A Model Agnostic Approach for Variable Basin Contributing Areas

Abstract

A good abstract will begin with a short description of the problem being addressed, briefly describe the new data or analyses, then briefly states the main conclusion(s) and how they are supported and uncertainties.

Introduction

The Prairie Pothole Region (PPR) of western North America, including the Canadian Prairies, is a characterized by its unusual topgraphy. The location of the region is mapped in Figure 1. This region is recently (~10,000 years B.P.) post-glacial (Christiansen 1979), and remarkably flat as a result. The climate of the region ranges from semi-arid to sub-humid. Therefore, there has not been sufficient time, energy or water to carve conventional dendritic drainage networks in many locations.

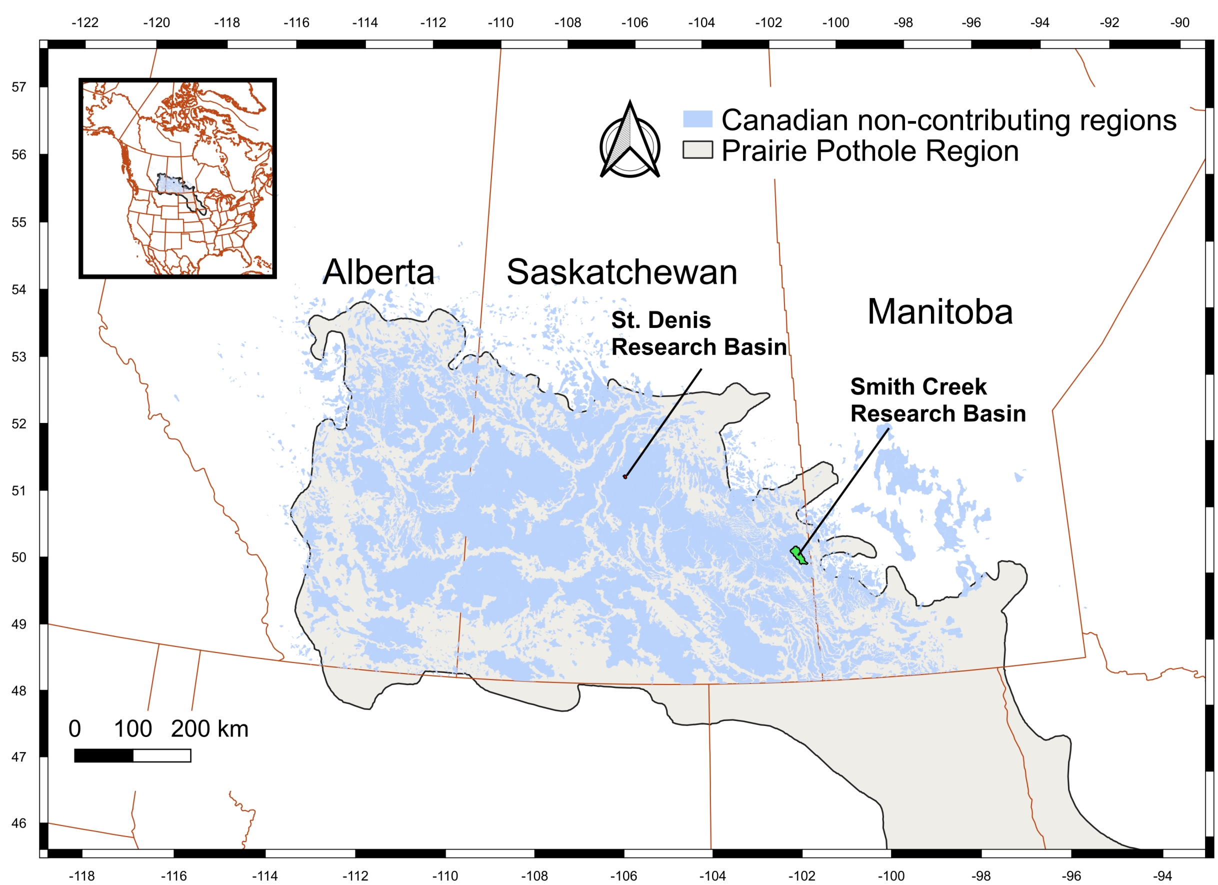

Figure 1: Canadian Prairie ecozone (in black), non-effective regions (in blue), St. Denis Basins and Smith Creek Research Basin. Projection is UTM 13.

Instead, much of the region is covered with depressions (known locally as "potholes" or "sloughs") which can intercept runoff. In many parts of the region, the surface is underlain with thick deposits of glacial till (Christiansen 1979), which is largely impermeable.

Unusually, the fractions of many basins in the PPR which are able to contribute flows to the outlet are dynamic, and change with the state of storage of water within each basin (Stichling and Blackwell 1957). When a depression is filled with water, any further addition of water, though direct precipitation, or intercepted surface runoff, will cause overland flows, through the process known as "fill and spill," which was first denoted for lakes in the Canadian Boreal Shield (Spence and Woo 2003). Where there is a filled path to a drainage channel, overland flows may contribute flow to the basin outlet.

