Author response to reviews: Development and testing of a large, transportable rainfall simulator for plot-scale runoff and soil parameter estimation

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The following pages are the responses to the anonymous reviews. These documents detail the significant changes made to the manuscript. In summary:

1. The introduction has been improved to include how this rainfall simulator will help improve the lack of repeated measurements at any given site.
2. The angle of the TDR probes has been justified.
3. More information has been added about the design choices for the tipping bucket flow gage.
4. Section 5 has been rewritten, not for content but for clarity in the logic and representation of the equations.
5. Section 2 has been expanded to include more detail about the components of the rainfall simulator.
6. A new section, 2.3 Simulator logistics, has been added to describe the practical deployment and operation of the rainfall simulator.
7. The overall cost of the rainfall simulator has been included.
8. The role of vegetation has been referenced with regard to future work.

RESPONSE TO COMMENTS FROM ANONYMOUS REFEREE #1

TIFFANY G. WILSON

Thank you very much for your comments. The typos you found will be corrected and your other comments will be addressed here. The format is first your quoted comment or question followed by the response or change to be made in the manuscript.

"Page 4269, lines 12-14: perhaps consider emphasizing the lack of repeated measurements of soil hydraulic properties over time and how your work will help to overcome this issue."

(1) On page 4269, replace the text starting with "Therefore" on line 12 through the end of the paragraph with "Specifically, there is currently a lack of studies that estimate soil hydraulic properties at multiple locations in a watershed and at multiple points in time. Indeed, such measurements are needed to improve the runoff response accuracy of watershed hydrologic models. In practice, this requires a large rainfall simulator that is capable of producing high rainfall intensities and can easily be transported between field sites for multiple measurements in space and time."

(2) On page 4272, add the following sentence to the end of the paragraph ending on line 15: "Overall, this device will improve the ability of researchers to make more soil hydraulic property measurements over space and time that accurately assess plot-scale runoff response."

"Page 4274: why were the soil moisture probes inserted at an angle? - also why was 0-15 cm depth range selected to measure soil moisture?"

> Replace the sentence starting on line 23 of page 4273 with the following: "Time domain reflectometry probes (Campbell Scientific CS616) were used to measure soil moisture. Due to the presence of large rocks in the soil below 20 cm and the desire to take measurements in a regular grid and over a uniform depth, the probes were inserted at approximately a 30° angle from horizontal to measure the top 15 cm of the soil."

"Would eroding soil in runoff water harm the tipping-bucket mechanism or result in errors in measured amount of water runoff?"

> Add the following to the end of the paragraph ending on line 9 of page 4274: "At the current field site, the amount of sediment was considered

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to be negligible compared to the mass of water. Additionally, no sediment appeared to collect in the buckets. In applications with higher erosion rates, a screen could be placed above the flow gate to filter sediment from the runoff."

"Page 4278: line 4: Did the value of K potentially change between 2008-2010?"

Given the premise of this work, it is certainly possible that the hydraulic conductivity at the time of the experiments was different than the 2008 estimate. However, this is the only measurement of K_s at this site other than the estimates made with the rainfall simulator, and neither land use nor overall vegetation cover at the site have changed during this time. We also recognize that the original point estimate is likely to be different from the the plot-scale effective estimate calculated here. That being said, the previous point estimate simply serves as an order-of-magnitude reference. Future work will address the effects of K_s varying in time.

“Page 4280: the meaning of condensed ponding time is unclear. Page 4280, line 15: what is the meaning of the prameters it, Kt, and theta? Page 4281: what is the meaning of T in equation 14? Page 4282: in equation 21 maybe consider using a different letter than Q for cumulative runoff as it is used to represent infiltration on page 4279”

These concerns are addressed with a revision of this section. First, Eq. (3) is revised to be

$$i_t^* = \frac{1}{2} S_t t^{-1/2} + A_t, \tag{3}$$

where i^* $[\mathrm{L\,T^{-1}}]$ is the infiltration rate at time t under ponded conditions...

Then, starting with Eq. (7) on page 4279, the remainder of Section 5 is revised as follows:

$$K_{t,bulk} = K_{s,bulk} \left(\frac{\theta_t}{\theta_s} \right)^{2b+3} \tag{7}$$

where $K_{\mathrm{s,bulk}}$ $[\mathrm{L\,T^{-1}}]$ is the saturated hydraulic conductivity of the bulk soil rather than the soil surface.

