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Improved Flood Dynamics and Visualization of the CREST Model Using a Fully Distributed Routing Scheme and a Novel Inundation Simulator

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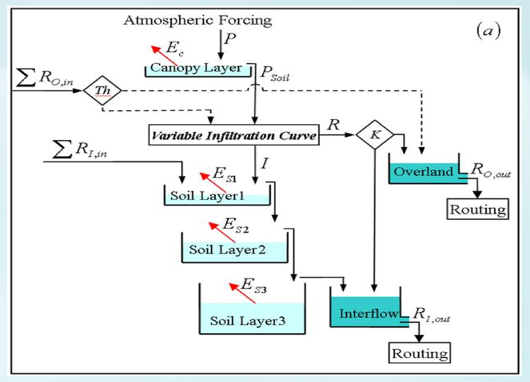
I Abstract

Hydrologic modeling is vital in water resources management and flood warning. The routing module, one of the most important components of hydrologic models, determines model performance to a great degree. In this study, we have proposed a fully distributed linear reservoir (FDLRR) scheme to replace the existing quasi-distributed (QDLRR) scheme in previous versions (v2.0 and earlier) of the Coupled Routing and Excess STorage (CREST) model. The new routing scheme is theoretically sounder and more suitable for distributed hydrological models than the QDLRR scheme. Consequently, the new scheme has effectively eliminated some unrealistic results in the previous versions of CREST. These unrealistic results include the tendency to underestimate channel flow at fine spatial or coarse temporal resolutions and discontinuous flow values along the river after storms. The FDLRR has been implemented in CREST v2.1 and tested in three basins at different spatial (250m and1km) and temporal (hourly and daily) resolutions. The results confirm that the proposed routing scheme embedded in CREST v2.1 are truly spatiotemporal scalable. At daily scale, the model error decreases with increasing drainage area: the Nash coefficient (NSCE) increases from 0.65 in the smallest basin to 0.90 in the largest basin, while correlation coefficient (CC) increases from 0.82 to 0.95 and the absolute value of the relative bias decreases from 10.6% to 1.57% accordingly. At hourly scale, CREST v2.1 has successfully replicated 6 out of 7 flood events during 2002-2013 in the Tar Basin with mean NSCE being 0.86, mean CC being 0.97, and mean absolute difference of peaks being 10.82%. In addition, CREST v2.1 produces a naturally continuous river flow pattern along the stream during and after the rainstorms, while CREST v2.0 tends to generate a bumpy, discontinuous discharge pattern along the stream.

Extended from CREST v2.1, we have further developed an inundation mapping tool, iMap. iMap aims at providing real-time inundation map with high resolution. Instead of using time consuming hydrodynamic approaches, iMap employs the rating curve to directly compute the cross-sectional area and stage height from the CREST output discharge. Different from other studies that uses the rating curve relationship, iMap obtains its distributed parameters of the rating curve from our newly developed global geomorphologic product at 1km resolution.

II Methodology

A. The CREST model



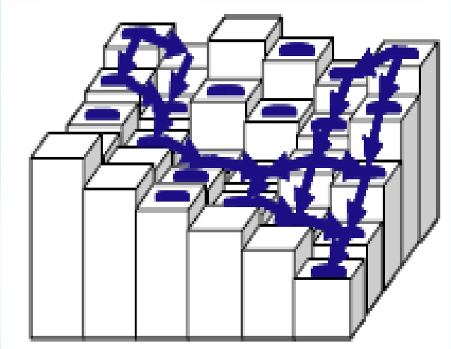
(a) The rainfall-infiltration diagram

Coupled Routing and **E**xcess **ST**orage (CREST) model (Wang, et.al, 2011) developed jointly by OU/NASA

- Three soil layers.
- Distributed, fully coupled runoff generation and routing model
- Simulates water and energy fluxes and storage on a regular grid

Step I: Rainfall-infiltration Partitioning (distributed and time-variant)
Step 2 (new): Cell-to-cell routing using fully distributed linear reservoir
Step 3 (new): Grid Point Hydrographs->Flood Inundation Mapping

