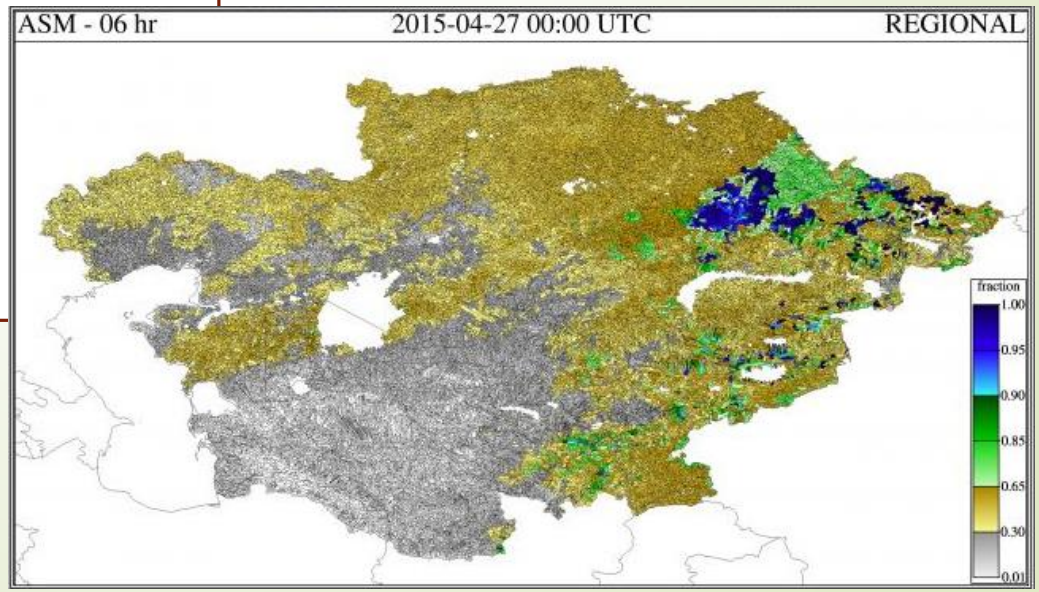
*Fast Response components are greatest concern for flash flooding.*



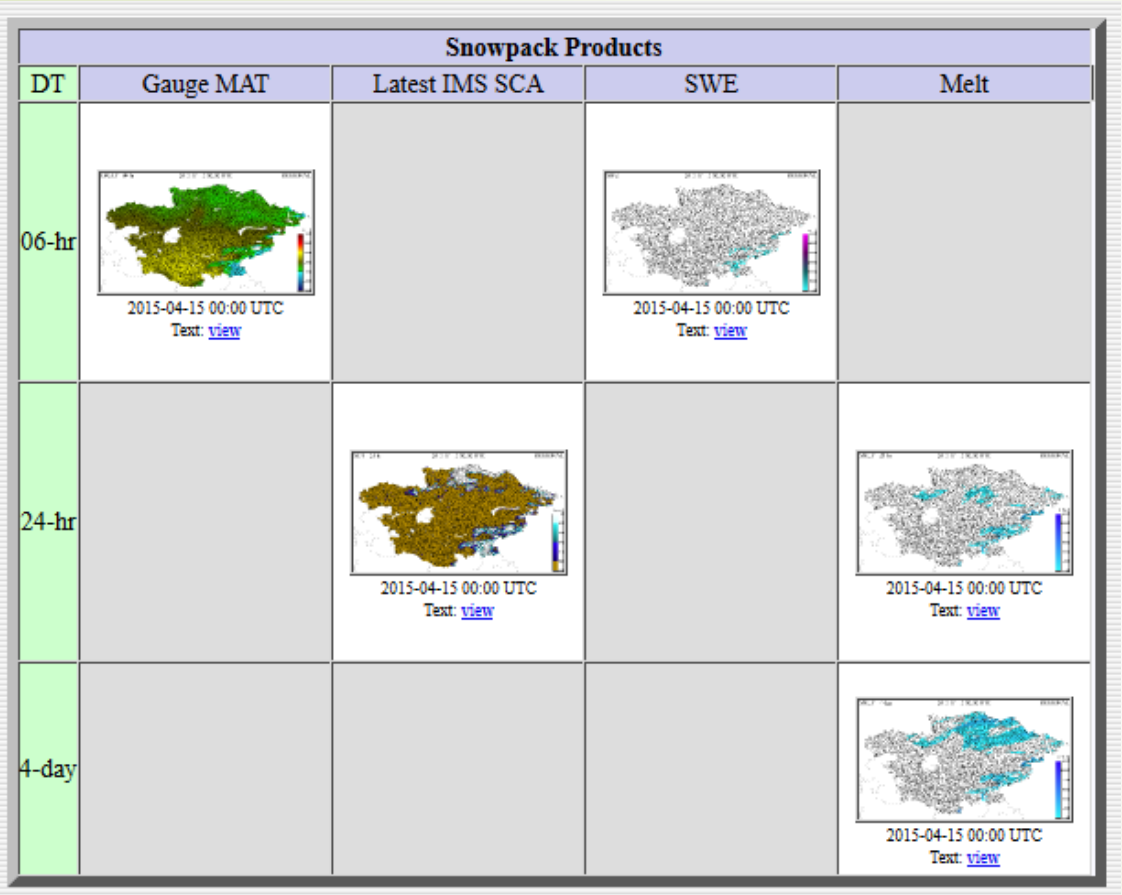

- Define soil moisture product based on Upper Zone:

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

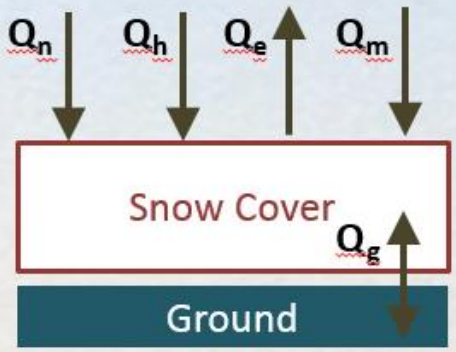



For regions with significant snow cover, a snow model is employed to account for snow storage and snow melt impact on soil moisture.

# 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)
$Q_e$ = latent heat transfer
$Q_h$ = sensible heat transfer
$Q_g$ = heat transfer at snow-soil interface
$Q_m$ = heat transfer by mass changes (e.g. advected by rain)
$\Delta Q$ = change in heat storage of snow cover

$= f(Q_{sw}, Q_{lw}, A, T_o)$
$= f(e_o, u_a)$
$= f(T_o, T_a, u_a)$
$= f(T_g, T_s)$
$= f(p)$

Energy Balance solution is data intensive!

# Snow Model – SNOW 17

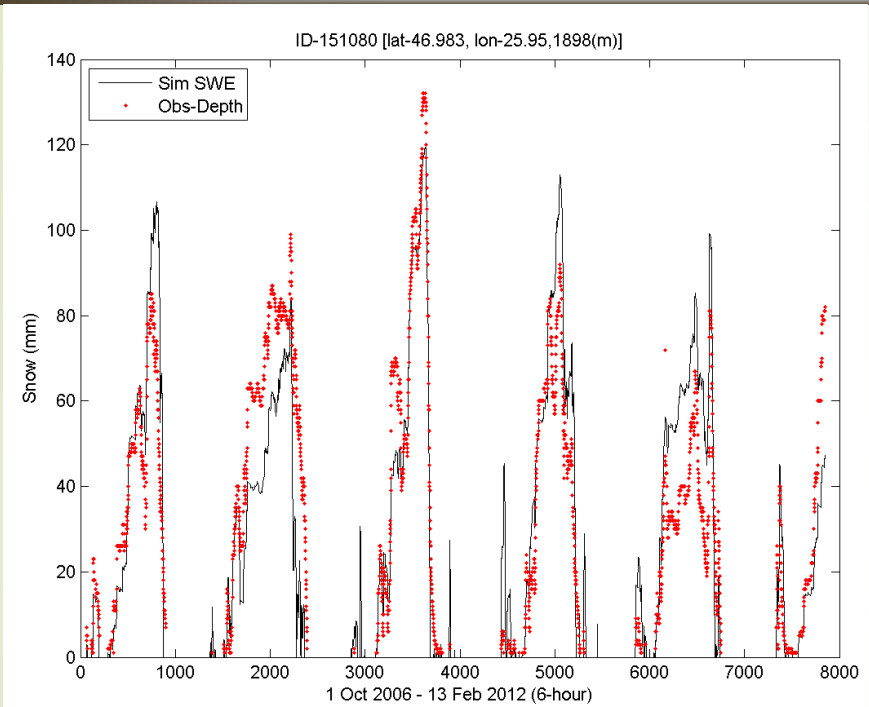
- Snow Accumulation and Ablation Model (SNOW-17) of the U.S. NWS (Anderson, 1973)
- Designed to use readily available operational data
- A conceptual areal lumped energy and mass balance model
- *Air Temperature* used as an index for pack energy and division of precipitation as rain or snow
- Considers: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