The calculation of soil moisture comes from a one-dimensional water balance on a soil layer with thickness $\mathrm{d}z$, beginning with $\Delta S = V_{\mathrm{in}} - V_{\mathrm{out}}$, where S is the water storage in the layer, V_{in} is the water entering the layer, and V_{out} is the water exiting the layer. S can be represented as $\theta \Delta z$, so $\Delta S = \Delta z(\theta_t - \theta_{t-\Delta t})$. V_{in} is the water infiltrating from above, so during a small time step Δt, $V_{\mathrm{in}} = i\Delta t$. Neglecting evapotranspiration, V_{out} is the drainage of water through the bottom of the layer. Use of Darcy's Law,

$v = -K\frac{\mathrm{d}h}{\mathrm{d}z}$, with a unit gradient yields $V_{\mathrm{out}} = K\Delta t$. Therefore, the soil moisture prediction equation is

$$\frac{\theta_t - \theta_{t-\Delta t}}{\Delta t} z = i_t - K_{t,\mathrm{bulk}}, \text{ or}$$

$$\theta_t = \theta_{t-\Delta t} + (i_t - K_{t,\mathrm{bulk}})\frac{\Delta t}{z} \tag{8}$$

where z [L] is the soil depth being considered and i_t [L T^{-1}] is the actual infiltration rate, defined by

$$i_t = \min(i_t^*, p). \tag{9}$$

See Table 3 for the parameters used in this analysis.

Infiltration is modeled using the above equations with a time step of $\Delta t = 1$ min. First, A and S are calculated according to Eqs. (6) and (4). Then, i_t^* and i_t are calculated using Eqs. (3) and (9). The current bulk soil hydraulic conductivity is calculated with Eq. (7), and then the bulk soil moisture θ_t is calculated using Eq. (8).

Since Eq. (3) is defined under ponded conditions, a correction must be made to the time used in the infiltration calculations to account for the time before ponding actually begins. Dingman (2004) accomplishes this using a condensed ponding time (t_{cp}), which acts to delay the start of runoff in the Philip model. Without it, modeled runoff begins much before observed runoff. Following Dingman's approach, t_s is defined as the first time in the original calculations when $p > i_t^*$. The total potential volume that can infiltrate before t_s is

$$I_p = \sum_{t=0}^{t_{\mathrm{s}}} i_t^*, \tag{10}$$

and since $p < i^*$ in this time period, the time it takes for the volume I_p to infiltrate is

$$t_{\mathrm{p}} = \frac{I_p}{p}. \tag{11}$$

The condensed ponding time is

$$t_{\mathrm{cp}} = t_{\mathrm{p}} - t_{\mathrm{s}}, \tag{12}$$

which can be thought of as a correction for when runoff will actually begin compared to when it would start under ponded conditions.

Then, the above calculations for i_t, $K_{t,\mathrm{bulk}}$, and θ_t are repeated using $\hat{t} = t - t_{cp}$ in place of t, generating the values $i_{\hat{t}}$, $K_{\hat{t},\mathrm{bulk}}$, and $\theta_{\hat{t}}$ that now account for the ponding correction. Finally, the modeled runoff is calculated as

$$q_{\hat{t}} = \max(p - i_{\hat{t}}, 0). \tag{13}$$

Equations (3), (4), and (6) show that the infiltration of water through the surface, and accordingly the runoff, depend strongly on $K_{\text{s, surf}}$ but not on $K_{\text{s, bulk}}$. Likewise, Eqs. (8) and (7) show that $K_{\text{s, bulk}}$ affects θ_t but not i_t. Therefore, for a period of total duration T and cumulative runoff Q,

$$e_{Q_{\mathrm{T}}} = |Q_{\text{T, mod}} - Q_{\text{T, obs}}| \tag{14}$$

and

$$e_\theta = \left(\frac{\sum_{t=0}^{T} (\theta_{t,\text{mod}} - \theta_{t,\text{obs}})^2}{T} \right)^{1/2} \tag{15}$$

can be used as measures of error that, when minimized, indicate the optimal values of $K_{\text{s, surf}}$ and $K_{\text{s, bulk}}$, respectively. $e_{Q_{\mathrm{T}}}$ uses the final Q value to capture the overall behavior of the plot in producing runoff, and e_θ uses the time series of θ to capture the evolution of soil moisture during the experiment.