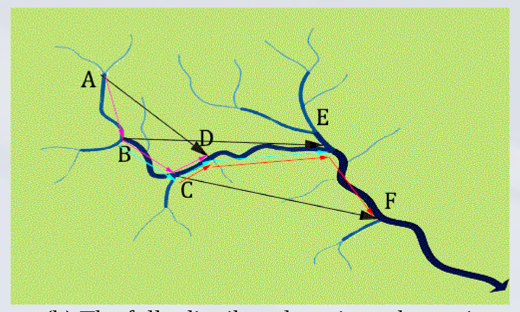
(b) The computational steps of CREST



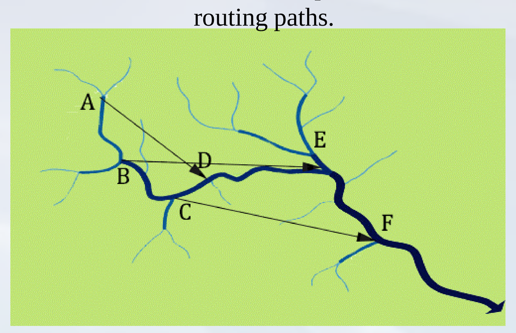
(c) The cell-to-cell routing scheme

Figure 1 The framework of the CREST model

B. The Fully Distributed Routing Scheme



(b) The fully distributed routing scheme, in which the colorful arrows represents the actual routing paths.



(a) The quasi distributed routing scheme which the black arrows represent the routing paths.

Figure 2. Schematic diagram of the routing scheme of CREST

The fully distributed FD-LRR scheme (Figure 1(a)) in CREST v2.1 realistically aggregates all water passes via a given cell of interest to compute the runoff while the quasi-distributed linear reservoir routing (QD-LRR) scheme (Figure 1(b)) in CREST v2.0 only takes the water that leaves a given cell into account of runoff contribution. Compared to the QD-LRR, the FD-LRR not only resolves the tendency to underestimate the discharge but also produces continuous flow value along the river. Furthermore, it makes CREST v2.1 spatial and temporal scalable and easier to be calibrated.

C. CREST_iMap (Inundation Mapping)

iMap is a static inundation mapping extension of CREST that utilizes the rating curve relationship, $Q = \alpha A^m$, in order to convert the CREST output channel discharge, Q, to cross sectional area, A, at each cell along the river. Using a high resolution DEM, we can obtain the water boundary from the cross-sectional area.

In practice, we face three major challenges to implement iMap: 1) the non-monotonic relationship between elevation (H) and the width (W) of the flood plan; 2) the availability of distributed rating curve parameters ($\boldsymbol{\alpha}$ and *m*) and 3) the turning point of rating curve. First, we have established monotonic relationships between A-H and A-W along the river purely using the high resolution(3') DEM. Secondly, we have employed an recently developed relationship (Vergara et.al, 2014) between rating curve parameters and basin morphologic variables extracted from a global geomorphologic product (Shen, et. al, 2014) we are about to release. Finally, the cross-sectional area is calculated by assuming a trapezoid shaped flood plan after the turning point.

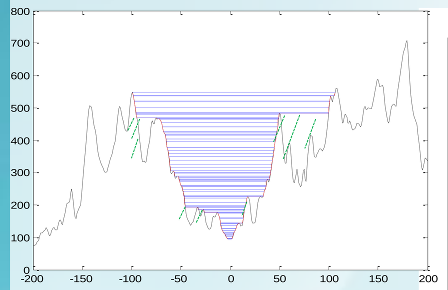
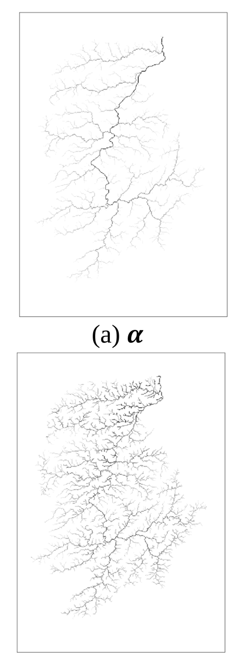


Figure 3. The cross-section of a river cell and the monotonic relationship of A-H and A-W.



(a) α (b) *m*

(c) BR (d) BL (e) RR

Figure 4. The global geomorphologic variables in Gan River.