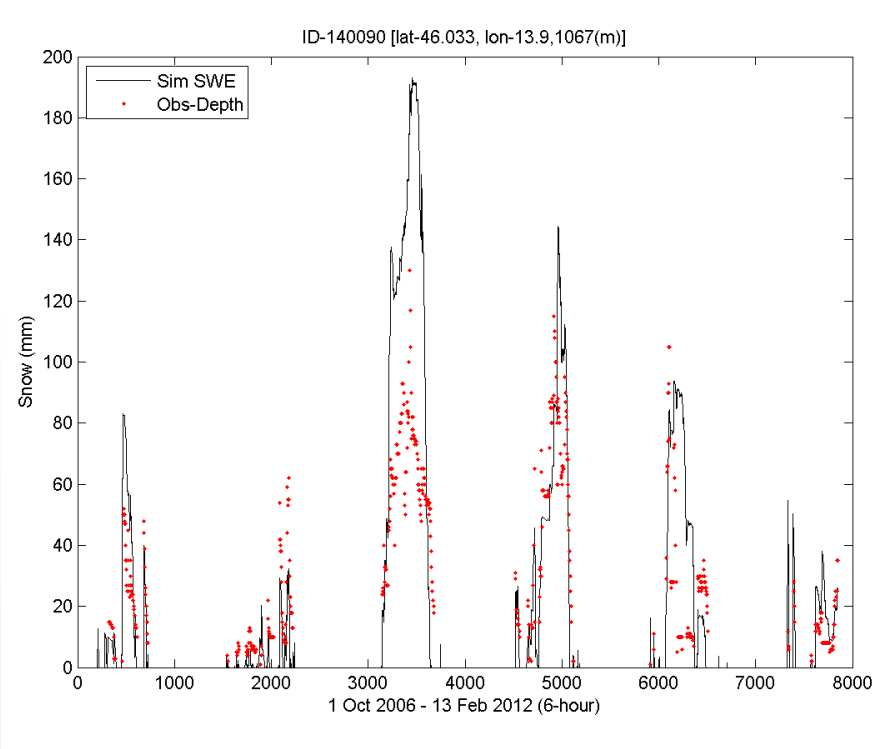
- Single vertical layer
- Three modules:

- 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



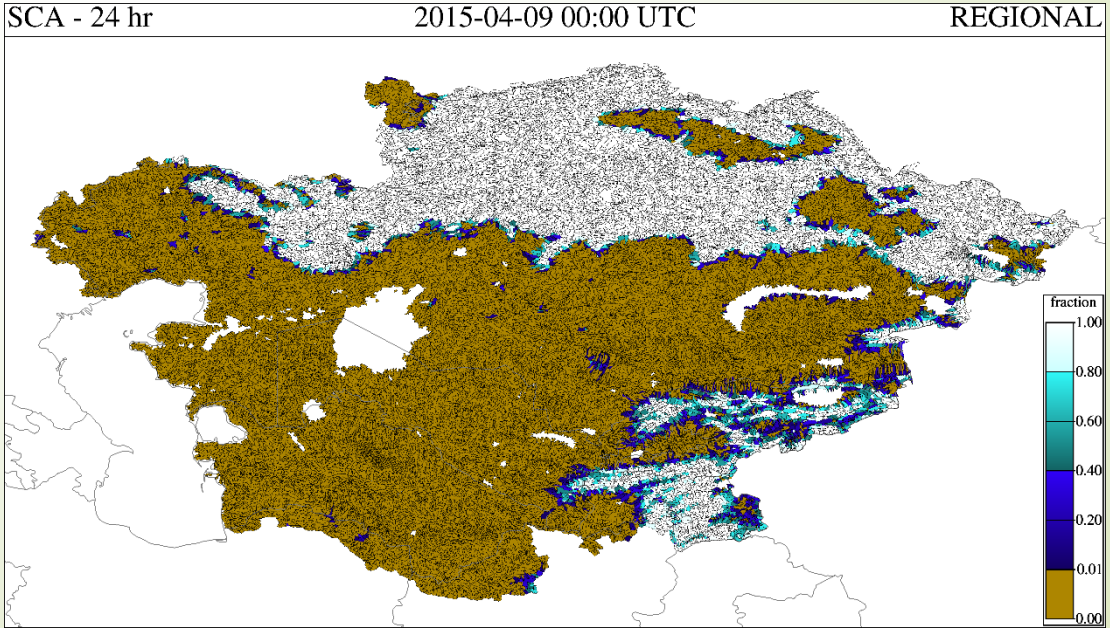



# Satellite Snow Covered Area

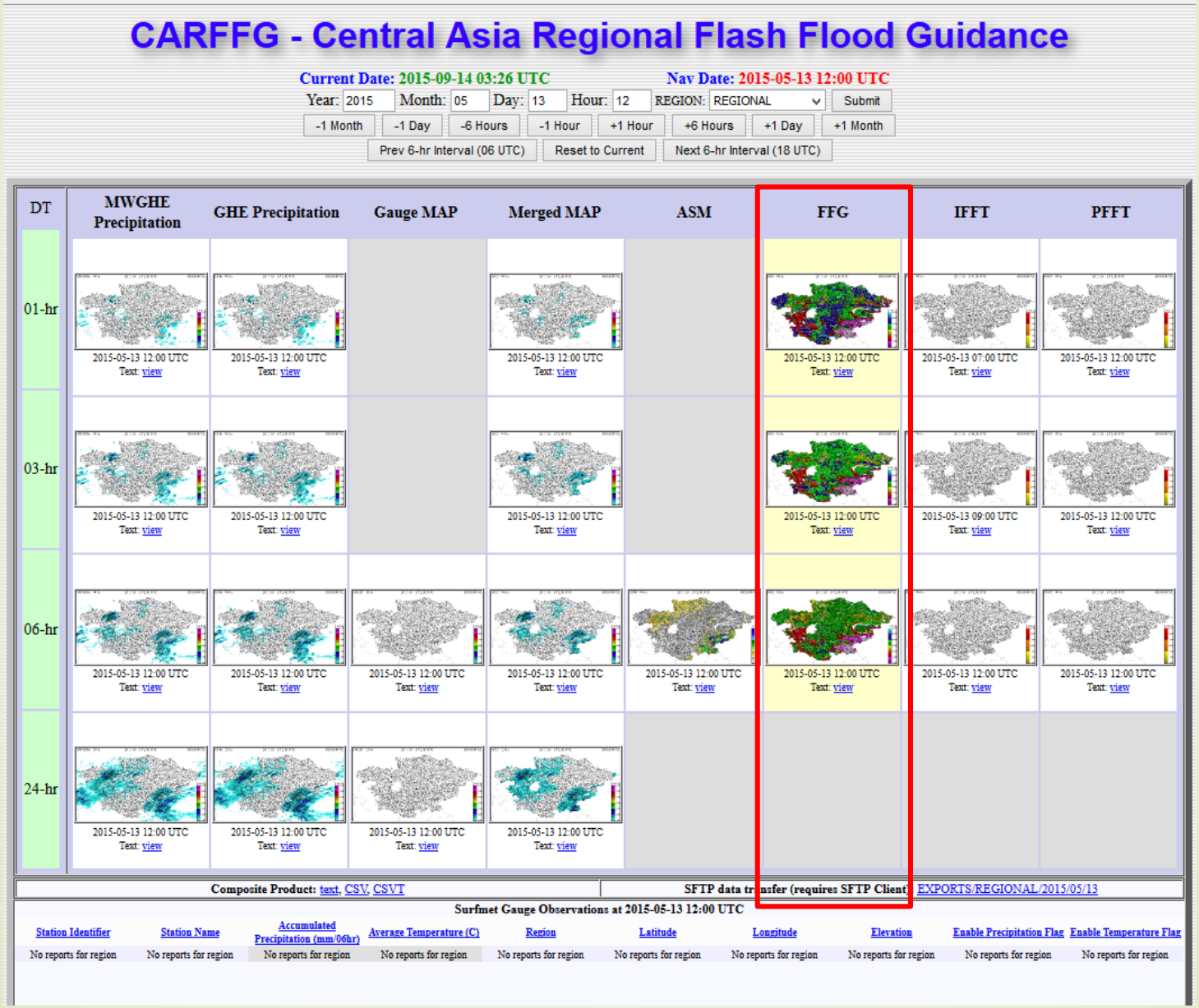
- Interactive Multisensor Snow and Ice Mapping System (IMS), made available through National Snow and Ice Data Center, NOAA.
  http://nsidc.org/data/docs/noaa/g02156_ims_snow_ice_analysis/index.html
- Daily snow cover based on summary of multiple satellites at 4km x 4km resolution.
  - Geostationary & 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.*

