Response to Editor's Remarks:

"Thanks to the reviewers and you for excellent discussion on your paper. It became clear your work is evaluated as a significant contribution to hydrology and landslide research. It also fits perfectly in HESS. However, there have been several technical issues -mainly extra explaining and terminology- to be addressed, most of which you already replied on and agreed to add to the paper. I want to stress that it is important to be as open, clear and complete as possible in terminology, pro- and cons of approach and possible application, explicitly discuss the way the model integration is done, etc. Both reviewers mentioned these points. This will help readers to use it, work with it and develop it."

Response:
We thank the editor for his positive comments and assessments. We have substantially revised our manuscript based on your remarks and the reviewer comments. In particular, we resolved the technical issues by adding additional explanation and clarifying terminology and the model integration. For more information on the revision, please refer to the following point-to-point reply to the review.

Response to Anonymous Referee #1:

1. "*This study General Comments: This paper represents a significant conceptual advancement in the modeling of flash flooding and shallow, rainfall-induced landslides. Combining CREST and TRIGRS appears to provide a fairly complete solution for modeling the surface water, shallow subsurface hydrology related to runoff and flooding as well as the initial hydrologic conditions, transient pressure head, and slope stability processes related to landslide initiation. The paper is generally well written and provides a general framework for modeling the hazards resulting from heavy or prolonged rainfall. The paper could be improved by stating more of the modeling assumptions (see specific comments) used in the case study and making a number of technical corrections.*"

Response:

We thank the reviewer for his/her positive comments. We totally agree with the reviewer's assessment that our paper presents a significant conceptual advancement in the modeling of flash flooding and shallow, rainfall-induced landslides. More importantly, revision based on the comments from this reviewer and the other has further improved this manuscript.

2. "*P. 1, lines 19-20 and p. 2, line 9: The phrase "leading to losses that are significantly greater than the sum of the losses from the individual hazards" seems a little nonsensical. I understand that the authors are trying to convey the synergistic effects of flooding and landslides, but the effect of combined versus separate action of the hazards needs to be expressed more clearly. Consider 'losses resulting from the combined hazards are significantly greater than the sum of losses from the hazards if acting separately'*"

Response:

We accepted this suggestion and made the corresponding change in the revised manuscript (see page 1, lines 18-20 and page 2, lines 5-7).

3. "*P.1 line 23. It is confusing to refer to this combined modeling system as an "early warning system." A modeling system is part of many early warning systems, but warning systems consist of much more than computer models. Change 'coupled flash flood and landslide disaster early warning system' to 'coupled flash flood and landslide initiation modeling system'*"

Response:

We agree that it's more accurate to denote the system as a "modeling system" rather than a "warming system". We have made the corresponding changes in the revised manuscript (see page 1, line 23 and page 3, line 30).

4. "*P. 2, lines 27 – 32. These two sentences seem somewhat contradictory. The emotional effects of the recent devastating tornado seems to have been more critical in determining public behavior than the source of the warnings. Either rephrase to clarify that different sources of the flash flood and storm forecasts had a lesser role or explain how this contributed to the fact that the public's attention was drawn to the tornado warnings.* "

Response:

We clarified these statements in the revised manuscript and changed them to "*This is partly due to the fact that the storm (accompanied by heavy precipitation and the tornado) and flash flood were forecasted by two separate warning systems and their warnings were issued separately (Uccellini et al., 2014); the public was well aware of the tornado threat but largely unaware of the flood threat in spite of several NWS products and outreach efforts (Uccellini et al., 2014). Moreover, the public's attention was mostly drawn to the tornado warnings (not to the flash flooding threat) mainly because this storm occurred only ten days after the disastrous EF-5 tornado which devastated Moore, OK and resulted in 24 fatalities and $2 billion in property damage*" (see page 2, lines 25-31).

5. "*P. 4, line 12. Is there a reference for the "multi-linear reservoir" concept?* "

Response:
We added the reference, i.e. Wang et al. 2011, in the revised manuscript (see page 4, line 12).

6. "*P. 4, lines 30 – 31. Delete reference to Iverson (2000) in line 31. The 'pressure diffusion solutions for pressure changes below the water table,' though somewhat similar to the pressure-diffusion solution presented by Iverson (2000) for specified flux at the ground surface use different boundary conditions.*"

Response:
We deleted the reference to Iverson (2000).

7. "*P. 6, line 6. Are the parameters a and b in equation 3 determined theoretically or empirically?* "

Response:
Symbol a in Equation 3 is not a parameter but a variable. It denotes the fraction of a grid cell whose water capacity is less than or equal to the mean water capacity of this grid cell. Parameter b is a conceptual parameter and is determined empirically, but it is a relatively insensitive parameter. We added additional explanation on the two symbols in the text (see page 6, lines 15-18).

8. "*P. 8, lines 10 – 20. A few more details are needed regarding modeling assumptions: What assumptions were made regarding soil depth (constant or spatially varying? If so, how?)? Did you check the factor of safety for prestorm initial conditions to confirm that no (or very few) grid cells had a factor of safety less than 1? For the pressure head computations used to compute factor of safety, did TRIGRS and iCRESTRIGRS use the unsaturated infiltration model as described at the bottom of p. 4? If so, why does table 1 not contain columns for the alpha (inverse height of capillary fringe) and residual moisture content values used in computing pressure head?*"

Response:
The soil depth data used in this study were derived from the SSURGO data and vary spatially. We confirm that no grid cells had a factor of safety less than 1 prior the storm

in our simulations. The unsaturated infiltration model was used in TRIGRS and CRESTRIGRS. Because the alpha parameter is a fitting parameter and we don't have its spatial information, we, therefore, treated this parameter a lumped parameter in this study.

9. "*P. 12, lines 6 – 8. A new MPI version of TRIGRS is available that could help with the large area and finer grid assessments suggested here. The citation is Alvioli, M., and Baum, R.L., 2016, Parallelization of the TRIGRS model for rainfall-induced landslides using the message passing interface: Environmental Modelling & Software, Vol. 81, July, p. 122 - 135. doi:10.1016/j.envsoft.2016.04.002* "

Response:
Thanks for providing the reference. We added the discussion and this literature in page 12, lines 30-32.

10. "*Figure 6. Please label key factor of safety values (0.9, 1.0, 1.1) along the ROC curve*."

Response:
We accepted this suggestion and added the labels into the new Figure 6.

11. "*Technical Corrections:P. 2, lines 16 – 17. Change 'damaging infrastructure based on the work of Wooten et al. (2008) and the following geological surveys." to "damaging infrastructure (Wooten et al. 2008; Bauer et al. 2012).'*"

Response:
We made the corresponding changes per the reviewer's suggestion (see page 2, line 13).

12. "P. 2, line 27. Change 'marking' to 'making'"

Response:
We corrected it (page 2, line 24).

13. P. 2, line 28. Change 'largely' to 'partly'

Response:
We accepted the suggestion and made the corresponding change (page 2, line 25).

14. P. 2, line 29. Change '(Uccellini et al., 2014); the public's attention' to '(Uccellini et al., 2014). Moreover, the public's attention'

Response:
We accepted the suggestion and made the corresponding change (page 2, lines 26-27).

15. P. 6, line 21. Change 'model realistically compute' to 'model to realistically compute'

Response:
We accepted the suggestion and made the corresponding change (page 6, line 30).

16. P. 7, line 34. Insert 'dataset' after '(STATSGO)'

Response:
We accepted the suggestion and made the corresponding change (page 8, line 6).

17. P. 8, line 2. Change 'Land Cover Database (NLDC) 2011 land cover database (Homer et al., 2015).' to 'Land Cover Database (NLDC) 2011 (Homer et al., 2015).'

Response:
We accepted the suggestion and made the corresponding change (page 8, line 9).

18. P. 8, lines 4 – 6. Change '15-minute streamflow observations from four USGS streamflow gauges (#03503000 at Little Tennessee River, # 03513000 at Tuckasegee River, # 03460795 at Pigeon River, and # 03453500 at French Broad River) were aggregated to hourly resolution and serve as streamflow validation data for the model.' to 'Streamflow observations from four USGS streamflow gauges (#03503000 at Little Tennessee River, # 03513000 at Tuckasegee River, # 03460795 at Pigeon River, and # 03453500 at French Broad River) were aggregated from 15-minute to hourly resolution and serve as streamflow validation data for the model.'

Response:
We accepted the suggestion and made the corresponding change (page 8, lines 10-12).

19. P. 9, line 11. Insert 'indicator' after 'global statistical accuracy'

Response:
We accepted the suggestion and made the corresponding change (page 9, line 26).

20. P. 9, lines 19 – 20. Change "Apparently, the storm was rapid and intense." to "The storm was rapid and intense."

Response:
We accepted the suggestion and made the corresponding change (page 9, line 34).

21. P. 9, line 29. Change "the land surface's slope is predicted to fail" to "the regolith that covers the sloping ground surface is predicted to fail"

Response:
We accepted the suggestion and made the corresponding change (page 10, line 14).

22. P. 10, line 7. Change "way how infiltration" to "way that infiltration"

Response:
We accepted the suggestion and made the corresponding change (page 10, line 28).

23. P. 11, line 34. Change "It is worth to note that there is still a large room for improving" to "It is worth noting that there is still much room for improving"

Response:
We accepted the suggestion and made the corresponding change (page 12, line 19).