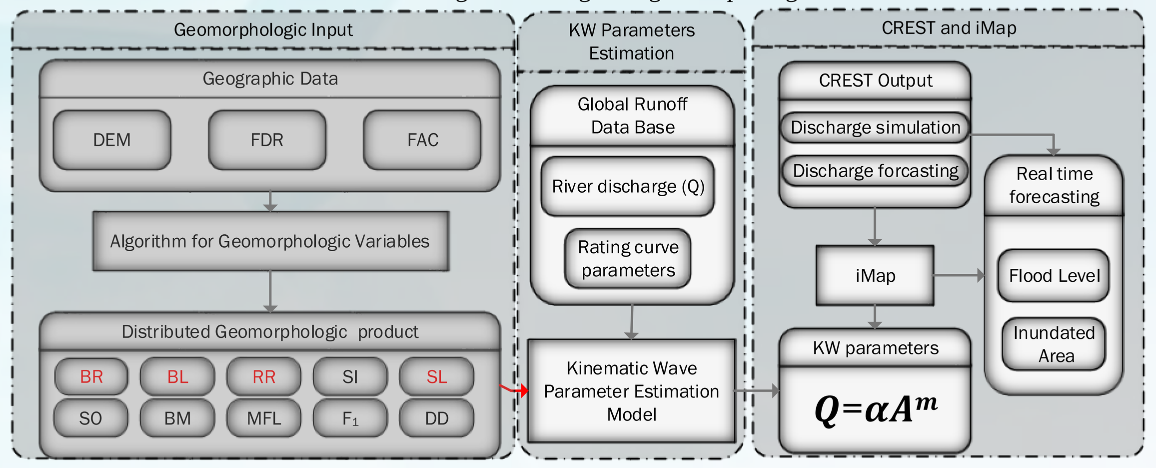
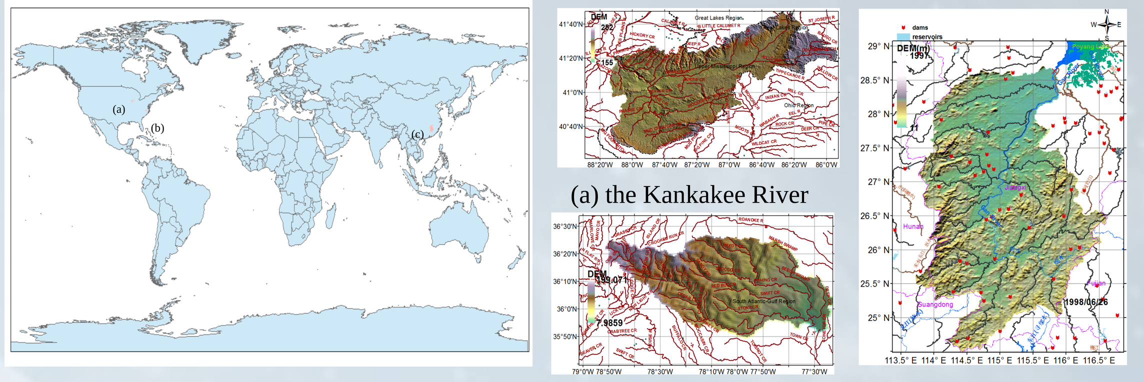


Figure 4. The framework of CREST_iMap. The red geomorphologic variables are used to derive the kinematic wave parameters. The full name of the geomorphologic variables is given here: BR- basin relief, BL-basin length, RR-relief ratio, SI-slope index, SL-slope, SO-stream order, BM-basin magnitude, MFL-maximum flow length, F_1-first-order channel frequency and DD-Drainage Density.

III The Study Region

A. Study Basins

CREST v2.1 have been tested in three basins with a wide range of size, climate condition and topography. They are the Tar River in North Carolina, USA, Kankakee River in Illinois, USA and Gan River in Jiangxi, China. The characteristics of these basins are summarized in Table 1.