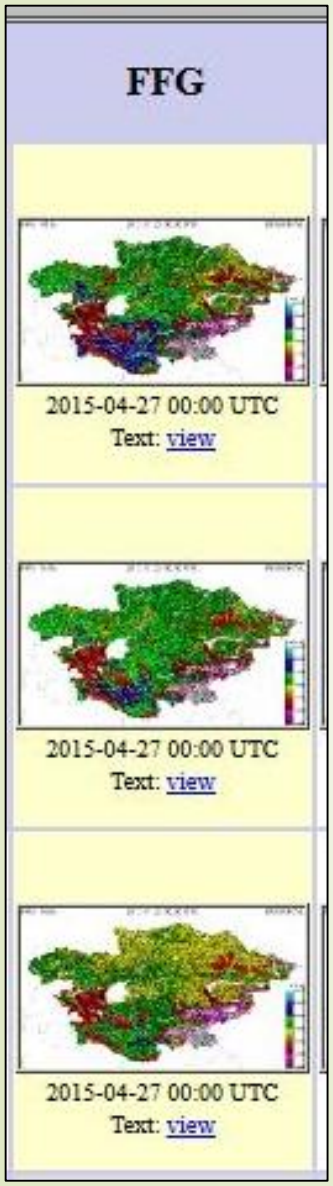
- *Apportion rain for uncovered areas*
- *Soil-snow interface leakage for snow covered areas*



# Flash Flood Guidance - FFG



# Flash Flood Guidance



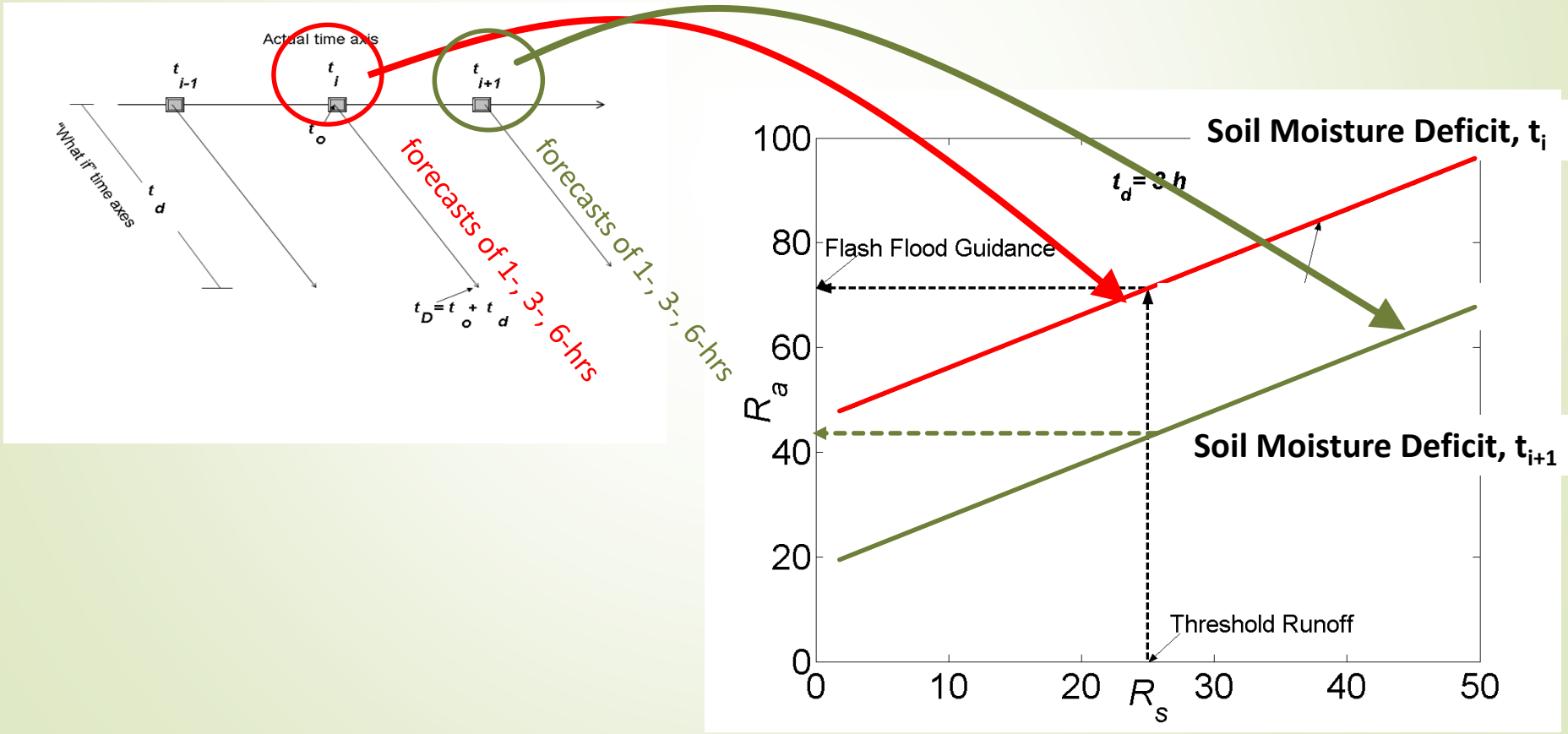

Flash Flood Guidance (FFG) is an estimate of the amount of rainfall of a given duration over a given small watershed which is enough to produce bankfull flow in the stream channel at the outlet of the watershed.

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

FFG is updated every six-hour in CARFFG System.

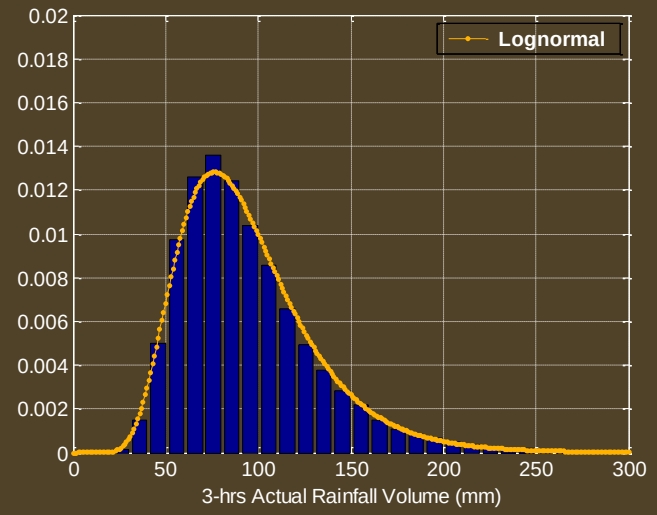
# Relationship b/t Threshold Runoff, Soil Moisture, & FFG