To optimize $K_{\text{s, surf}}$ and $K_{\text{s, bulk}}$, the infiltration model was run using all combinations of the two values ranging from 1 to 30 $\mathrm{mm\,h^{-1}}$ at a step of $\Delta K = 10^{-7}\ \mathrm{m\,s^{-1}} = 0.36\ \mathrm{mm\,h^{-1}}$. $e_{Q_{\mathrm{T}}}$ and e_θ were calculated for each combination, and the combination with the smallest value of

$$e^* = e_{Q_{\mathrm{T}}} + e_\theta \tag{16}$$

was selected for the optimal values of $K_{\text{s, surf}}$ and $K_{\text{s,bulk}}$.

Again, thank you very much for your comments, particularly in regards to Section 5. We hope you find that the responses are adequate and improve the manuscript.

RESPONSE TO COMMENTS FROM ANONYMOUS REFEREE #2

TIFFANY G. WILSON

Thank you very much for your comments. Here are our responses to your individual concerns.

"The paper needs to discuss in more detail the specifics of the rainfall simulator design and costs in section 2.1."

> We recognize that some readers may desire additional information on the components of the rainfall simulator. We will incorporate the overall cost of the rainfall simulator into the paper and elaborate on the system components. However, many aspects of the simulator such as the nozzle line supports, structural frame, collection system, and runoff flow meter, do not need to be of a particular design or manufacturer. Furthermore, there is just as much emphasis on the parameter estimation method in the paper as there is on the rainfall simulator itself; including far more details on the customizable aspects of the rainfall simulator itself appear to the authors to be too much for one paper and unnecessary. We will instead explicitly state in the paper which components of the rainfall simulator are open to design changes. The overall cost of the rainfall simulator is less than 1,000 USD.
>
> The following will replace the current section 2.1, which addresses several of your comments:
>
> The rainfall simulator consists of several parts: nozzle lines, nozzle supports, structural frame, and water delivery system. The four independently-operated nozzle lines have either 11 or 12 nozzle assemblies (46 total) connected with 1.5 cm inner diameter PVC pipe and compression fittings. Each nozzle assembly, as shown in Fig. 1a, consists of a 0.5 mm opening pressure washing nozzle, threaded hex connector, and threaded hose barb. The barbed ends of the hose barbs were wrapped in teflon tape and gently hammered into a short length of PVC pipe, which was then attached to the compression tees on the main line as shown in Fig. 1b. The centers of the nozzles are 33.3 cm apart; the lengths of pipe between the nozzles were cut to attain this length and will vary based on the pipe fittings used in other applications. Each line is a total of 4.2 m long with a plugged length of pipe at one end and a 0 - 600 mbar pressure gage and elbow at the other end

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that connects to the water delivery system. The nozzle lines are configured as shown in Fig. 5 [figure location will be moved], with two sets of nozzles that face each other at a distance of 2.3 m apart.

The nozzle assemblies are supported by L-shaped pieces of metal mounted to stiff metal rods as shown in Fig. 1b. The nozzles point upwards at alternating angles of 48 and 54 degrees from horizontal; the drops then fall from a height of approximately 3 m. Shorter lengths of the stiff rod support 15 cm bolts that are used to set and maintain the angle. Plastic zip ties hold the nozzles in place on top of the bolts during the experiments. Other than the spacing and angles of the nozzles, other aspects of the support system may be adapted to suit the needs and available materials of other researchers.

The structural frame, shown in schematic in Fig. 2, consists of six 2 m vertical beams, three 4 m horizontal beams to which the nozzles are mounted, and two 4 m horizontal beams to complete the frame. The present frame uses 6 cm metal tubing and clamp connectors since it was readily available, but other materials may be used; Schedule 40 PVC is a good inexpensive alternative. Additionally, a plastic mesh attached to these final two beams helped randomize the spray pattern (Foster et al., 2000). The mesh was a heavy gauge 4 mm grid mesh that was doubled along the edges to prevent ripping and attached to the frame using plastic mesh clips and zip ties to prevent sagging.

The water delivery system conveys water from the 2 m^3 tank to the nozzle lines. A submersible pump with a filter, powered by a gasoline generator, pumps water out of the tank via flexible hose. Three tees are used to split the single line into four, and each of these four lines contains a butterfly valve near the pressure gages so the pressure can be adjusted if necessary.

The overall cost of the rainfall simulator in 2010 was less than 1,000 USD. This cost includes the simulator components above and the instrumentation discussed below. The dimensions and operating parameters should be matched to what is discussed here, but other components may be changed to suit the needs of other researchers.

"Why was 2 m selected for the height of the simulator?"

The nozzle height is 2 m to make the parts of the simulator easier to see and access. However, as noted in Section 2.1, the nozzle are pointed upwards, so the actual fall height of the drops is slightly higher. A full drop size and velocity analysis was conducted and is documented in Corona (2013), which is referenced in the original manuscript.