24. P. 13, line 1. Change "and Anders, C. F.:" to "and Anderson, G. F.:'"

Response:
We have corrected it (page 13, line 41).

Response to Anonymous Referee #2:

1. "*I read with interest this research paper which describes a coupled system for prediction of landslide occurrences triggered by intense precipitation. The system is based on the use, in a cascade manner, of the models CREST and TRIGRS. Finally, the authors describe the results of an interesting case study. In the Introduction, the issues of flood and landslide disasters are well described in the context of natural hazards, which characterize the study area. The general objects of the work are clear and well stated, the proposed methodology is of good scientific interest, and also the presentation quality is satisfactory. However, I have some doubts on the efficiency of the created system and I argue the use of the terms 'early warning system' and 'flood'.*"

Response:
We thank the reviewer for his/her positive and constructive comments. We agree with the reviewer that our study is of good scientific interest and have a good quality. In terms of the naming of this system, we agree that the system we developed is a modeling system rather than an early warning system; thus, we have revised the corresponding statements and deleted the "early warning system" term (see page 1, line 23 and page 3, line 30). Regarding the "flood" term used in this study, please see Item 2 of Responses to Anonymous Referee #2 (i.e. the following item).

2. "*I am not sure if using the term 'flood' is here appropriate. If I understood correctly, CREST model predict the discharge at outlet and the spatially distributed surface runoff. I did not see here any flood disaster forecasting analysis (as claimed by the authors), which normally expects identification of floodplains, critical discharges, etc.. Does the model include a propagation module? Also, note that in flash flood events, the evapotraspiration is almost negligible, whereas the spatially distributed component of CREST model mainly derives, if I understood correctly, from the use of LAI and vegetation cover, from which evapotraspiration and interception processes are estimated.*"

Response:
We respectively insist that the 'flood' term used in our modeling system is appropriate. It is widely known in our field that hydrological models, either lumped models or distributed models, are used to simulate streamflow (discharges) at the outlet or any grid cell. These simulated streamflow values can be used to detect the risks and occurrences of floods based on flood frequency analysis of retrospective model simulations. Based on this idea, several well-known global or regional flood forecasting/monitoring systems have been established (please refer to http://www.gdacs.org/flooddetection/, http://flash.ou.edu, http://flood.umd.edu, and http://eos.ou.edu). In addition, the CREST model is able to simulate discharges at any stream cell and surface flow at any grid cell. We didn't represent much flood analysis simply because we didn't run the model long enough to generate enough samples for this type of analysis. The CREST model doesn't have a water-wave propagation module but it does have a routing module. The CREST/iCRESTRIGRS model is able to use LAI to estimate evapotranspiration (ET),

but we directly used the remote-sensing based ET data as input in this study (see page 7, lines 29-31). In terms of evapotranspiration, it is trivial for the simulation of a flash flood event. However, it impacts the long-term water balance, which can impact the accurate simulation of hydrograph in turn.

3. "*Similarly, an early warning system is a more complex system which includes the definition of a 'chain of different communication systems working together and aimed at the detection, analysis and mitigation of potentially hazardous events'. For example, they normally includes a monitoring network for real-time analysis and the definition of thresholds for launching alert/waning signals. I would simply say that the developed system could be potentially used within an early warning system' (P1L23)*"

Response:

We agree that "an early warming system" is more complicated than a modeling system. Like we mentioned in Item #1 of Responses to Anonymous Referee #2, we only called the system as an "early warning system" once in the manuscript. We have revised the statement and corrected the wording in the revised manuscript to make it more accurate.

4. "*Authors state that 'studies on dynamically coupling hydrological processes predicted by distributed hydrological models with soil physics and mechanics determining slope stability are still in a very early stage' (see discussion at P3L16-25). Actually I do not agree with authors analysis. Literature provides many examples of spatial distributed and coupled hydrological-stability models, which have been successfully utilized. Besides the ones cited by the authors (Simoni et al., 2008 and Lanni et al., 2012), authors can refer, for example, to Burton and Bathurts (1998), Claessens et al. (2007), Arnone et al. (2011), Lepore et al. (2013), Tao and Barros (2014) (these last two are also cited and described by Bogard and Greco (2014) as 'good examples' of coupled physically based hydrological and slope stability modeling at catchment scale). Also, you may more deeply discuss the sentence 'due to lack of knowledge of interactions between these processes and differences in the spatiotemporal scales of the flood and landslide events'.*"

Response:

We mean that there is still large room for conducting studies on the coupling of distributed hydrological model with the landslide model for large-scale flood and landslide prediction. Therefore, we revised the statement in the revised manuscript (see page3, lines 21-22). We also cited the most relevant studies listed above by the reviewer (see page 3, lines 19-21).

5. "*If I understood correctly, CREST model does use only precipitation, LAI and vegetation cover as distributed in input variables (as said above). Other model parameters I guess are homogenous across the watershed. How about the soil parameters that influence the infiltration processes, and slope stability, such as porosity, hydraulic conductivity, retention curve parameters? Please specify whether these are distributed or homogeneous.*"

Response:

Most of model parameters for the CREST model in this study are distributed, including the soil parameters that influence the infiltration processes, and slope stability. We determined these parameter values at each grid cell according to its soil class through a look-up table (Table 1). We described how we determined these parameters in Section 2.2.3 (see page 8, lines 21-31).

6. "*There is no mention on how FS is computing and which are the parameters affecting stability. I would like to see the FS equation, explain whether is based on classical Mohr-Coulomb or Bishop failure criterion (for unsaturated conditions) and if it is computed ad a fixed soil thickness of different soil depths. Indeed, FS varies significantly with depths, at given parameters (see other comments below).*"

Response:

We followed the way that TRIGRS computes FS and the depth of slope initiation. FS is calculated as the ratio of resisting basal Coulomb friction to gravitationally induced down-slope basal driving stress (Baum et al. 2010, JGR, doi:10.1029/2009JF001321). FS is calculated for transient pressure heads at multiple depths, Z. Failure is predicted when FS < 1 and stability holds where FS >= 1. Thus, the depth Z where FS first drops below 1 will be the depth of landslide initiation (see Baum et al. 2010, JGR, doi:10.1029/2009JF001321). In the unsaturated zone, a simple approximation for Bishop's (1959) effective stress parameter (χ) is used in computing the factor of safety. To compute the factor of safety above the water table, the matric suction in the FS computation equation is multiplied by χ. More details can be found in Baum et al. 2010, JGR. We added the description of FS computation in the revised manuscript (see page 5, lines 11-17).

7. "*The integration between the two models is not very clear to me. TRIGRS model has its own infiltration module, which is based on an analytical solution of the Richards equation for vertical infiltration. As input, it requires rainfall intensity; based on the hydraulic properties, which vary in space, it computes the infiltration rate and thus the pore-pressure (or soil moisture), which are used to compute the FS. My question is, how this framework interfaces with CREST model? My impression is that the two models are simply used in 'cascade' and therefore they are run separately, to evaluate first the runoff, and then the FS, which use a different infiltration scheme. This is not a really 'coupled model' , as compared to others existing (same references as before, i.e., Burton and Bathurst, 1998, Claessens et al. 2007, Simoni et al., 2008, Arnone et al., 2011, Lepore et al., 2013, Tao and Barros, 2014). The 'initial condition' (P5L9) are updated at each time? These means that, in TRIGS, each time step is 'independent' from the previous. Honestly, I don't see the efficiency of such a system when many other models exists that do the same in a continuous way. Actually, I would directly substitute the TRIGRS infiltration model within CREST and then implement the FS equation as a function of the moisture and water table. (they are both written in fortran language); it is more complex but more efficient and functional.*"

Response:

It is obvious that there is some misunderstanding here. We coupled the CREST model with TRIGRS model through a one-way coupling approach rather than running separately. The CREST model simulates all hydrologic storages and fluxes, and feeds the infiltration and its history and soil moisture condition into the TRIGRS model; the TRIGRS model is then implemented to compute pore-pressure and slope stability correspondingly. The soil moisture condition at the beginning of a storm and the infiltration history during the storm is required for the TRIGRS model. In the iCRESTRIGRS model, this information is recorded automatically at each time. This updating is simple and computationally efficient. In other words, each time step is dependent on the previous time step. The detailed description on the model integration is provided in Section 2.2.3, in particular page5, lines 6-11 and page 6, lines 33-35.

8. "*Are all the input data listed in fig.1 fed to both the models?*"

Response:

No. We have revised Figure 1 to show the accurate data flow in the revised manuscript.

9. "*Working spatial resolution is 90m (P7L18). How this size is compared to the landslide average size? Since you build up a confusion matrix, you need to convert the inventory map into raster structure. Some studies (e.g. Claessens et al., 2005 and Tarolli and Tarboton, 2006) have demonstrated the model performances also depend on the comparison of the landslide size and resolution cell (the impact on model results is mainly caused by the effects of landform parameters, i.e. slope, aspect, curvature). I believe that a description of landslide types and characteristics (size, depths) should be given in Section 2.2.1. Also, It should be reminded somewhere that such models fit well for shallow landslide.*"

Response:

The reviewer is right that model performance also depends on the landslide size and the resolution of grid cells. We accepted the reviewer's suggestion to evaluate the model by accounting for the actual landslide size. Therefore, we requested more survey data, mainly the slope movement outline data, from North Carolina Geological Survey. We re-evaluated the model performance using the movement outline data. In the evaluation procedure, we regard that the model successfully predicts a real landslide if one or more cells that overlap with the slope movement outline of this landslide have a FS value of < 1; the model fails to capture a landslide event if none of these cells overlapping the outline of this landslide is modeled to be unstable (see page 10, lines 17-22). Because majority of the slope movement outlines have a long and narrow shape rather than a circular shape, which was assumed in the previous manuscript, and are distributed along the hill slopes, we achieved better values for all evaluation metrics (see page 10, lines 28-31). We provided additional information on the landslide size in the text (see page 8, lines 14-18). The other information such as landslide types and depths are unfortunately unavailable.