(a) the Kankakee River (b) the Tar River (c) The Gan River

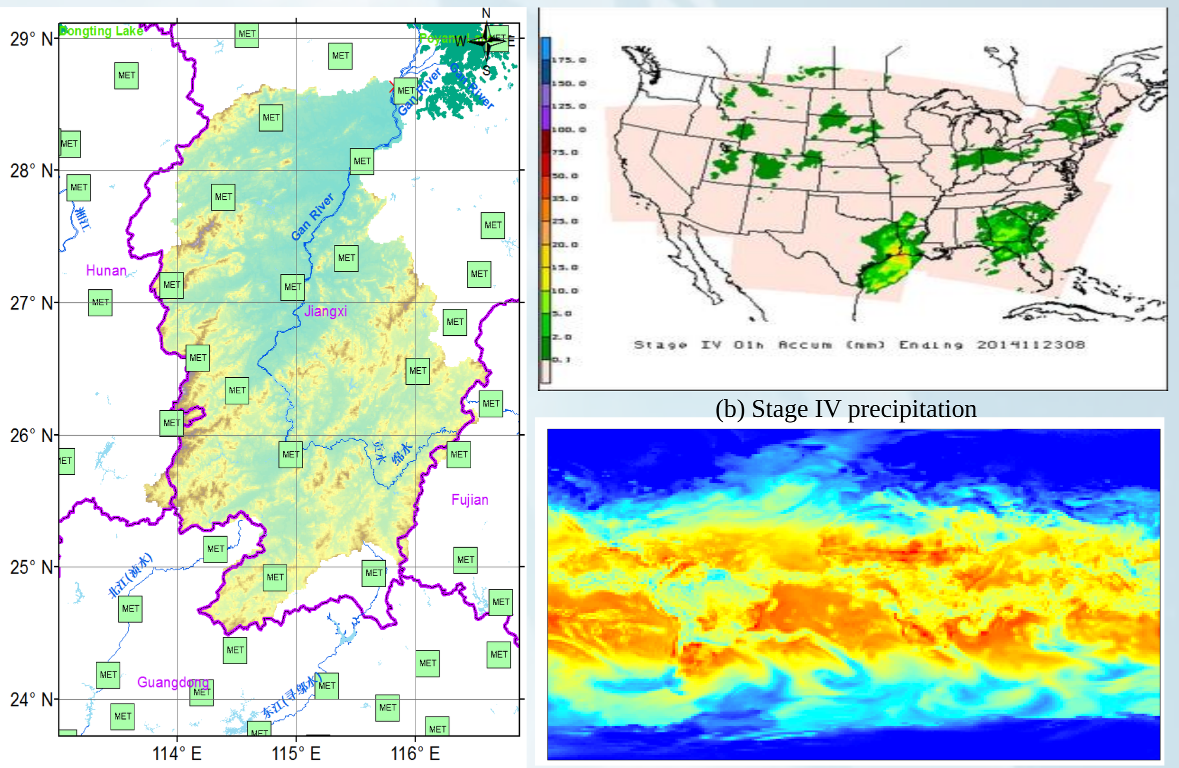
Figure 5. Terrain and location of the three study basins, (a) and (b) are extracted from NED dataset while (c) is extracted from the USGS HydroSHEDS 1km dataset.

Table 1 Attributes of study basins

Basin (River) Name	Observation Sites (No.)	Drainage Area (km^2)	Mean Annual Rainfall (mm)	Spatial Resolution	Mean Runoff (m^3/s)	Climate Type	Maximum Height Difference (m)
Tar, NC, USA	02083500	5777	1102	1km	52.95	humid subtropical	192
Kankakee, IL, USA	05527500	13482	963	250m	155.45	humid continental	127
Gan, Jiangxi, PRC	62302500	80353	1109	1km	2628.62	subtropical monsoon	1986

B. Forcing Data

National Stage IV multi-sensor precipitation analyses product precipitation, Famine Early Warning Systems (FEWS) daily Potential Evapotranspiration (PET) and Shared meteorological (gauge) data by China meteorology agency are used as forcing data in this study.



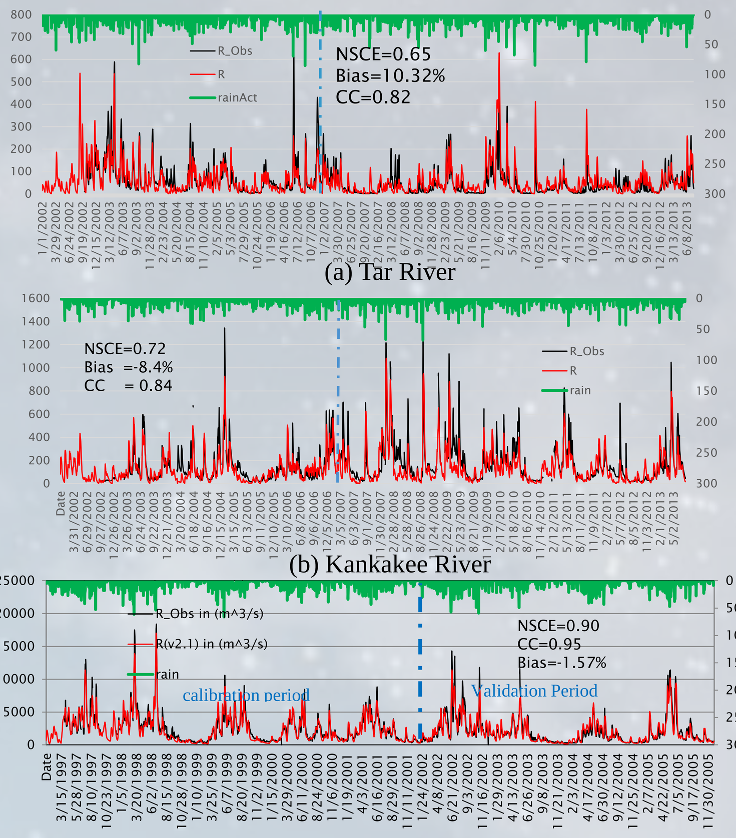
(b) Shared meteorological (gauge) data (b) Stage IV precipitation (c) FEWS PET

Figure 6. Forcing data used in this study.