"Number of hours required to build the simulator"

> This particular simulator was constructed over the course of several months through an extensive trial and error process. It is therefore very difficult to estimate an overall construction time.

"Number of hours required to construct onsite and number of hours and staff required to disassemble and move to next plot"

> To address this and other concerns regarding the operation of the rainfall simulator, a new section 2.3 will be added as follows:
>
> **2.3 Simulator logistics**
>
> The components of the rainfall simulator can fit on a small truck with a flat bed approximately 3 to 4 meters long. Once on site, it takes four people approximately 90 minutes to set up the rainfall simulator. Ideally, the water tank will be located close to the plot to reduce the pressure required of the submersible pump, so the tank should be able to be filled on site. If the simulator is to be moved to a nearby plot, it can be picked up by four people and walked to the new location instead of disassembled and reassembled, leaving only the soil moisture sensors, plot border, and collection system to be re-installed.
>
> Operation of the rainfall simulator can be accomplished with a staff of three to four people. Once the simulator and other components are installed, the generator is started and the pump is turned on. The simulator is run for a short time to prime the system, adjust the butterfly vales so each pressure gage reads 100 mbar (8 $\times 10^3$ Pa), and verify that the data logger is working. Then, the starting value of the in-line flow meter and start time are recorded as the system pump is turned back on. During operation, it is useful to have one person monitoring the pressure in the nozzle lines, another monitoring the tipping bucket, and a third person observing the plot to record when and where ponding occurs and to make sure water is draining properly. To turn off the system after the desired experiment time, the pump is turned off and the butterfly valves are closed. The data logger is allowed to continue recording until runoff stops.

"Why is the rainfall simulator set inside the plot walls?"

> The rainfall simulator is set inside the plot walls in order to be able to balance the measured water delivered to the plot and the calculated water delivered.

"Why the development of a large scale tipping bucket device to measure runoff?"

> The tipping bucket device was developed as a way to measure the runoff using the materials that were already on hand in the lab. This caveat

> will be added to the manuscript. The details are included in the paper for completeness, but in reality any other researchers may use whatever device they choose to measure the runoff. Concerning the chatter in the record, since experiments are not performed unattended and are not very long, it is easy to manually check the runoff record for any extra tips that may be present. Furthermore, the parameter estimation method uses the cumulative runoff and continuous soil moisture to optimize the values of the saturated hydraulic conductivity, so high temporal accuracy in the runoff record are not critical to the analysis.

"Did the authors consider installing an in-line water filtration system to prevent clogging of the nozzles during rainfall simulation? If not why not?"

> The submersible pump had a filter that prevented clogging. This detail has been added to the Section 2.1 rewrite as shown above.

Requests for pictures

> Details describing the water supply and screen have been added to Section 2.1 as shown above. The authors feel that photos of these items are not necessary, as other investigators may do whatever works best for their application as long as the stated operational criteria are met.

Again, thank you very much for your comments, particularly in regards to Section 2. We hope you find that the responses are adequate and improve the manuscript.

RESPONSE TO COMMENTS FROM ANONYMOUS REFEREE #3

TIFFANY G. WILSON

Thank you very much for your comments. Here are our responses to your individual concerns.

"However the low cost of the installation in terms of materials and time has to be better proven."

> The overall cost of the rainfall simulator was less than $1000. This cost, in addition to further details on the components of the rainfall simulator, have been included in a re-write of Section 2.1. Referee #2 also brought up this concern; please see the response to those comments for the new content of this section.

"The role of the vegetation coverage is not clearly explained...this can affect the results"

> The authors agree that vegetation has an impact on the infiltration results. In fact, the choice of a vegetated plot was intentional, as future work with this rainfall simulator is to assess the effect of vegetation on the infiltration parameter estimates. This effect was not investigated in the present work since the goal was simply to establish the rainfall simulator and the parameter estimation method. This acknowledgement of will be added to section 4.1 describing the field site.

"Some information about the root zone of these plants should also [be] provided"

> The root zone of the grasses is approximately 15 cm. This detail will be added to the section describing the TDR probes.

"Please justify the 30° angle of the CS616."

> The TDR probes were inserted at this angle to avoid the rocks present below the depth of 15 cm. Referee #1 brought up this concern; please see the response to that comment for the addition to Section 2.2.

Again, thank you very much for your comments. We hope you find that the responses are adequate and improve the manuscript.

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