**Model Forecast Run Time (6-hours)**

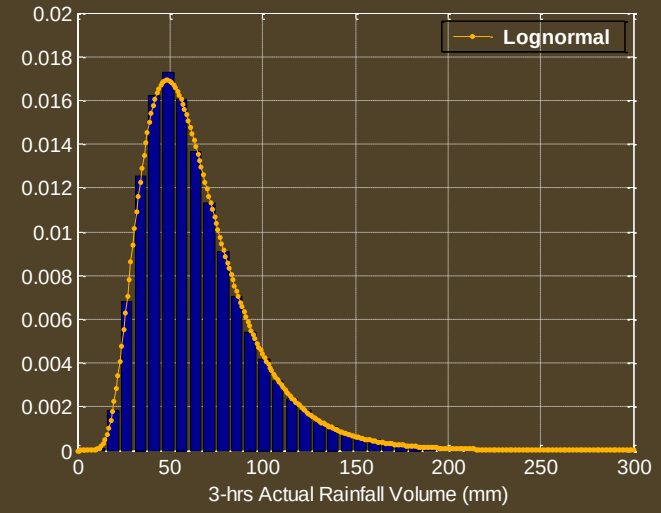


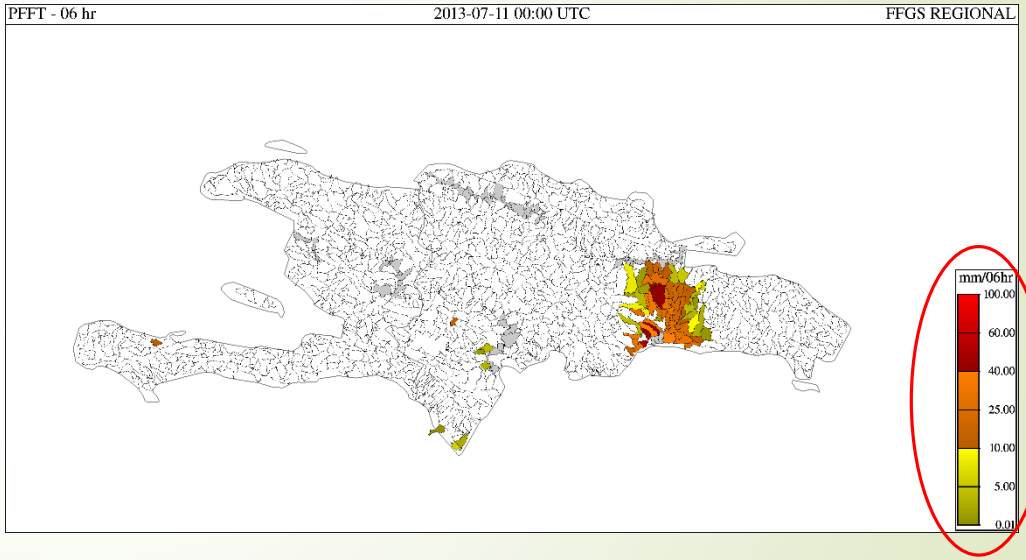
# Uncertainty in FFG

## Dry Conditions




## WetConditions



# Summary

- CARFFG 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.

# CARFFG System Development and Theoretical Background:

## 3. Satellite Precipitation & Bias Adjustment

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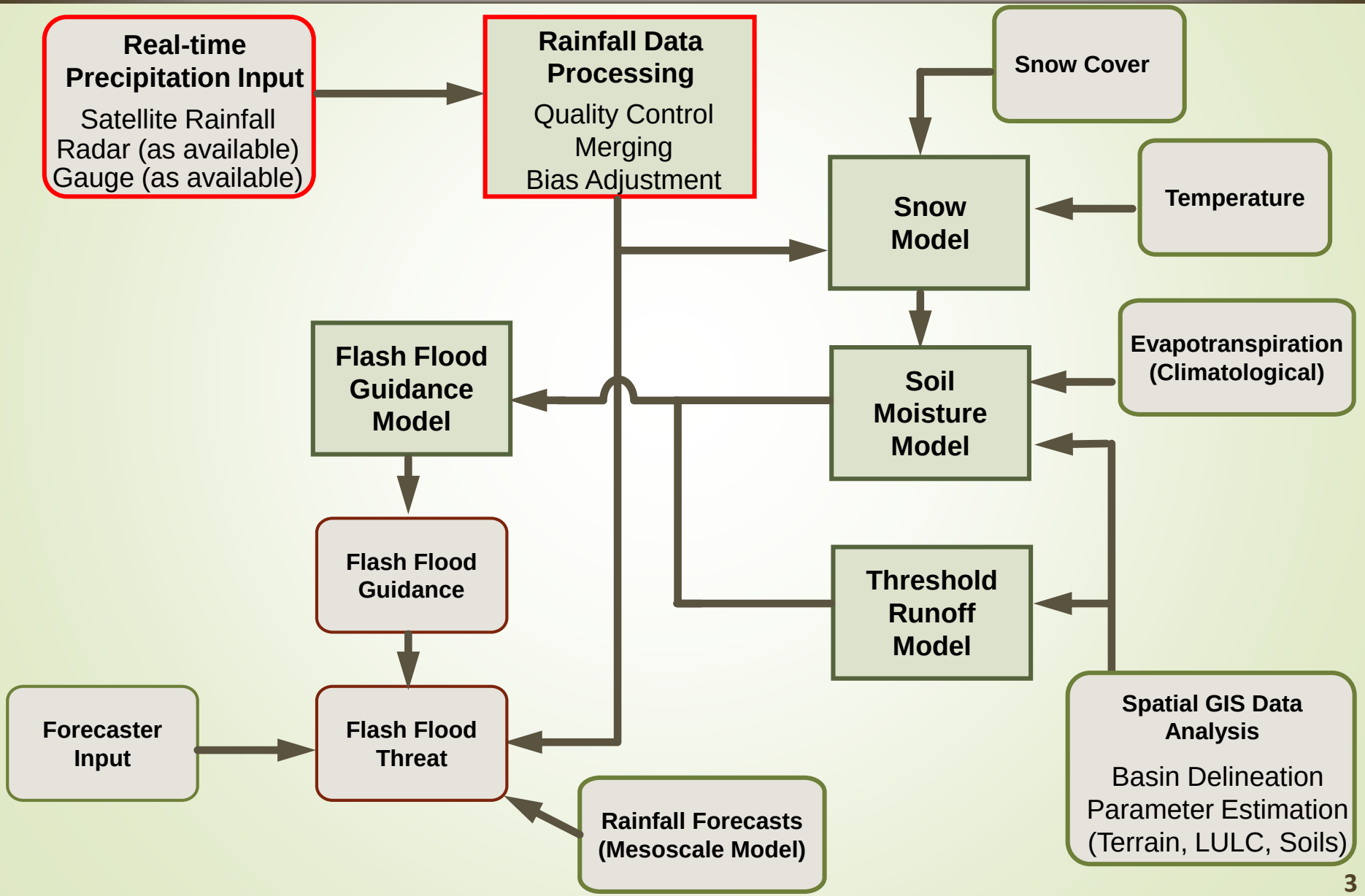
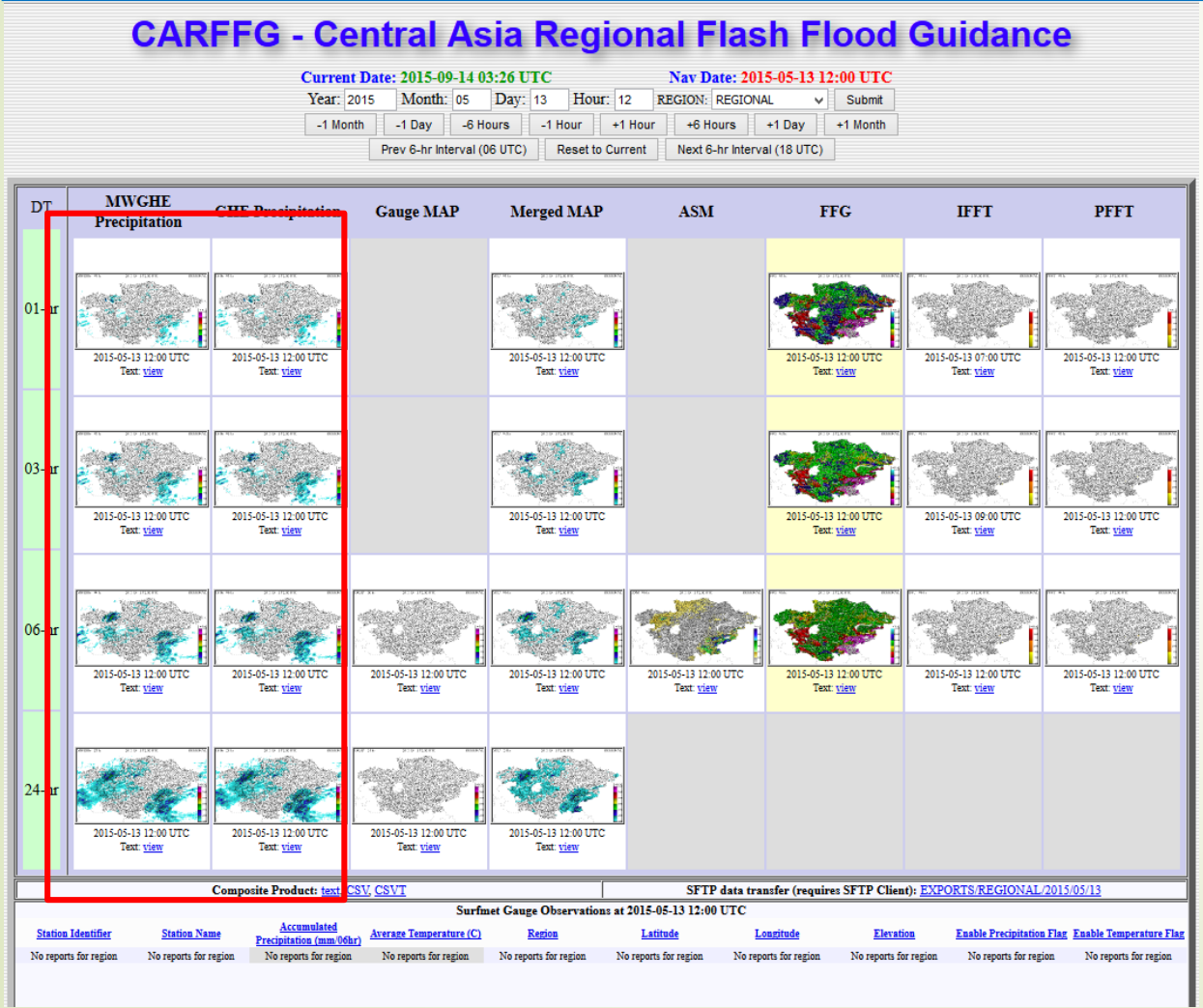
15 SEPTEMBER 2015