IV Results

The hydrographs of the first group are given in Figure 8. It shows that CREST v2.1 generates reasonably good results at all three basins and the performance is not affected much by the spatial resolution and climate condition. Furthermore, as a distributed hydrological model, the model error decreases with the increase of the drainage area. At daily scale, in the Gan River basin, all flood peaks and base flows are well captured and the relative errors are small.

In Figure 9(a), it is clear that CREST v2.0 produces bumpy and discontinuous daily runoff values along the mainstream because of the previously mentioned water jumping, which is unnatural.



(a) Tar River (b) Kankakee River (c) Gan River

Figure 8. hydrographs of the three basins at daily scale

On the contrary, Figure 9(b) shows that the FDLRR method produces naturally continuous and basically monotonic daily runoff values from the upstream to the downstream as a result of taking the contribution from all the water that passes through the observing cell into account.

In Figure 10, CREST skill on flood events is evaluated. Among the 7 flood events, the NSCE of two events exceeds 0.9, of 6 events exceeds 0.8 and the CC of all events exceeds 0.95.

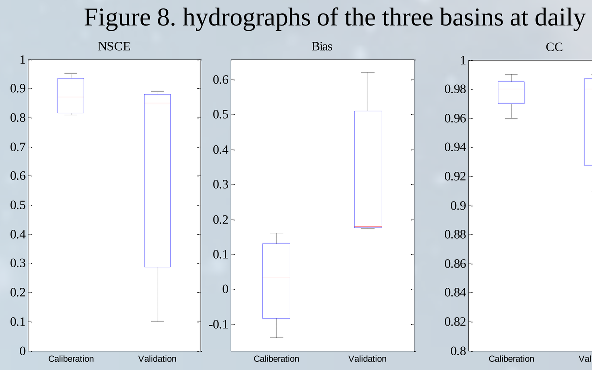
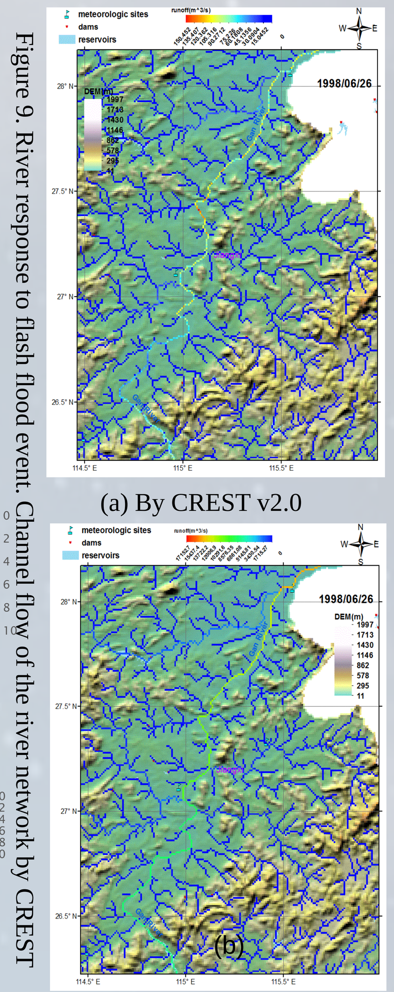


Figure 10. Flood event skill at hourly scale in Tar River.