Figure 1 plots in blue the regions which are denoted as being "non-effective," i.e. which contribute flow to a stream channel less than one year in two.

Modelling connected/contributing fractions

The variable connected (having a path to the outlet) and contributing (having water flowing to the outlet) fractions of prairie basins are challenging to model, and are not able to be simulated by the vast majority of hydrological models. Several methods have been developed, which have been used by models specific to this region. However, all of the existing models of the variable connected/contributing fractions of prairie basins have significant disadvantages that have limited their successful incorporation in hydrological models.

Parametric model

The model PDMROF was developed ....

PDMROF contributing fraction vs. fractional volume for varying values of b

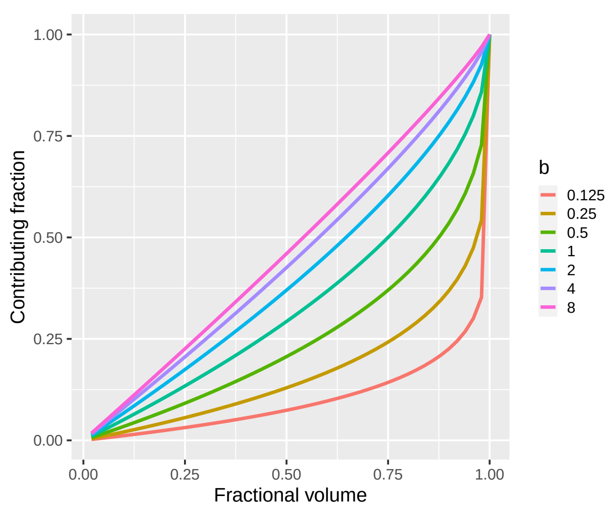

Figure 2: PDMROF contributing fraction vs. fractional volume for varying values of b

Discrete depression models

The Pothole Cascade Model (PCM) models the storage of water in discrete storages. The PCM uses the scaling relationships between the depression water depth (h), and area (A_w) as defined by Hayashi and van der Kamp (2000) in Eq. 1:

$$A_w = sh^{2/p}, (1)$$

where s and p are constants.

The relationships between the area of the a given depression (A_d), and the area of its carchment (the region draining directly to the depression) (A_c) have been shown to be well represented by power functions for depressions (including lakes) in the Canadian Prairies (K. Shook et al. 2013),as shown in Eq. 2:

$$A_c = aA_d^b, (2)$$

where a and b are constants.

Because b < 1, the catchments of large depressions are relatively smaller than those of small depressions.

These relationships are also incorporated

The PCM has been incorporated in CRHM (Cold Region Hydrologicalm Modelling platform) models of the Canadian Prairies, where it contributed to improved modelling of Prairie basins (John W. Pomeroy et al. 2014).

DEM-based models

Several hydraulic models redistribute direct precipitation and runoff over a Digital Elevation Model (DEM) of a basin, including WDPM (K. Shook et al. 2021), PRIMA (Ahmed et al. 2021) and FlowFill (Callaghan and Wickert 2019). Although the algorithms used by the models differ, all of the models are iterative and are too computationally expensive to be used successfully as components of hydrological models. However, these models are very useful for modelling the spatial distribution of water on prairie landscapes, and can be used to validate the model results against remote sensing Armstrong et al. (2013). These models can also be used for developing simpler, more conceptual models which are less conceptually expensive.

DEM-based models require high resolution data (LiDAR) which is does not exist in many regions in the Canadian Prairies. Where DEM data is available, it may require a great deal of pre-processing to be useful, including burning in culverts and bridges.

Need for a new type of model

As discussed above, the DEM-based models are too computationally expensive to be incorporated in hydrological models. However, all of the existing model types have severe disadvantages which restrict their utilities.

The Canadian Prairies have experienced historical and ongoing drainage of the surface depressions in many locations (Dumanski, Pomeroy, and Westbrook 2015). It is very necessary for models to be able to simulate the effects of drainage, or addition of storage. Parametric models, such as PDMROF cannot easily do this, because their parameters are calibrated, and are specified at basin scales. DEM-based models, such as WDPM, can incorporate changes in storage, but this requires modification to the basin DEM, which can be very difficult and time consuming. Changing the storage in individual depressions, as used by PCM, is much more feasible.

However, PCM cannot simulate the aggregation and disaggregation of water bodies as depressions fill and empty. Adding many depressions to a model increases its complexity, as well as the execution time. In practice, models are unable to simulate the many thousands of depressions present in a real basin. John W. Pomeroy et al. (2014) solved this problem by using a small set of depressions to statistically represent all the depressions within a basin, and upscaling the calculated stream discharge, accordingly. Although this method did work, K. Shook, Papalexiou, and Pomeroy (2021) demonstrated that the quality of the simulation is adversely affected by using small numbers of simulated depressions.