# 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

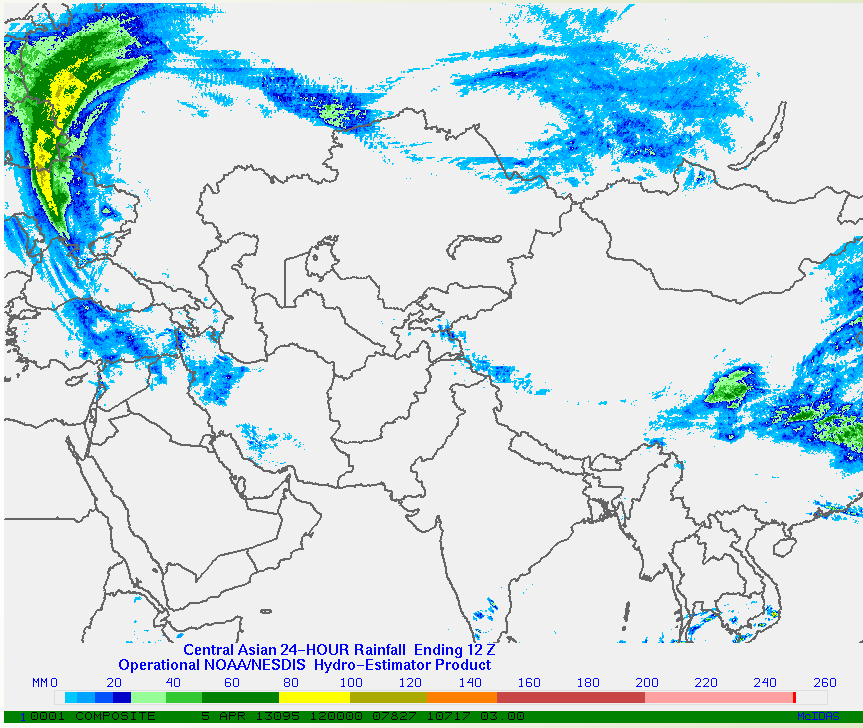
Research/development on HE since 1970s

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

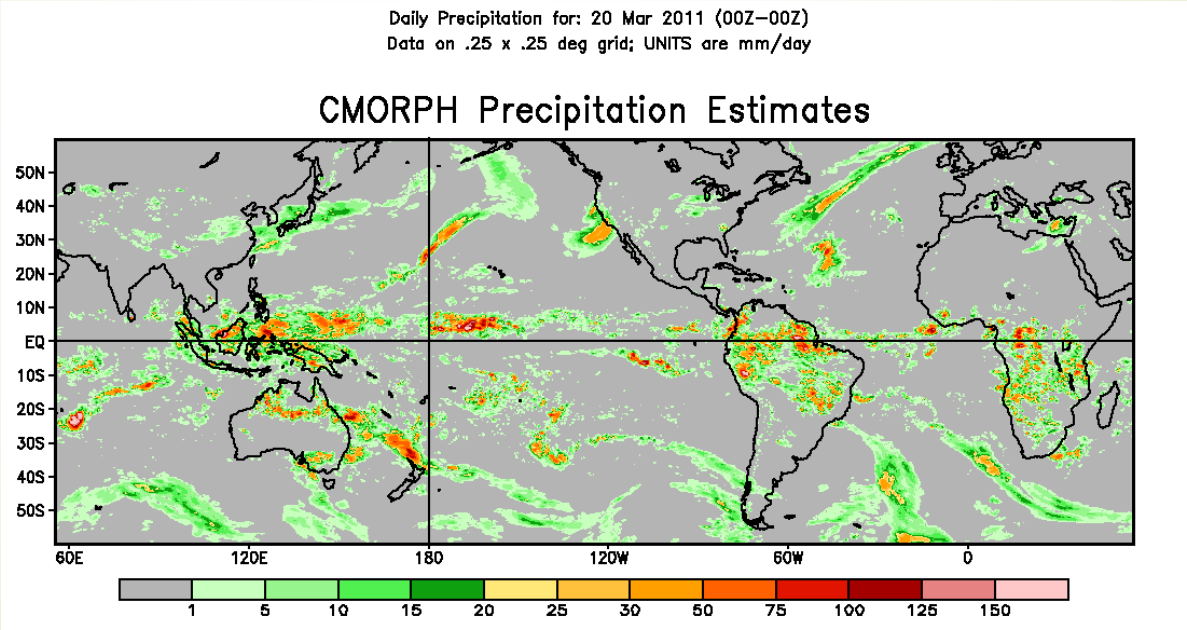
Based on measurements of microwave scattering from raindrops