10. "*P6L30. This sentence is misleading. It's true that the 'minimum forcing data' are precipitation and evapotraspiration, but it requires various parameters and input maps. Note that, other models, needs only the precipitation forcing.*"

Response:

We respectively argue that the parameters and input maps are static input data not the forcing data. The "minimum forcing data" for this model indeed just include the precipitation and evapotranspiration. In addition, we don't mean to comment the other models here. We just simply describe the minimum requirement of forcing for this model.

11. "*P7L34. It is not clear to me whether the soil properties are spatialized in CREST. How the soil texture classes are involved in the model?*"

Response:
As we mentioned in Item 5 of Responses to Anonymous Referee #2, the soil properties are distributed and derived from the SSURGO dataset (please refer to Section 2.2.3 and Fig. 2c). We built a look-up table to assign specific parameter values to each soil class (Table 1) based on valued provide in the literature. We then used the soil class of each grid cell to determine the parameter values of the same grid cell.

12. "*P8L14. USDA textural soil classification does not provide the mechanical properties (i.e. friction angle and cohesion). How did you estimated these? FS is obviously extremely sensitive to these parameters?*"

Response:
The friction angle and cohesion values of the USDA textural soil classes were derived as the means of the ranges determined from Das (2008), Hough (1969), Terzaghi et al. (1996) and (Dysli, 2000). The mechanical properties of the USDA textural soil classes are summarized in Table 1.

13. "*P9L27 – Are you able to explain the shift between modeled and observed peak discharges?*"

Response:
There are a couple of possible reasons causing this shift. It could be due to the uncertainty in the routing scheme of this model. It could be caused by the uncertainty in the spatial distribution of rainfall data. We added more discussion on the possible causes in the revised manuscript (see page 10, lines 7-10).

14. "*P9L29 – Which is the depth of failure? Please specify. This is crucial.*"

Response:
Depth of failure calculated by the CRESTRIGRS and TRIGRS models vary spatially and temporally.

15. "*P9L30 – In both Fig.5a and 5b, the second basin from the left (Tuckasegee River basin?) is the one in which landslide are overpredicted. I guess because it's the basin with most the steepest areas. Moreover, I would like to see the corresponding pore-pressure map (TRIGRS and iCRESTRIGRS)*"

Response:

The reviewer is right that landslides in the Tuckasegee River basin are overpredicted are mainly due to the steep slopes in this basin (see Fig. 2b). In terms of the pore-pressure map, we already provided these maps in Fig. 8. We think that it will be redundant to plot them again in Fig. 5.

16. "*P9L35 – radius 500 m means _78.5 ha that means _96 computation grid cells. This means that 'your model success' when 1 over 96 cells success. Again, in such analyses the landslide size should be taken into account.*"

<u>Response:</u>
There is one mistake here. We mean a radius of 250 m (a perimeter of 500m). Anyway, we have redone the evaluation procedure by accounting for the landslide size in the revised manuscript (please refer to Point 9 of Response to Anonymous Referee #2).

17. "*P10L15 – Please, report the corresponding AUC values in the figure.*"

<u>Response:</u>
We added the AUC values in this figure in the revised manuscript (see Fig. 6).

18. "*P12L2 – you could also work on FS equation and mechanical properties (a better soil characterization?). Also, as said before, model performances are very sensitive to the landslide size and characteristics, which here are not taken into account in no way.*"

<u>Response:</u>
We accepted the reviewer's suggestion by changing the statement on P12L2 to "*In addition, better characterization of soil properties, improved model formulation, and more information on fine-scale topography can help improve model accuracy. In particular, slope stability is highly dependent on the slope, which is highly dependent on resolution*" (page 12, lines 22-25). In addition, we re-did the model evaluation using the observed landslide size (see Point 9 of Response to Anonymous Referee #2).

19 "*MINOR P7L30 – it should be Fig.2a. P7L33 – please specify Fig.2c (map of soil) and Fig.2d (land cover map)*"

<u>Response:</u>
Thanks for pointing this out. We have corrected the error and cited Fig. 2c and Fig. 2d in the revised manuscript (see page 8, lines 1-12).

References:
Das, B.: Adanced soil mechanics, Taylor & Francis, London & New York, 2008.

Hough, B.: Basic soil engineering, Ronald Press Company, New York, 1969.

Terzaghi, K., Peck, R., and Mesri, G.: Soil Mechanics in Engineering Practice, Wiley, New York, 1996.

Uccellini LW, Suffern P, Harding K, Brown V, Keeney J, Stammer K, Stefkovich J (2014) Service assessment: May 2013 Oklahoma tornadoes and flash flooding. pp 42, Silver Spring, Maryland, U.S. Department of Commerce, National Oceanic and Atmospheric Administration; National Weather Service.

iCRESTRIGRS: A coupled modeling system for cascading flood-landslide disaster forecasting

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Abstract. Severe storm-triggered floods and landslides are two major natural hazards in the U.S, causing property losses of $6 billion and approximately 110-160 fatalities per year nationwide. Moreover, floods and landslides often occur in a cascading manner, posing significant risk and leading to losses that are significantly greater than the sum of the losses from the hazards if acting separately. It is pertinent to couple hydrological and geotechnical modelling processes toward an integrated flood-landslide cascading disaster modeling system for improved disaster preparedness and hazard management. In this study, we developed the iCRESTRIGRS model, a coupled flash flood and landslide initiation modeling system, by integrating the Coupled Routing and Excess STorage (CREST) model with the physically based Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) landslide model. The iCRESTRIGRS system is evaluated in four river basins in western North Carolina that experienced a large number of floods, landslides and debris flows, triggered by heavy rainfall from Hurricane Ivan during September 16-18, 2004. The modelled hourly hydrographs at four USGS gauge stations show generally good agreement with the observations during the entire storm period. In terms of landslide prediction in this case study, the coupled model has a global accuracy of 98.9% and a true positive rate of 56.4%. More importantly, it shows an improved predictive capability for landslides relative to the stand-alone TRIGRS model. This study highlights the important physical connection between rainfall, hydrological processes and slope stability, and provides a useful prototype model system for operational forecasting of flood and landslide.

Key words: Flood, Landslide, Modeling System, Hazards, Slope Failure, and Infiltration

1. Introduction

Severe flooding and landslides are two major natural hazards in the U.S and world. Flooding causes property losses of $3.7 billion and approximately 110 fatalities per year nationwide (Ashley and Ashley,

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2008), while landslides are responsible for 25–50 deaths and damage exceeding $2 billion annually (Spiker and Gori, 2003). Shallow landslides induced by heavy rainfall have posed significant threats to human lives and property worldwide (Hong et al., 2006;Kirschbaum et al., 2010). Moreover, heavy rainfall, floods and landslides often occur in a cascading manner, where a relatively low-consequence event like heavy rainfall could trigger a severe flood and/or landslide that poses significant risk to an affected community. Losses resulting from the combined hazards may be significantly greater than the sum of the losses from the hazards if acting separately. One example is the intense precipitation in the Colorado Front Range on September 11-12, 2013 that triggered flash floods and at least 1,138 debris flows, resulting in 8 fatalities and more than 20,000 buildings, 485 miles of roads and 50 bridges either damaged or destroyed (Coe et al., 2014). Another example of the devastating impacts of cascading multiple hazards: rain from the remnants of Hurricanes Frances and Ivan triggered 400 reported slope failures of various types in the Blue Ridge Mountains of North Carolina, and at least 33 debris flows and major floods in Macon County, causing 5 deaths, destroying 16 homes, and damaging infrastructure (Wooten et al., 2008;Bauer et al., 2012). Such events make it critical to provide the public with risk-informed forecasting and warning systems in which multi-hazard threats are assessed and quantified.

According to a global natural disaster synthesis report (Dilley et al., 2005), over 790 million people are exposed to more than one natural hazard, based on the past two decades of historical loss data. Concurrent or time-lagged cascading multi-hazards are worldwide phenomena. In spite of their cascading nature, forecasts and warnings and risk assessments for such events conventionally are oriented towards single-hazards, treating the cascading events as independent phenomena (Hsu et al., 2011;Wastl et al., 2011). One example is the severe storm system accompanied by a deadly tornado, heavy rain, and flash flooding that occurred in Oklahoma City (OKC) on 31 May 2013, in which more people were killed unexpectedly by the flash flooding than by the tornado, making it the deadliest flooding event that ever occurred in OKC. This is partly due to the fact that the storm (accompanied by heavy precipitation and the tornado) and flash flood were forecasted by two separate warning systems and their warnings were issued separately (Uccellini et al., 2014); the public was well aware of the tornado threat but largely unaware of the flood threat in spite of several NWS products and outreach efforts (Uccellini et al., 2014). Moreover, the public's attention was mostly drawn to the tornado warnings (not to the flash flooding threat) mainly because this storm occurred only ten days after the disastrous EF-5 tornado which devastated Moore, OK and resulted in 24 fatalities and $2 billion in property damage. Although several recent studies have investigated multi-hazards and multi-hazard risk assessment (Budimir et al., 2014;Gill and Malamud, 2014;May, 2007;Mignan et al., 2014), these multi-hazard studies are still in the early stages of conceptual development (Gill and Malamud, 2014;Kappes et al., 2010). Knowledge gaps and disciplinary barriers in the development of multi-hazard approaches remain formidable. It is essential to understand the cascading effects of multiple natural hazards in an integrated way in order to accurately forecast their occurrence and assess their potential risks and societal impacts.