(a) By CREST v2.0 (b) By CREST v2.1

Figure 9. River response to flash flood event. Channel flow of the river network by CREST

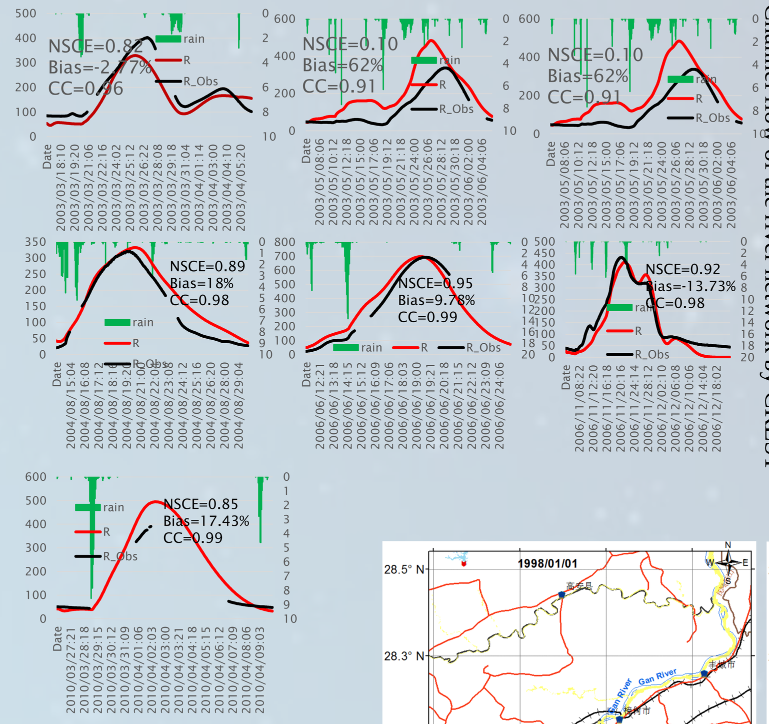


Figure 11. Hydrographs of flood events at hourly scale in Tar River.

In Figure 12, the water covered area on Jan 1, 1998 when there is no flood and June 26 1998 when a flood event of 20-year return period occurred in Gan River is generated by CREST_iMap using the daily channel runoff.

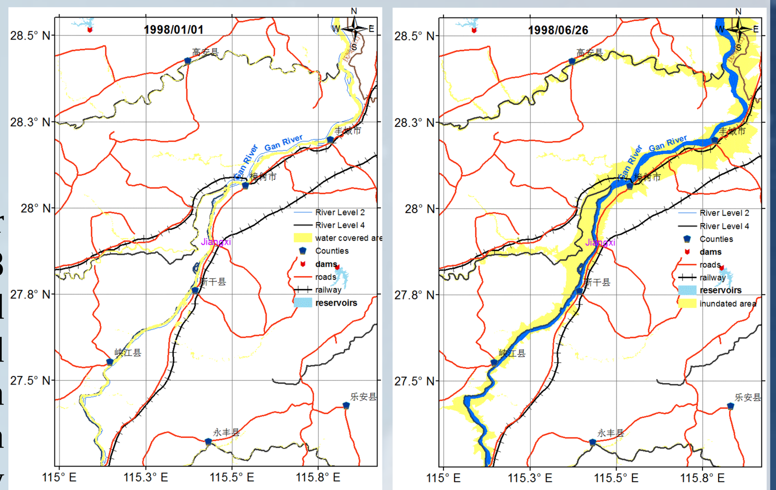


Figure 12. Inundated area produced by CREST_iMap.

V Conclusions

The FDLRR scheme overcomes the major drawbacks of the QDLRR and is adopted in the most updated version of CREST, CREST v2.1. Compared to the previous versions, CREST v2.1 eliminates the tendency to underestimate the stream flow when the spatial resolution is fine or the time step is coarse and produces continuous flow value along the river.

Based on the output of CREST v2.1, rating curve-geomorphologic model and a global geomorphologic product we recently released, we have further developed CREST_iMap to statically map the inundated area.

References:
1. Wang. J., Y. Hong, L. Li, J.J. Gourley, K. Yilmaz, S. I. Khan, F.S. Policelli, R.F. Adler, S. Habib, D. Irwn, S.A. Limaye, T. Korme, and L. Okello, 2011: The Coupled Routing and Excess STorage (CREST) distributed hydrological model. *Hydrol. Sciences Journal*, 56, 84-98.
2. Xinyi Shen, Yang Hong, Ke Zhang and Zengchao Hao, "Refine a Distributed Linear Reservoir Routing Method to Improve Performance of the CREST Model" (submitted to Journal of Hydrologic Engineering).
2. Humberto, Vergara, et. al, "A Method To Estimate A-Priori Kinematic Wave Model Parameters Based On Geomorphological Properties of Watersheds For Regional Flood And Flash Flood Forecasting In The Conterminous United States" (to be submitted to *Journal of Hydrology*).
3. Xinyi Shen, Humberto Vergara, Yang Hong and Ke Zhang "A global geomorphologic product" (to be submitted to *Scientific Data*, *Nature*).

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