MW–based

Produced by NOAA/CPC

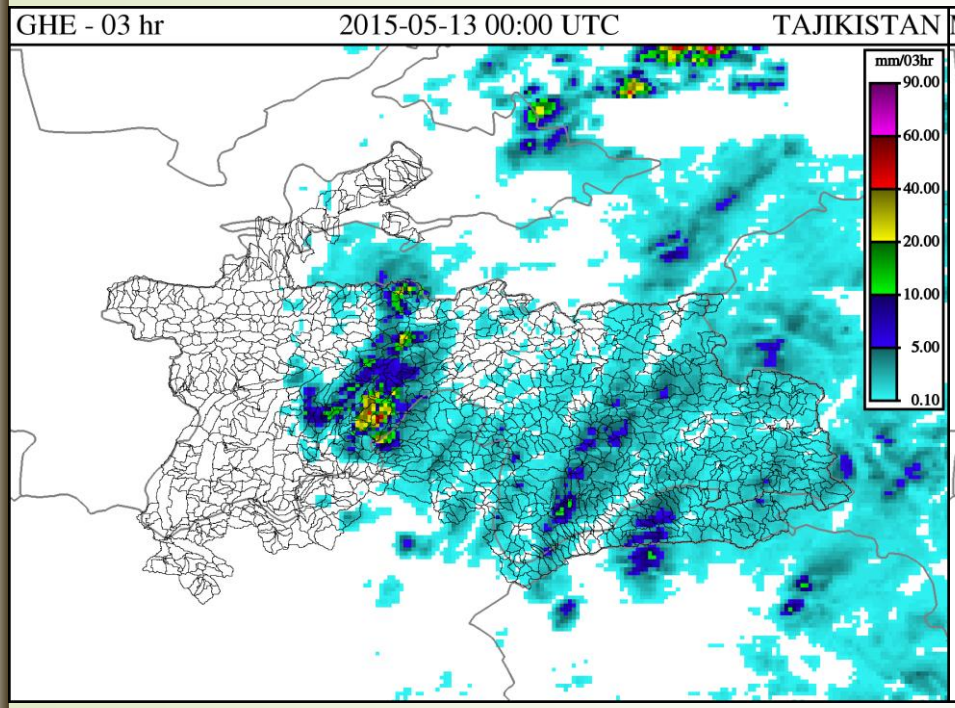
18-26 hour latency in operations

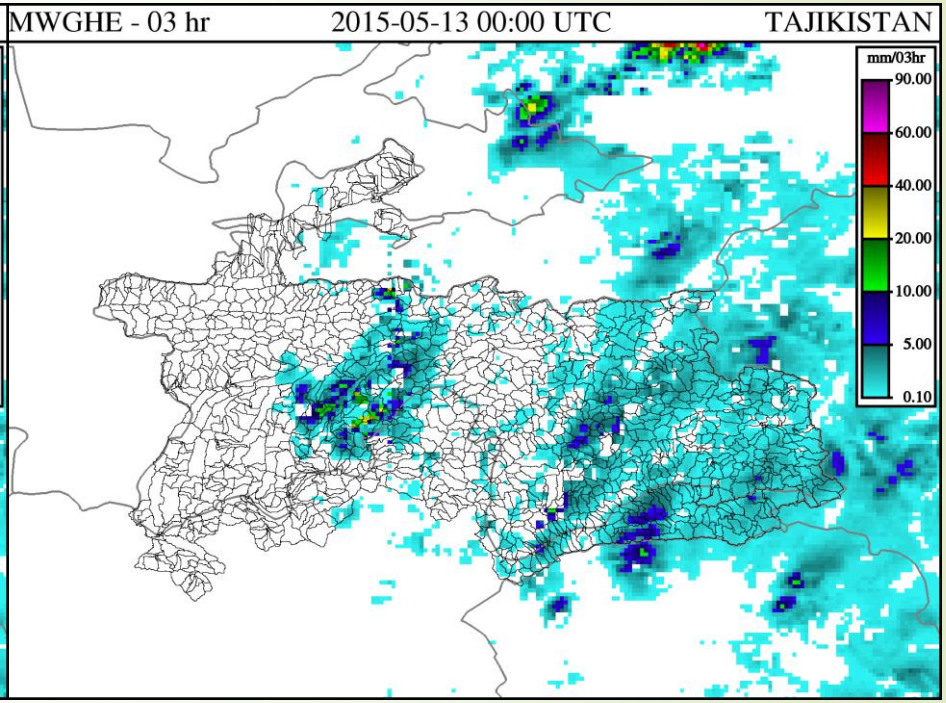
~ 8km resolution



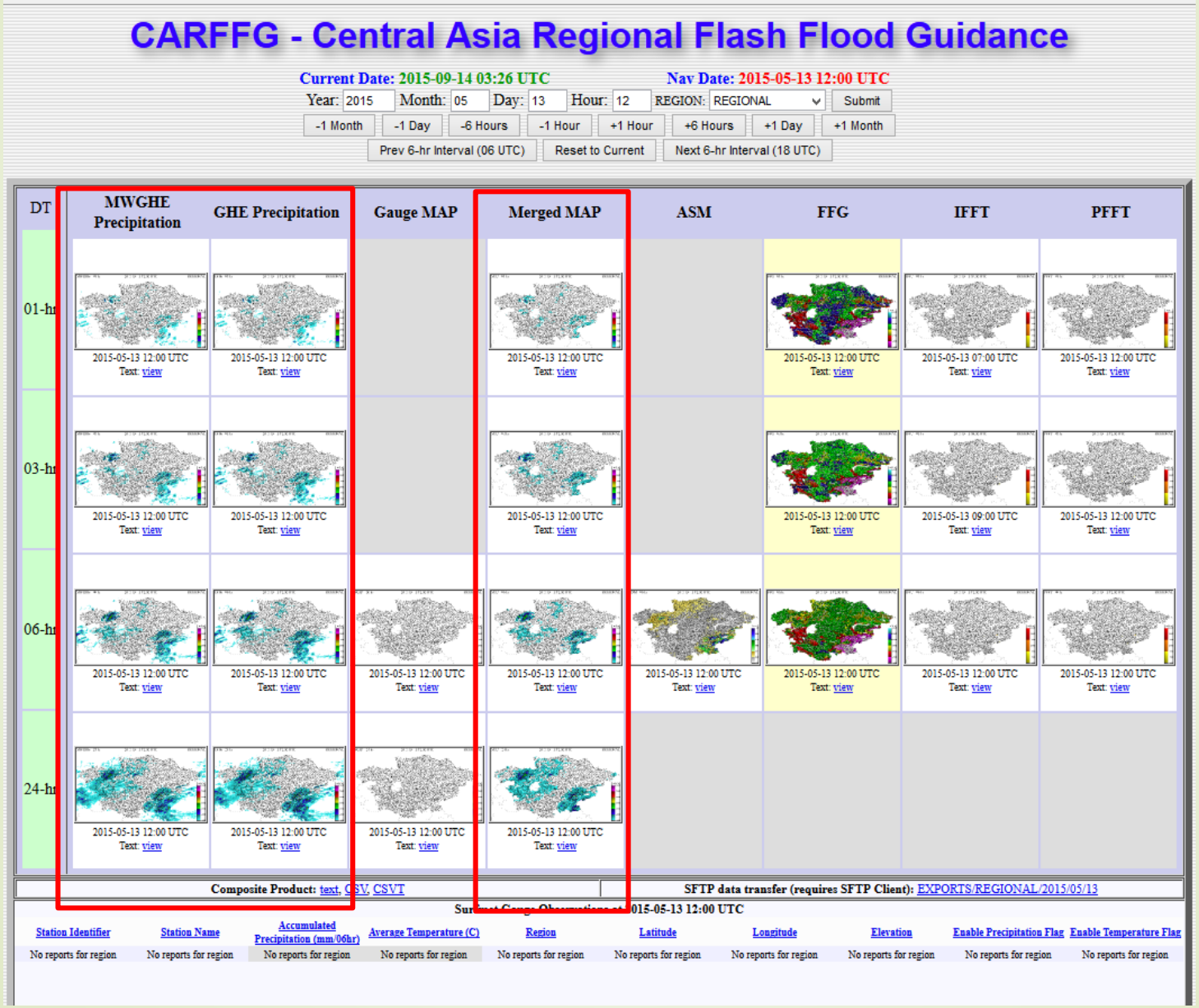

**FFGS Product combines IR-based GHE with MW-based CMORPH: MWGHE**

# Example from CARFFG



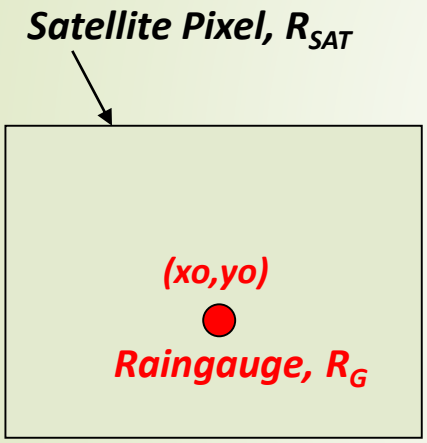



# CARFFG Interface



# Satellite Precipitation Bias Adjustment

Bias may exist in remotely sensed precipitation and should be removed for "best estimate" to provide input to hydrologic models.