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Hydrological models have been used for operational flood forecasting since the development of the first watershed hydrological model in 1966 (Crawford and Linsley, 1966). Hydrological models have evolved from lumped-process models (Williams and Hann, 1978;Sugawara et al., 1984) to semi-distributed models (Beven and Kirkby, 1979;Zhao et al., 1980) and fully distributed models (Abbott et al., 1986;Wigmosta et al., 1996;Wang et al., 2011). Several regional to global real-time flood forecasting systems using hydrological models as major tools have been implemented, including the NASA-University of Oklahoma's Ensemble Framework For Flash Flood Forecasting (EF5) (Clark III et al., 2016), Flooded Locations and Simulated Hydrographs Project (FLASH) (Gourley et al., 2014), the European Commission Global Flood Awareness System (Alfieri et al., 2013), and the NASA-University of Maryland Global Flood Monitoring System (Wu et al., 2014), among others. In the last decade, physics-based, rainfall-triggered landslide models (Baum et al., 2010;Godt et al., 2009;Dietrich et al., 1995;Iverson, 2000;Liao et al., 2010;Lu and Godt, 2008;Raia et al., 2014) have been developed to simulate slope stability influenced by topography, geology, and hydrological processes. Some pioneering studies have been conducted to couple hydrological models with landslide or slope stability models to link the hydrological process with soil mechanics. For example, Simoni et al. (2008) combined a distributed hydrological model called GEOtop with a geotechnical model for probabilistic estimation of landslide occurrence. Lanni et al. (2012) utilized a dynamic topographic hydrological model to describe the subsurface processes and linked it with a simple hillslope slope stability model for modeling the initiation of shallow landslides. Arnone et al. (2011), Lepore et al. (2013), Camera et al. (2013), and Tao and Barros (2014) have also conducted similar studies among others. However, there is still a large room for conducting studies on coupling hydrological model with landslide model for large-scale flood and landslide predication (Bogaard and Greco, 2014).

In this study, we present a framework that couples an established distributed hydrological model–Coupled Routing and Excess STorage distributed hydrological model (CREST) (Wang et al., 2011)–with a well-known landslide model–Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) (Baum et al., 2010)–to realize systematic and dynamical simulation of hydrological processes and their effects on slope stability. This integrated, coupled system is designed to serve as a prototype model for potential operational use. The objectives of this study are (1) to develop a coupled flood-landslide forecasting model system that can be forced by satellite- or radar-based Quantitative Precipitation Estimation (QPE) systems or can be easily forced with numerical weather prediction models or other weather models, and (2) to evaluate the performance of this coupled modeling system in forecasting streamflow and slope failures.

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2. Methodology and Data

2.1. Methodology

In this study, we developed an integrated modelling system in which the CREST distributed hydrological model is coupled with the TRIGRS landslide forecasting model (Fig. 1); therefore, the system is called "integrated CREST-TRIGRS" or iCRESTRIGRS. The CREST and TRIGRS models are briefly introduced in the following two sub-sections, while the integration method is described in detail in Section 2.1.3.

2.1.1 CREST model

The CREST model is a grid-based distributed hydrological model developed by the University of Oklahoma (http://hydro.ou.edu) and NASA SERVIR Project Team (www.servir.net). It partitions net precipitation into surface runoff and infiltration using the variable infiltration capacity curve (VIC), a concept originating from the Xinanjiang Model (Zhao, 1992;Zhao et al., 1980) and later represented in the VIC Model (Liang et al., 1996;Liang et al., 1994). Multi-linear reservoir concept (Wang et al., 2011) is used to represent surface and subsurface water storages in the CREST model. It uses a cell-to-cell routing scheme to route overland flow to downslope cells where it is further partitioned to infiltration and overland flow moving downslope using the VIC based runoff generation scheme; in this way, interaction between surface and subsurface water flow processes is accounted for (Wang et al., 2011;Shen et al., 2016). The SCE-UA (shuffled complex evolution method developed at The University of Arizona) optimization scheme (Duan et al., 1992) is implemented to automatically calibrate the distributed model parameters.

The CREST model has been widely used for regional to global studies, including flood inundation mapping over ungauged basins (Khan et al., 2011), statistical and hydrological evaluation of multi-satellite precipitation products (Xue et al., 2013), and detection and prediction of extreme flood events (Zhang et al., 2015b). It has also been implemented in several operational systems, such as the FLASH (Flooded Locations And Simulated Hydrographs) project (http://www.nssl.noaa.gov/projects/flash/) and a near real-time global hydrological simulation and flood monitoring demonstration system (http://eos.ou.edu).

2.2.2 TRIGRS model

The TRIGRS V2.0.06b model computes transient pore-pressure changes and attendant changes in the factor of safety (FS) due to rainfall infiltration using a two-layer system that consists of an unsaturated zone above a saturated zone (Baum et al., 2010). This model links analytical solution for transient, unsaturated, vertical infiltration above the water table (Srivastava and Yeh, 1991) to pressure-diffusion solutions for pressure changes below the water table. The solutions are linked through a transient water table that rises as water accumulates at the base of the unsaturated zone. Pore pressures computed by the models are subsequently used in one-dimensional slope-stability computations to estimate the timing and locations of slope instability (Baum et al., 2010). The TRIGRS model assumes that water can infiltrate with a maximum

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infiltration rate, i.e., the saturated hydraulic conductivity (K_s) at each grid cell. It also has a simple surface runoff routing scheme for water movement from cells that have excess surface water to adjacent downslope cells where it can either infiltrate or flow farther down slope. Detailed description of the TRIGRS model can be found in Baum et al. (2008) and Baum et al. (2010).

2.2.3 Integrated Model System

We integrated the CREST and TRIGRS model through one-way coupling. In this way, the CREST model computes all hydrologic storages and fluxes, including interception by vegetation, infiltration, runoff generation, water routing, and re-infiltration of excess surface runoff from upstream cells to downstream cells, and provides the initial conditions, e.g. soil wetness and depth of water table (Fig. 1). The CREST model feeds infiltration and its history and soil moisture condition into the TRIGRS model; the TRIGRS model is then implemented to compute pore-pressure and slope stability correspondingly. FS in iCRESTRIGRS is calculated in the same way that the TRIGRS model does. FS is calculated as the ratio of resisting basal Coulomb friction to gravitationally induced down-slope basal driving stress (Baum et al., 2010). FS is calculated for transient pressure heads at multiple depths. In the unsaturated zone, a simple approximation for Bishop's effective stress parameter is used in computing FS. To compute FS above the water table, the matric suction in the FS computation equation is multiplied by Bishop's effective stress parameter. Further details can be found in Baum et al. (2010). The coupling between CREST and TRIGRS is seamlessly executed in a distributed fashion at every time step and continuously computes runoff, infiltration, FS, pore-pressure, and other water balance components at each grid cell. As shown in Fig. 1, this integrated system has an open interface that provides a utility to couple this integrated model with any other Numerical Weather Prediction (NWP) model, climate model, or radar/satellite based Quantitative Precipitation Estimation (QPE) system that provides precipitation and other necessary weather data to form an operational real-time forecasting or nowcasting system.

As mentioned above, the original TRIGRS model has its own schemes to estimate infiltration and runoff routing. In TRIGRS, it is assumed that runoff occurs when the precipitation and runoff supplied to a cell exceed its infiltrability. The infiltrability is set to the saturated hydraulic conductivity (K_s) based on previous studies (Iverson, 2000;Hillel, 1982). The infiltration (I) at each cell is computed as the sum of the precipitation (P) plus any runoff from upslope cells (R_u) with the limitation that infiltration cannot exceed K_s (Baum et al., 2010):

$$I = \begin{cases} P + R_u, & P + R_u \le K_s \\ K_s, & P + R_u > K_s \end{cases} \tag{1}$$

At each cell where $P + R_u$ exceeds K_s the excess is considered runoff (R_d) and is diverted to adjacent downslope cells:

$$R_d = \begin{cases} P + R_u - K_s, & P + R_u - K_s > 0 \\ 0, & otherwise \end{cases} \tag{2}$$

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Overland flow between adjacent cells is assumed to occur instantaneously; thus, the rate of overland flow is not considered or computed in TRIGRS. TRIGRS enforces mass balance for each time step but does not carry runoff over from one time step to the next or track water that enters storm drains (Baum et al., 2010;Baum et al., 2008).

