SAsiaFFG System Development and Theoretical Background

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Hydrologic Research Center

SAsiaFFG Steering Committee Meeting 27 APRIL 2016
New Delhi, INDIA
Key Technical Components of the SAsiaFFG System

- **Real-time Precipitation Input**
  - Satellite Rainfall Radar (as available)
  - Gauge (as available)

- **Rainfall Data Processing**
  - Quality Control
  - Merging
  - Bias Adjustment

- **Flash Flood Guidance Model**

- **Flash Flood Guidance**

- **Flash Flood Threat**

- **Rainfall Forecasts**
  - Mesoscale Model

- **Snow Cover**

- **Snow Model**

- **Soil Moisture Model**

- **Threshold Runoff Model**

- **Temperature**

- **Evapotranspiration (Climatological)**

- **Spatial GIS Data Analysis**
  - Basin Delineation Parameter Estimation
    - Terrain, LULC, Soils
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 km².
- 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.
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.
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);

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

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

Carpenter et al, *J. Hydrology*, 1999
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
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.
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 hydrograph* 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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Quality Control
Merging
Bias Adjustment

Rainfall Forecasts (Mesoscale Model)

Real-time Precipitation Input → Rainfall Data Processing
Rainfall Data Processing → Snow Model
Snow Model → Threshold Runoff Model
Threshold Runoff Model → Soil Moisture Model
Soil Moisture Model → Snow Cover
Snow Cover → Temperature
Temperature → Evapotranspiration (Climatological)
Evapotranspiration (Climatological) → Spatial GIS Data Analysis
Spatial GIS Data Analysis → Basin Delineation Parameter Estimation (Terrain, LULC, Soils)

Flash Flood Guidance Model

Flash Flood Guidance Model → Flash Flood Guidance
Flash Flood Guidance → Flash Flood Threat
Flash Flood Threat → Forecaster Input
Forecaster Input → Real-time Precipitation Input
ASM – Average Soil Moisture

SAsia-FFG - South Asia Flash Flood Guidance System

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<th>DT</th>
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<th>GHE Precipitation</th>
<th>Gauge MAP</th>
<th>Merged MAP</th>
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<th>FFG</th>
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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

- \( \text{Soil Water} = \text{depth integrated soil moisture} \)
- 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
Reasonably good reproduction of depth integrated soil water deficit
A priori Parameter Estimation

Soil Texture (from surveys)

Soil Texture Classification

Soil Hydraulic Properties ($\theta_{wlt}$, $\theta_{fld}$, porosity, $K_s$)

Model Parameters
SAsiaFFG Soil Information: FAO Database

Soil Texture (FAO)
- Clay
- Clay Loam
- Loam
- Sandy Loam
- Silt Loam
- Water

Soil Depth (FAO)
- Very shallow (<10 cm)
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Fast Response components are greatest concern for flash flooding.

- Define soil moisture product based on Upper Zone:
  - $X_{To}$ – upper zone tension capacity
  - $X_T$ – upper zone tension content
  - $X_{Fo}$ – upper zone free capacity
  - $X_F$ – upper zone free content

$$ASM = \frac{(X_T + X_F)}{(X_{To} + X_{Fo})}$$
For regions with significant snow cover, a snow model is employed to account for snow storage and snow melt impact on soil moisture.
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

\[ Q_n = f(Q_{sw}, Q_{lw}, A, T_0) \]
\[ Q_e = f(e_o, u_a) \]
\[ Q_h = f(T_0, T_a, u_a) \]
\[ Q_g = f(T_g, T_s) \]
\[ Q_m = f(p) \]

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

SAsia-FFG - South Asia Flash Flood Guidance System

Current Date: 2016-04-25 09:48 UTC
Nav Date: 2016-03-25 09:00 UTC

Year: 2016
Month: 03
Day: 25
Hour: 09
REGION: REGIONAL

DT | MWGHE Precipitation | GHE Precipitation | Gauge MAP | Merged MAP | ASM | FFG | IFFT | PFFT | Icon Model Forecast | FMAP | FFTE
---|---------------------|-------------------|-----------|------------|-----|-----|------|------|---------------------|------|-------
01-hr
03-hr
06-hr
24-hr

Composite Product: text, CSV, CSW, SFTP data transfer (requires SFTP Client): EXPORTS/REGIONAL 2016-03-25

Surfexs Gauge Observations as 2016-03-25 06:00 UTC

Station Identifier | Station Name | Accumulated Precipitation (mm/96h) | Air Temperature (°C) | Rainfall | Latitude | Longitude | Elevation | Rainfall Precipitation Flag | Temperature Flag | No reports for region | No reports for region | No reports for region | No reports for region | No reports for region | No reports for region | No reports for region | No reports for region
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 Update Time (6-hours)

Soil Moisture Deficit, $t_i$

Soil Moisture Deficit, $t_{i+1}$

$t_d = 3\, h$

Flash Flood Guidance

Threshold Runoff

$t_{d}=t_{o}+t_{d}$

Forecasts of 1, 3, 6-hrs

$t_{i-1}$

$t_{i}$

$t_{i+1}$

Actual time axis

Time axis

Model Update Time (6-hours)
Uncertainty in FFG

Dry Conditions

Wet Conditions

3-hrs Actual Rainfall Volume (mm)
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.
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Temperature

Evapotranspiration (Climatological)

Spatial GIS Data Analysis
Basin Delineation
Parameter Estimation (Terrain, LULC, Soils)

Soil Moisture Model
Threshold Runoff Model

Snow Model

Flash Flood Guidance Model

Flash Flood Guidance

Flash Flood Threat

Forecaster Input

Rainfall Forecasts (Mesoscale Model)
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
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
Log Bias:

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

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:**
\[ \hat{\beta}_{t+1}^- = \hat{\beta}_t^+ \]
\[ P_{t+1}^- = P_t^{++} + Q_{t+1} \]

**Updating:**
\[ \hat{\beta}_{t+1}^+ = \hat{\beta}_{t+1}^- + K_{t+1}(z_{t+1} - \hat{\beta}_{t+1}^-) \]

Kalman Gain

Stochastic Approximations Algorithm
An Example From Costa Rica, Central America

$$\langle \beta \rangle = 0.5$$

$$\langle B \rangle = e^{0.5} = 1.65$$
Real-Time Gauge Data

FROM CARFFG System “DASHBOARD”

FROM CARFFG System “PRODUCT CONSOLE”