**Bias Error Model:**

$$g(R_{SAT}) = \alpha g(R_G) + B + \varepsilon$$

*Transformation for Normality*

*Regional Bias*

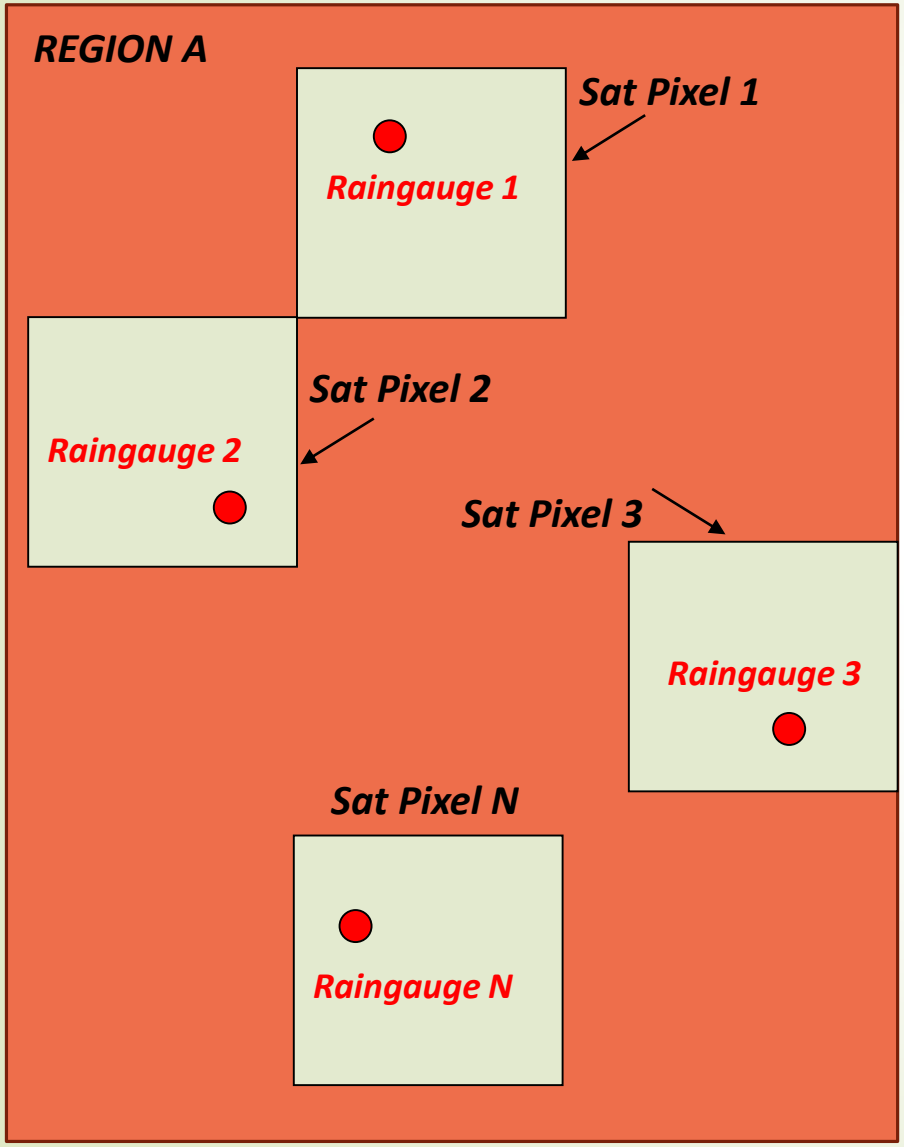
*Random Error*

Two applications of bias adjustment within FFG Systems

(Applied to each remotely sense product prior to merge MAP)

- Climatological bias adjustment
- Dynamic (real-time) bias adjustment

# Satellite Precipitation Bias Adjustment




**Log Bias:**

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

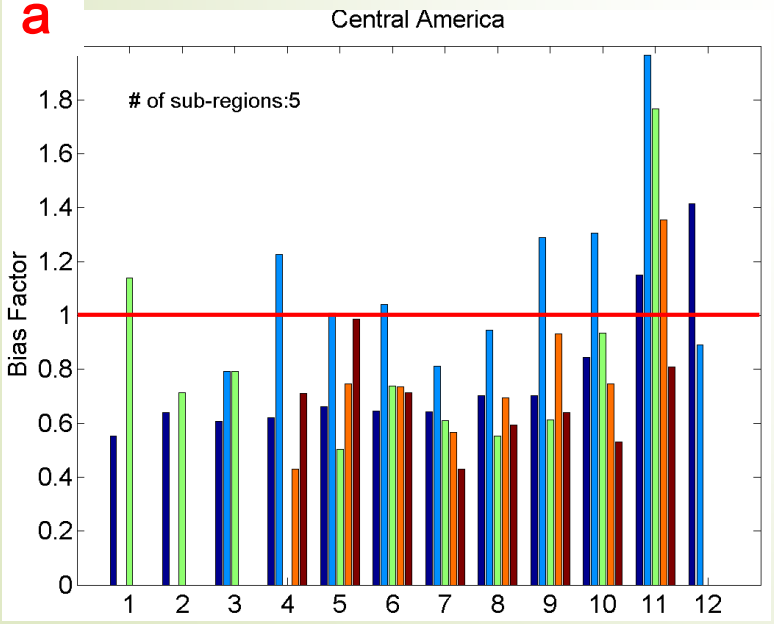
***This is foundation of both the real-time and climatological bias adjustment.***

# Climatological Bias Adjustment

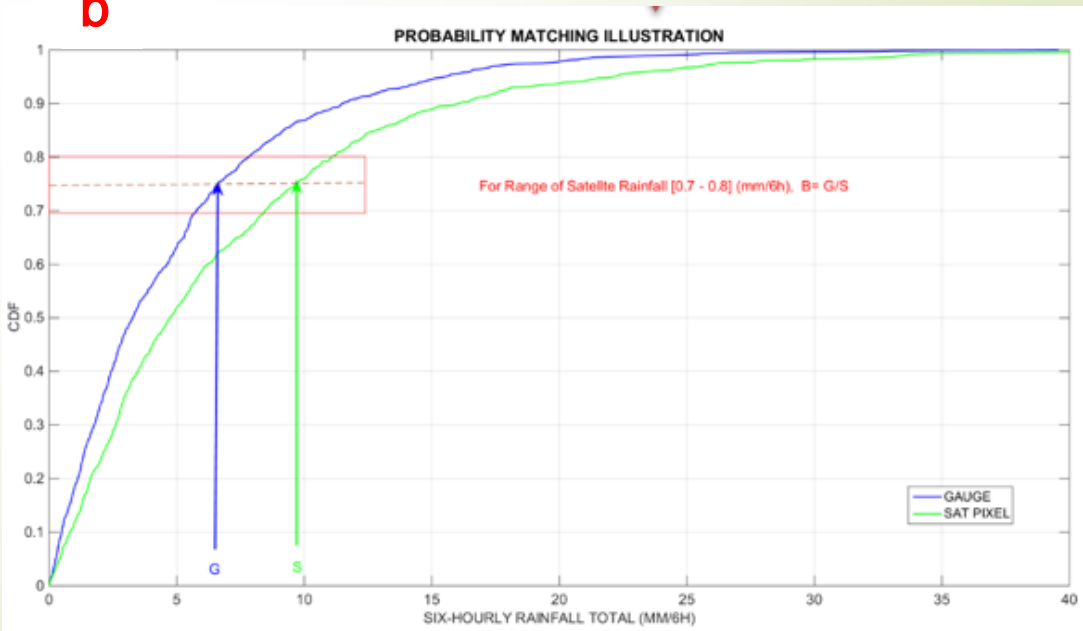
Goal is to determine long-term bias in satellite precipitation within a given region using historical records