Unlike TRIGRS, the CREST model is a distributed hydrological model, which specializes in modeling all major surface hydrological processes. The rainfall-runoff generation processes in CREST start from the canopy interception. After P passes the canopy layer, the excess precipitation that reaches the soil surface is net precipitation (P_{soil}), which is further divided into surface runoff (R) and infiltration (I) according to the variable infiltration curve (VIC), a concept originating from the Xinanjiang Model (Zhao, 1992;Zhao et al., 1980) and later represented in the VIC Model (Liang et al., 1996;Liang et al., 1994). This model assumes that the point infiltration capacity i, which is the maximum water depth that can be stored in the soil column, varies over an area in the following relationship (Wang et al., 2011):

$$i = i_m\left[1-(1-a)^{\frac{1}{b}}\right], \qquad (3)$$

where i_m is the maximum infiltration capacity of a cell and is determined by soil properties; a is the fraction of a grid cell whose water capacity is less than or equal to the mean water capacity of the whole cell; b is an empirical shape parameter. The amount of water available for infiltration can therefore be calculated as follows (Wang et al., 2011):

$$I = \begin{cases} W_m - W, & i + P_{soil} \geq i_m \\ (W_m - W) + W_m \cdot \left[1 - \frac{i+P_{soil}}{i_m}\right]^{1+b}, & i + P_{soil} < i_m \end{cases}, \qquad (4)$$

where W_m and W are the cell's maximum water capacity and total mean water of the three soil layers, respectively. The overland and subsurface flows are further separated from excess rain governed by the saturated soil hydraulic conductivity. Then the cell-to-cell routing of the overland and subsurface runoff is simulated using the multi-linear reservoir method at each time step. CREST couples the runoff-generation process and the routing scheme to better represent the interaction between the surface and subsurface flow in three ways than simply routing surface flow downslope without considering its contribution to infiltration in downslope cells. First, overland runoff from upstream cells is treated as additional precipitation at the appropriate downstream cells available for infiltration and runoff partitioning. Second, soil water can be increased by lateral interflow from upstream cells. Third, channel runoff from upstream cells contributes to the receptor cell's overland reservoir depth. This implemented cell-by-cell runoff routing enables this model to realistically compute the spatially and temporally varying values of runoff, soil moisture and infiltration. It also tracks the water movement through the basin.

In theory, replacing the simple infiltration and runoff routing schemes in TRIGRS with the more sophisticated runoff generation and routing methods in CREST will produce more realistic estimates of infiltration history in areas with nontrivial contribution of overland flow to infiltration. Moreover, the CREST model is able to simulate and provide necessary initial conditions and other inputs for the TRIGRS

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model. The iCRESTRIGRS model is, therefore, able to continuously, seamlessly simulate hydrological processes and solve pore-pressure and factor of safety for each cell at each time step with available forcing data. The minimum forcing data required to run this model are only precipitation and evapotranspiration, making it an easily implementable model.

2.2. Case Study and Data

2.2.1 Study area and Case Study

We chose four adjacent river basins, the Upper Little Tennessee River basin, the Tuckasegee River basin, the Pigeon River basin, and the French Broad River basin, located in western North Carolina (Fig. 2a) as our study area. The drainage area of the four basins ranges between 1,390 km^2 and 4,050 km^2.

Hurricane Ivan, the 10th most intense Atlantic hurricane ever recorded, passed through this region between Sept. 16 and Sept. 19, 2004. It triggered over 110 landslides across the study region, and at least 33 debris flows occurred in Macon County, causing 5 deaths, destroying 16 homes, and damaging infrastructure (Wooten et al., 2008). Hurricane Ivan produced rainfall rates of 150-230 mm/h and precipitation totals from 52 to 351 mm across the study area (National Oceanic and Atmospheric Administration, 2004). The flood and landslide events triggered by the precipitation from Hurricane Ivan across western North Carolina serves as an ideal case study to test the integrated flood-landslide forecast system.

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2.2.2 Input and Validation Data

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Data used in this study include radar-measured rainfall and satellite based estimates of actual evapotranspiration, digital elevation model (DEM), land cover and soil texture maps, observed river streamflow from gauges, and an inventory of landslide events (Bauer et al., 2012). All gridded data were either downscaled or aggregated to a spatial resolution of 3 arc-seconds (3″, i.e., ~90m) to ensure the forcing and auxiliary data match with each other. Bilinear interpolation is the method for spatial downscaling in this study, whereas area-weighted resampling is used for aggregation.

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The precipitation data were from the hourly, 4-km National Stage IV Quantitative Precipitation Estimation (QPE) product based on gauge and radar observations at NCEP (Lin and Mitchell, 2005). The Stage IV data were downscaled to 3″ using bilinear interpolation. The actual evapotranspiration (ET) data were derived from a daily satellite remote sensing based ET record as input for the iCRESTRIGR model and are available at a spatial resolution of 8 km (Zhang et al., 2010;Zhang et al., 2009;Zhang et al., 2015a). The daily, 8 km ET data were first downscaled to a spatial resolution of 3″ using bilinear interpolation and further downscaled to hourly resolution using solar zenith angle as a function of solar declination, latitude, and hour angle of each grid cell.

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The 3″ DEM (Fig. 2a), flow direction, and flow accumulation data were obtained from the USGS HydroSHEDS 3″ geo-referenced data sets (http://hydrosheds.cr.usgs.gov). These data serve as basic data for the distributed iCRESTRIGRS model to establish topological and geomorphological connections among grid cells and derive further topographical information such as slope (Fig. 2b). The map of soil type (Fig. 2c) was from the State Soil Geographic (STATSGO) dataset, distributed by the Natural Resources Conservation Service (NRCS) of the US Department of Agriculture. The soil texture classes were converted to 12 USDA soil texture classes plus rock and organic matter. The land cover/land use map (Fig. 2d) was derived from the 30-m National Land Cover Database (NLDC) 2011 (Homer et al., 2015). Streamflow observations from four USGS streamflow gauges (#03503000 at Little Tennessee River, # 03513000 at Tuckasegee River, # 03460795 at Pigeon River, and # 03453500 at French Broad River) were aggregated from 15-minute to hourly resolution and serve as streamflow validation data for the model.

The locations and slope movement outlines of landslide events during Hurricane Ivan shown in Fig. 2e were identified by the North Carolina Geological Survey through field surveys and other remote-sensing techniques (Wooten et al., 2008;Bauer et al., 2012). The areal extent of individual slope movements ranges from 22 m^2 to 139,000 m^2 with an average size of 6,000 m^2. Majority of these slope movement outlines have a long and narrow shape (Fig. 2e).

2.2.3 Model Parameters and Initialization

As the developed prototype model system is aimed for operational use over a large region, we determined the values of model parameters at each grid cell based on its soil class rather than using very limited local measured values. For this purpose, we built a parameter look-up table based on the USDA textural soil classification. Table 1 summarizes the values of key common parameters used in both TRIGRS and iCRESTRIGRS. The values of all these parameters were roughly estimated as the means of their value ranges determined from the literature. Parameter W_m of the iCRESTRIGRS model was determined from topography using *a priori* estimation method developed by Yao et al. (2012), while parameter b is set to a constant (1.5) across the study region based on our past experience. For the rest of iCRESTRIGRS parameters that are inherited from CREST, we determined their distributed values using the parameter look-up table provided by the CREST user manual (Xue et al., 2015) based on land cover map and soil texture map.

Because all model parameters were determined from soil types *a priori*, we did not conduct model calibration in this study. To minimize the uncertainty in the initial conditions, the iCRESTRIGRS model was spun-up for one year beforehand.

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2.3 Statistical Metrics for Evaluating Model Performance

To evaluate the performance of this integrated model system, we applied a suite of statistical metrics to evaluate the model results. We computed relative bias, Pearson correlation coefficient (CC), and Nash–Sutcliffe Coefficient of Efficiency (NSCE) for the modeled hourly discharge series using the four USGS gauge stations.

To quantitatively measure the predictive capabilities of the models for landslide prediction, we calculated the confusion matrix through comparison between the binary predictions of slope failure and the landslide inventory database. The confusion matrix consists of four possible outcomes (Fawcett, 2006): (1) a modeled landslide is a true one (True Positive, TP), (2) a modeled landslide is a false one (False Positive, FP), (3) an observed landslide is not captured by the model (False Negative, FN), and (4) a grid cell is stable in both model and observation (True Negative, TN). Based on the confusion matrix, a series of indices can be calculated:

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$$TPR = TP/(TP + FN), \quad (5)$$

$$TNR = TN/(TN + FP), \quad (6)$$

and $$Efficiency = (TP + TN)/(TP + TN + FP + FN), \quad (7)$$

where TPR is the True Positive Rate and also called sensitivity, and TNR is the True Negative Rate and also called specificity. The sensitivity statistic measures the percentage of positive cases correctly predicted, while the specificity statistic quantifies the percentage of negative cases correctly predicted (Begueria, 2006;Fawcett, 2006). The Receiver Operating Characteristic (ROC) curve analysis was further applied to evaluate model results for landslide predictions and to compare differences between the TRIGRS and iCRESTRIGRS models. A ROC curve consists of TPR and TNR pairs, which are computed from the respective confusion matrices for different cutoff values. In our case, the cutoff variable is FS. A ROC curve shifted towards the upper-right corner means better model performance. The better the performance of the model the larger is the Area Under the ROC Curve (AUC); therefore, the AUC index serves as a global statistical accuracy indicator for the model.

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3. Results

3.1 Characteristics of Hurricane Ivan Induced Storm

Hurricane Ivan passed through western North Carolina between Sept. 16 and 18, 2004. The storm in this region started around 11 UTC September 16, 2004 and completely ceased around 3 UTC September 18, while the majority of rainfall occurred in the first 24 hours (Fig. 3a). It brought an average rainfall of ~130 mm within 24 hours across the region (Fig. 3a), while accumulated rainfall reached maximum values in the southern parts of the four river basins (Fig. 3b). The storm roughly moved from southwest to northeast (Fig. 3c); differences in peak time of rainfall across this region can be as large as five hours (Fig. 3c). The storm was rapid and intense.

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3.2 Model Evaluation and Comparison

The modeled hourly discharge series between September 16 and 24, 2004 by the iCRESTRIGRS model were compared with the observations at the four USGS gauge stations (Fig. 4a-d). The modeled hydrographs show generally good agreement with the observations. CC is larger than 0.80 at all stations. Relative bias falls within ±34%. The NSCE values at three stations except the one located at French Broad River are larger than or equal to 0.65. The low NSCE value at the French Broad River is largely due to a time shift between modeled and observed peak discharges (Fig. 4d). The delayed peak discharge in the model implies that there is likely some uncertainty in the flow concentration and routing module of the iCRESTRIGRS model. In addition, uncertainty in the spatial distribution of Stage IV rainfall data can also cause some uncertainty in the process of flow concentration. In general, the above results indicate that the iCRESTRIGRS model is generally capable of simulating runoff process well and predicting the flood events.

In the model, whenever the FS value is less than 1.0, the regolith that covers the sloping ground surface is predicted to fail and there is a corresponding landslide. Fig. 5a and Fig. 5b show the maps of minimum FS values during the whole storm period modeled by TRIGRS and iCRESTRIGRS, respectively. In Fig. 5, the reported landslide events are plotted as magenta circles. When we actually evaluated the model performance, we compared the model results with the surveyed slope movement outlines. Therefore, we regard that the model successfully predicts a real landslide if any of the grid cells that overlap with the slope movement outline of this landslide has a FS value of < 1; on the other hand, the model is believed to fail to capture a landslide event if none of these cells overlapping the slope movement outline is simulated to be unstable. The spatial distribution of reported landslides generally corresponds with the spatial patterns of model minimum FS values (Fig. 5a,b). In other words, the actual landslides are mostly located in the areas in which models predict unstable or close to unstable conditions (Fig. 5a,b). A notable difference in the spatial patterns of FS by the two models is that more areas in TRIGRS (Fig. 5a) have unstable slopes than in iCRESTRIGRS (Fig. 5b). This confirms that factor of safety computed by the models is sensitive to hydrological processes, in particular the infiltration process, because the largest difference between TRIGRS and iCRESTRIGRS lies in the way that infiltration and runoff routing are computed. For the TRIGRS model, the TPR, TNR, and accuracy statistics are 59.0%, 97.5%, and 97.7%, respectively, when FS=1 is set as a cutoff value for slope stability. For the iCRESTRIGRS model, the three metrics are 56.4%, 98.8%, and 98.9%. These results indicate that the iCRESTRIGRS model shows generally better results and that coupling the CREST distributed hydrological model with the TRIGRS model leads to an improved model performance at least for this case study.

The ROC analysis demonstrates that the coupled system generally has higher specificity relative to the original TRIGRS model (Fig. 6). The AUC values for the TRIGRS and iCRESTRIGRS models are 0.90 and 0.92, respectively, suggesting that iCRESTRIGRS performs better than TRIGRS in this case study. As

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mentioned above and shown in Fig. 7, the largest difference between the two models lies in the model infiltration values. It is clear that the simple infiltration and rain excess routing schemes implemented in the TRIGRS model leads to higher values of infiltration than in the iCRESTRIGRS model (Fig. 7a). The regional average accumulated infiltration during the Sept. 16-18 storm modeled by TRIGRS is 104.9 mm, while the value modeled by iCRESTRIGRS is just half of it, i.e. 52.2 mm (Fig. 7a). The larger infiltration rate in TRIGRS than in iCRESTRIGRS appears across the whole region (Fig. 7b,c). This explains why the TRIGRS results have generally lower FS values than the iCRESTRIGRS results and why TRIGRS has a higher false positive rate than iCRESTRIGRS (Fig. 5).

3.3 Evolution of Modeled Cascading Flood-Landslide Hazards

We further investigated the evolution of the storm in terms of accumulated rainfall during a 6-hour period and the corresponding responses of hydrological processes (e.g., infiltration and overland runoff), slope stability, and pressure modeled by the iCRESTRIGRS model (Fig. 8). In Fig. 8, the rainfall and infiltration are 6-hour accumulated values, while overland runoff is the average value during each 6-hour period. Factor of safety is the minimum value during each period, while pore-pressure is the value at the depth and at the time corresponding to the lowest FS.

During the first 6-hour period, rainfall intensities are low across the region. The accumulated rainfall is generally less than 10 mm during this period (Fig. 8). In response to this, modeled infiltration rate and its accumulated value are low as well, while simulated overland runoff mainly appears in the main river channels. Very few unstable slopes appear across this region in the model and pore-pressure is generally low. During the second 6-hour period, rainfall rate and modeled infiltration rate increase to some extent, especially in the Little Tennessee River and Tuckasegee River basins. The model results show that overland flow starts to appear in the small tributaries and creeks (Fig. 8). Pore-pressure reaches high values in some areas of the Little Tennessee River and Tuckasegee River basins, resulting in some unstable slopes. These unstable slopes are largely located in the areas with steep slopes. During the third 6-hour period, rainfall reaches maximum and has an accumulated value larger than 30 mm over most of the region. Correspondingly, infiltration rates also reach maximum and overland runoff appears everywhere with rapid rises of stream flow in the drainage network. The number of modeled landslides has increased dramatically accompanied by large increases in pore-pressures. As the storm enters the fourth 6-hour period, rainfall and infiltration intensities decline but still maintain high levels. Pore-pressures in some regions continue to rise, resulting in some new landslides. During the fifth period, rainfall and infiltration intensities reduce greatly. Runoff on the land and in many upstream reaches of these rivers starts to subside. Pore-pressure declines in many areas but remain high in some areas in response to accumulative infiltration processes. The number of modeled landslides during this period also decreases. The detailed analyses of rainfall, and modeled hydrological and geotechnical responses on a phase-by-phase basis show that the model results show reasonable responses to the evolution of the storm in space and time. It also emphasizes the cascading nature of rainfall-triggered floods and shallow landslides.

4. Conclusion and Discussion

This study presents a new, coupled model system, which integrates the CREST distributed hydrological model with the TRIGRS landslide model for flood and landslide forecasting. Driven by the hydrological states and fluxes modeled by CREST, iCRESTRIGRS improves over TRIGRS by the providing more accurate initial conditions such as degree of soil saturation and depth of the water table. Furthermore, CREST specializes in the simulation of hydrological processes and fluxes and can thus provide more realistic hydrological fluxes such as infiltration for TRIGRS, leading to better accuracy for landslide forecasting. The case study demonstrates that the integrated model shows better results than the stand-alone TRIGRS model for landslide forecasting.

The modelling system presented in this study is also developed as a framework and is able to adopt other hydrological models and landslide models as alternatives to compute hydrological processes and soil stability. Therefore, this can be easily expanded to build an ensemble-based system. This coupled modelling system has low requirements for input data as well, making it easy to couple with other numerical weather prediction models and real-time QPE forcings.

It is worth noting that there is still much room for improving the predictive capabilities of iCRESTRIGRS for flood and landslide forecasting. In particular, the true positive rate for landslide forecasting in iCRESTRIGRS in the case study is not high. This can be improved through further parameter optimization and/or implementation of reliable pedotransfer functions. In addition, better characterization of soil properties, improved model formulation, and more information on fine-scale topography likely help improve model accuracy. In particular, slope stability is highly dependent on the steepness of hillslopes, which is highly dependent on model's spatial resolution. In this study, the grid spacing is set to 90-m rather than a finer resolution because we were limited by computational burden; plus, this prototype system is designed from operational use, so it is impractical to run this system with an extremely fine resolution over a large region. However, a nested modeling approach, which executes the hydrological model at a coarser resolution, and allows the landslide model to be executed at finer and coarser resolutions in the landslide prone areas and stable areas, respectively. Introducing parallel computing into the iCRESTRIGRS model using a new MPI (Multiple Point Interface) version of TRIGRS (Alvioli and Baum, 2016) will facilitate the application of the iCRESTRIGRS model at a finer resolution. Additional evaluation of this model in larger regions and under different conditions will better support the predictive capability and robustness of this model.