- 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

a




b



# 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:***

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

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

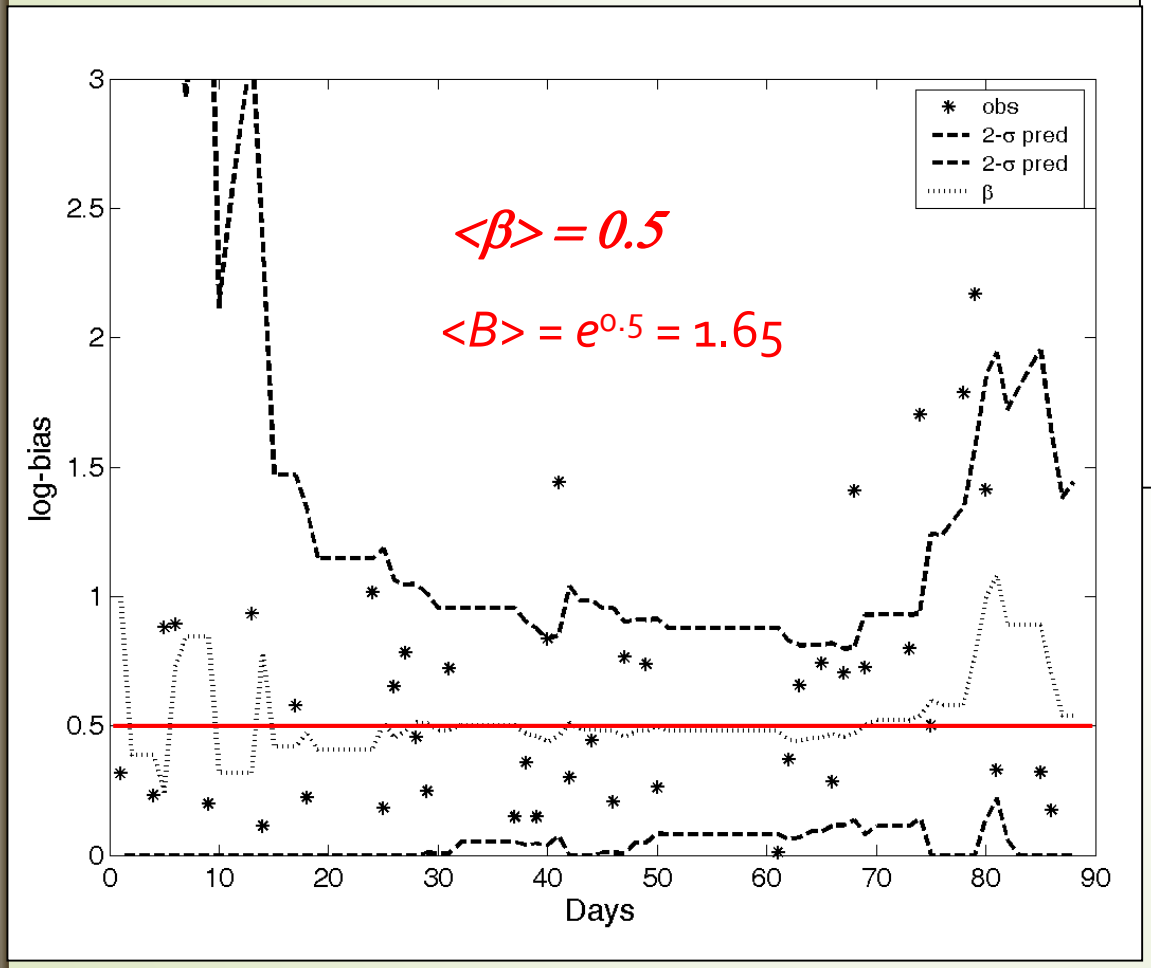
***Stochastic Approximations Algorithm***

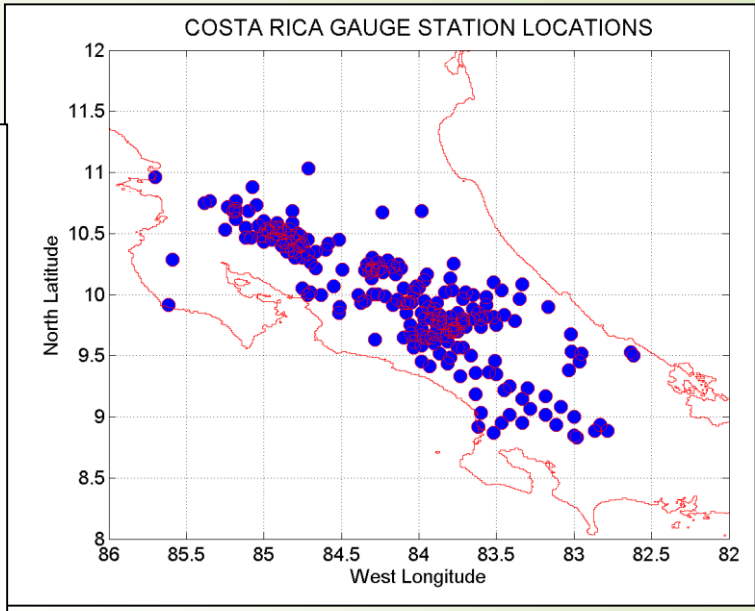
***Updating:***

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

***Kalman Gain***

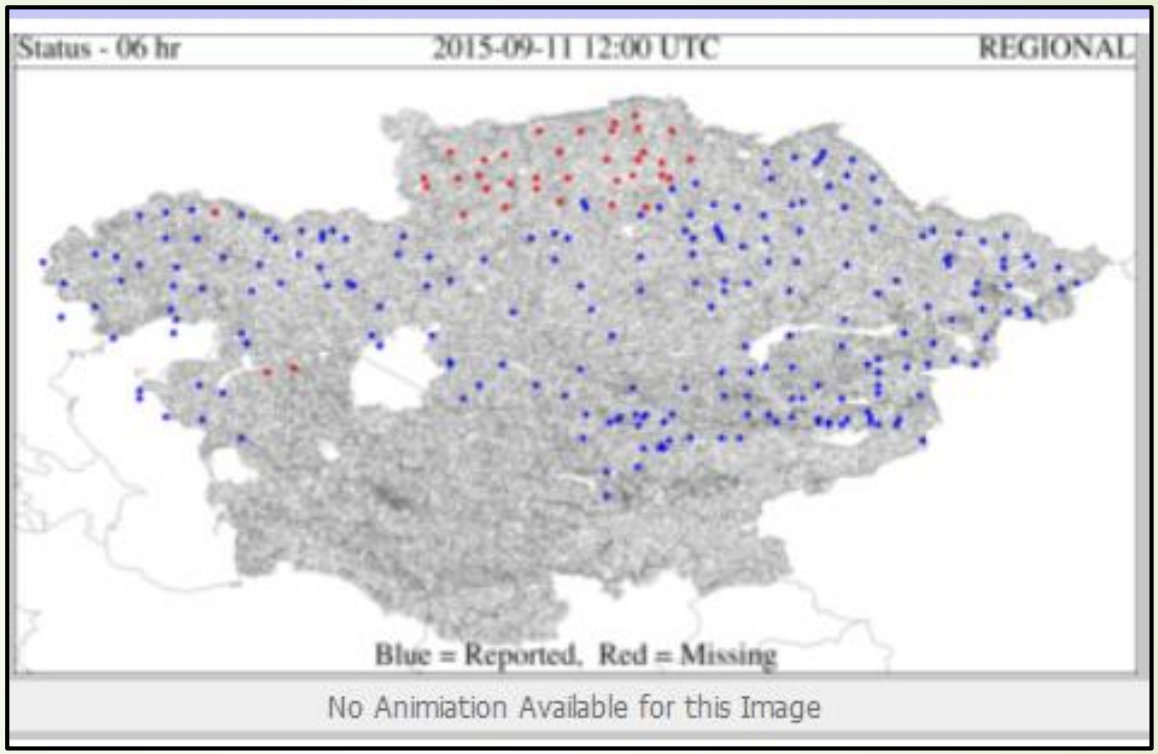
# An Example From Costa Rica, Central America



# 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 |