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Acknowledgement

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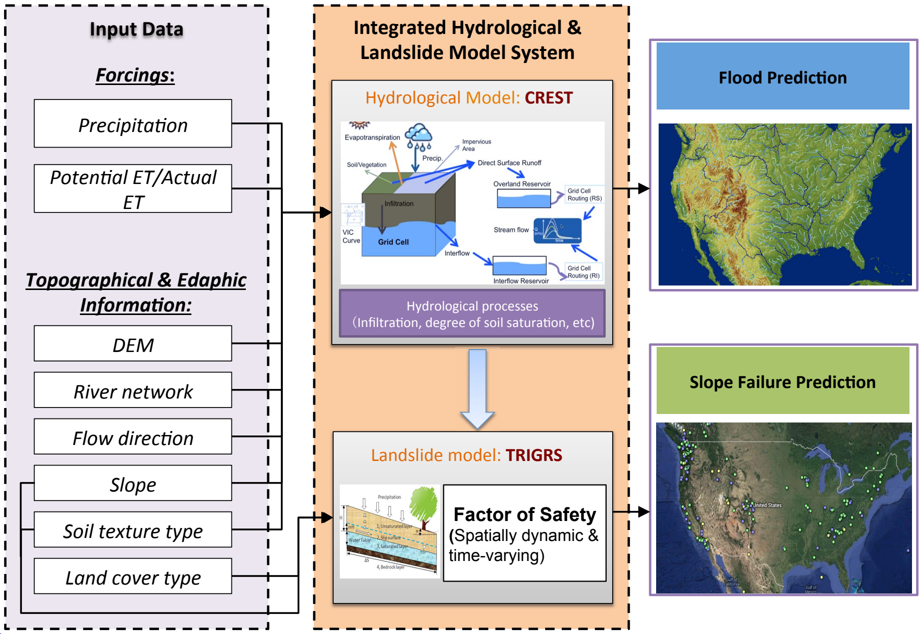

Figure 1. The framework of the proposed integrated CREST and TRIGRS modeling system, which is able to forecast flood and rainfall-triggered landslide events.

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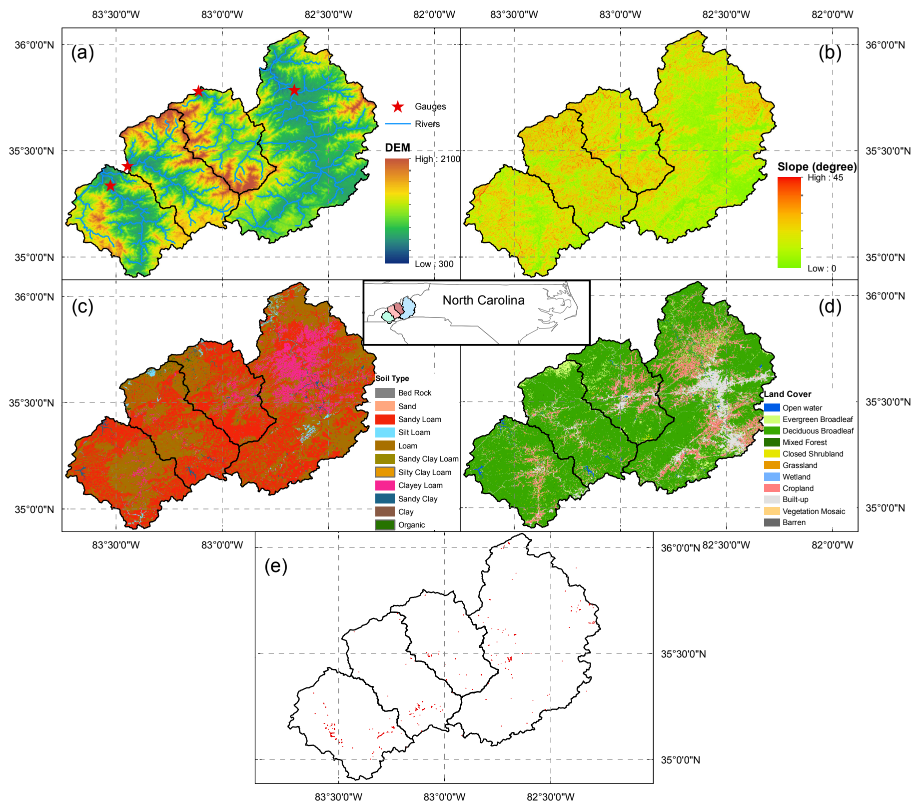

Figure 2. (a) Elevations, (b) slopes, (c) soil types, (d) land cover types, and (e) areal extent of reported individual slope movements during the study period in the study region, which include four river basins, the upper Little Tennessee River basin, Tuckasegee River basin, Pigeon River basin, and French Broad River Basin (from left to right); the inset shows the locations of the four basins within North Carolina.

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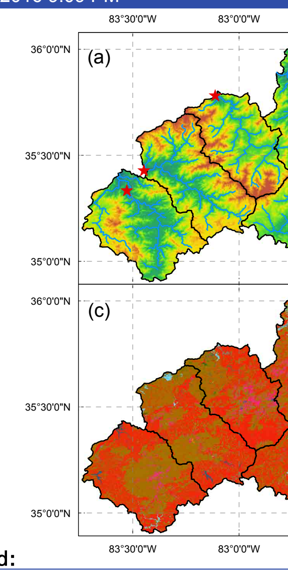

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Figure 3. (a) Accumulated and hourly regional-average rainfalls during the Sept. 16-18 storm period in the study region, (b) spatial pattern of accumulated rainfall during the storm period, and (c) spatial pattern of rain peak times since Sept. 16, 11 UTC.

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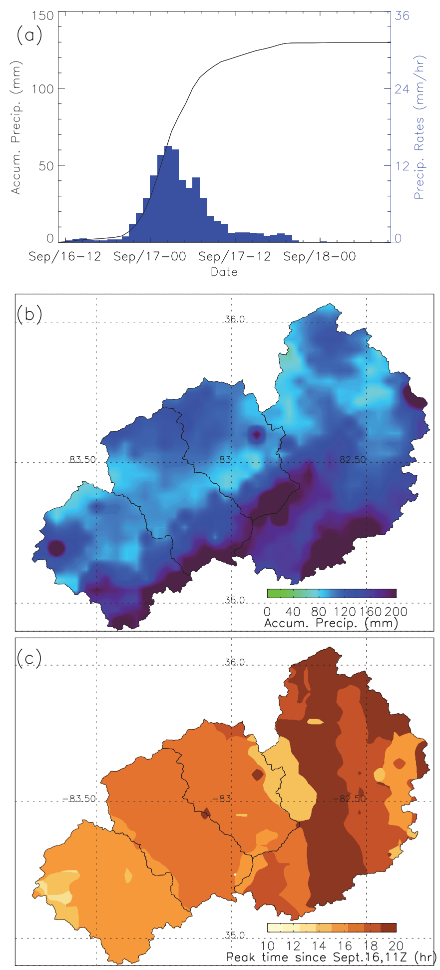

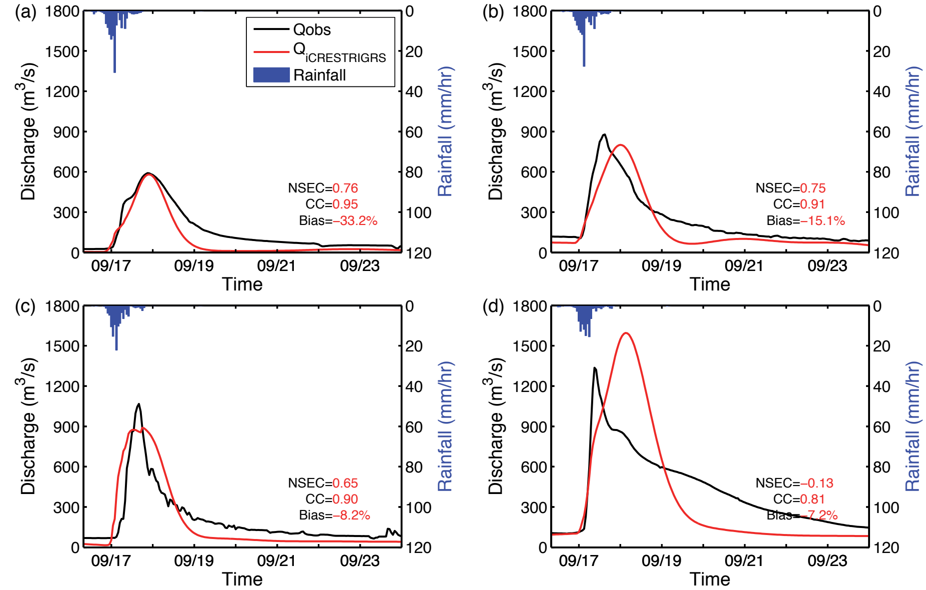

Figure 4. Observed and modeled hydrographs and basin-average rainfall rates at (a) the upper Little Tennessee River basin, (b) Tuckasegee River basin, (c) Pigeon River basin, and (d) French Broad River basin.

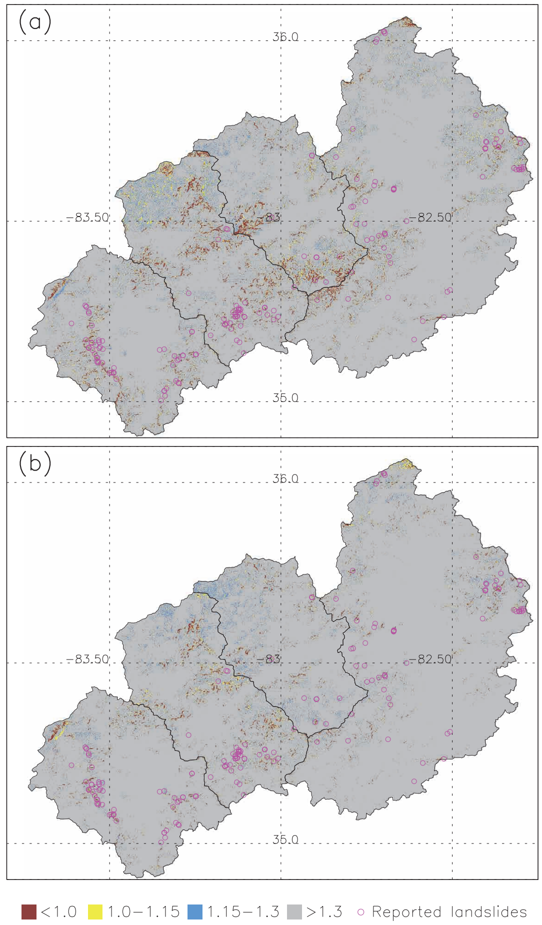

Figure 5. Comparisons (a) between TRIGRS modeled FS and reported landslide events, and (b) between iCRESTRIGRS modeled FS and reported landslide events.

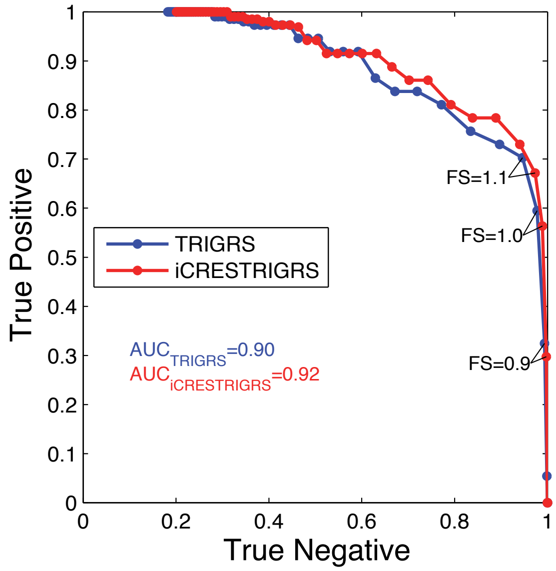

Figure 6. Receiver operator characteristic (ROC) graph comparing slope stability results from the TRIGRS and iCRESTRIGRS models.

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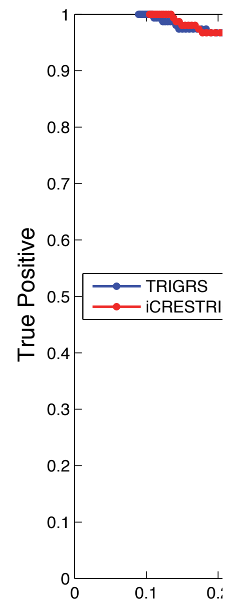

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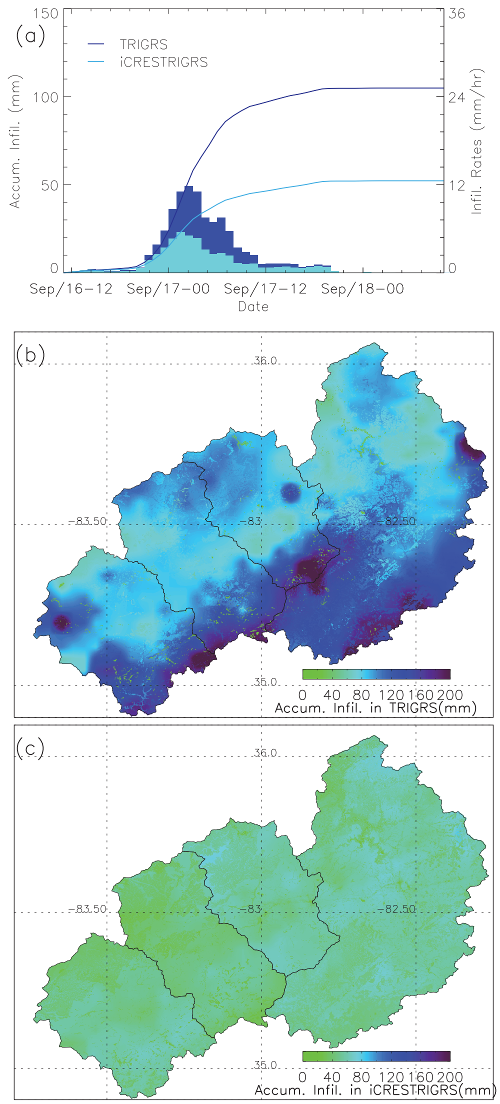

Figure 7. (a) Accumulated and hourly infiltration values from the TRIGRS and iCRESTRIGRS models, and spatial patterns of accumulated infiltrations from the (b) TRIGRS and (c) iCRESTRIGRS models.

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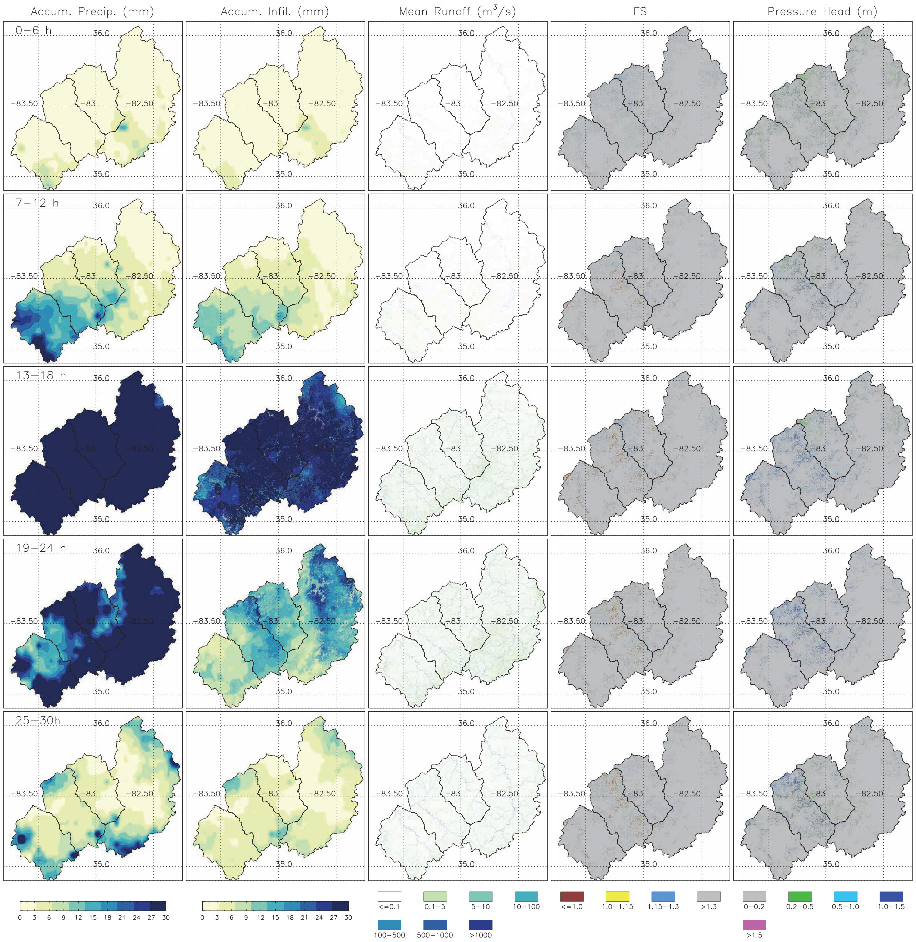

Figure 8. Maps showing the evolution of storm (rainfall), hydrological responses such as infiltration and runoff, slope stability, and pressure head at the depth corresponding to the lowest factor of safety.

Table 1. Summary of key parameter values used in both TRIGRS and iCRESTRIGRS in this study.

USDA Soil Texture Type	Soil Cohesion[1] (kPa)	Porosity[1]	Saturated Hydraulic Conductivity[2] (m/s)	Friction Angle[1] (degree)	Soil Dry Unit Weight[1] (kN/m^3)
Sand	5.0	0.43	2.44×10^{-5}	40.0	21.0
Loamy sand	7.5	0.42	1.78×10^{-5}	28.5	20.5
Sandy loam	6.0	0.40	1.02×10^{-5}	32.0	15.0
Silt loam	9.0	0.46	2.50×10^{-6}	24.0	14.0
Loam	10.0	0.43	4.53×10^{-6}	22.5	13.0
Sandy clay loam	29.0	0.39	6.59×10^{-6}	20.0	15.0
Silty clay loam	50.0	0.48	1.44×10^{-6}	16.5	14.0
Clayey loam	35.0	0.46	2.72×10^{-6}	20.0	14.0
Sandy clay	24.5	0.41	4.31×10^{-6}	22.5	18.5
Silty clay	30.0	0.49	1.06×10^{-6}	18.5	18.0
Clay	40.0	0.47	1.31×10^{-6}	16.5	19.5
Silt	9.0	0.52	2.05×10^{-6}	26.5	16.5

[1.] Values were roughly set to the means of the ranges determined from Das (2008), Hough (1969), Terzaghi et al. (1996) and (Dysli, 2000);

[2.] Values were estimated by the pedotransfer equations of Cosby et al. (1984) using the mean sand and clay fractions of each soil class.

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