One of the most important findings of K. Shook, Papalexiou, and Pomeroy (2021), was that the relationship between the connected/contributing fraction of a depression-dominated prairie basin, and the fraction of depressional storage is hysteretic. The hysteresis was shown to arise from two causes:

1. The frequency distribution of water ponded areas is non-reversible, changing differently when water is added to and removed from surface storage. This is related to the differing areas affected by evaporation (the area of a given pond) and runoff (the basin of a given pond). Therefore the shape of the rising limb will depend on the initial state of storage of water.
2. Because evaporation affects all ponds very similarly, the water levels of all the ponds in a basin will be reduced to below their sill elevation (the elevation at which spilling can occur) simultaneously with the onset of evaporation. Thus the connected/contributing fraction of a basin will drop to zero with the advent of evaporation.

The WDPM and PCM were demonstrated to display very similar hysteretic relationships between water storage and connected/contributing fractions. Because it uses a single-valued function, PDMROF cannot produce hysteresis in these relationships.

Other important findings of K. Shook, Papalexiou, and Pomeroy (2021) related to the phenomenon of gatekeeping, whereby large depressions prevent the regions upstream from contrinuting flows downstream untill they are filled. The term was coined for lakes in the Canadian Boreal shield (Phillips, Spence, and Pomeroy 2011), but also applies to depressions in the Prairies.

Through many Monte-Carlo simulations, K. Shook, Papalexiou, and Pomeroy (2021) demonstrated that where the area of the largest depression was only a small fraction ($< 2\%$) of the total depressional area, the gatekeeping of the largest depression is negligible. However, when the largest depression is larger, its location within the basin is important, as it gatekeeps the fraction of the basin upstream.

Research objectives

The overall objective of this research is to develop and test a new method for simulating the variable connected/contributing fractions of Prairie basins. The method is to have the following characteristics

1. It must be generic, able to estimate the connected/contributing fraction for any Prairie basin.
2. It must be able to simulate the hysteretic relationship between the connected fraction and the storage of water in a basin.
3. It must be able to be parameterized from GIS/remote sensing, without use of any form of calibration.
4. It must have a reasonably small number of parameters and state variables.
5. It must be able to easily simulate changes in depressional storage.
6. It must be able to execute quickly.

Materials and Methods

HGDM

The Hysteretic Gatekeeping Depression Model (HGDM) has been developed to meet all of the above requirements. The development of the model was suggested in K. Shook, Papalexiou, and Pomeroy (2021), which found that the behaviour of depressional storage in Prairie basins could be divided into two categories, which can be modelled separately.

Small depressions are hysteretic, because of their very large number of unobserved states (i.e. water storages), which are generally combined together to create basin scale states (water storage and connected/contributing fraction). However, the gatekeeping of the small depressions can be ignored, due to their small sizes, relatively large basins, and many connective pathways.

Large depressions (those having areas greater than 2% of the total depressional area) may have strong gatekeeping effects on the connected/contributing fraction, depending on their location within the basin. If a large depression is located near the top of the basin, it may never fill, due to the small upstream potentially contributing area. On the other hand, a large basin located near the outlet will gatekeep the entire basin, but may fill because it traps all of the basin surface runoff. Because the largest depression(s) is/are modelled individually, their properties are never hyseteretic.

The HGDM basin conceptual model is illustrated by the schematic diagram in Figure 3. The basin is divided into regions above and below the large depression. The regions shaded in gray are controlled by the storage in the small depressions. The regions in white have no depressions and drain either to the large depression, or directly to the outlet.

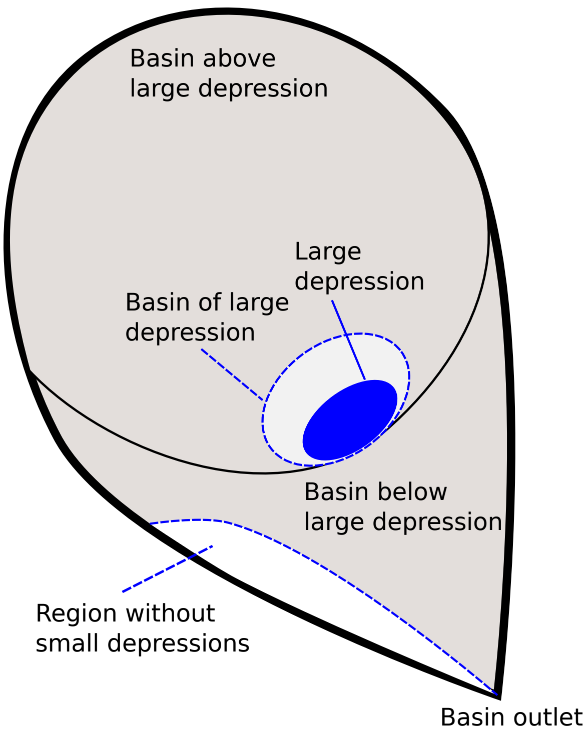

Figure 3: Schematic diagram of HGDM basin. Gray areas are dominated by small depressions, white areas have no small depressions.

It is assumed that the properties of the regions with and without the small depressions are each identical in the fractions of the basin above and below the large depression. The resulting water flows among the landscape units are as shown by the flow diagram in Figure 4.

Runoff is generated from uplands in all regions of the basins. Some fractions of the upland runoff will flow directly to the outlet and to the large depression. The remainder will flow to the small depressions. Depending on the state of storage in the small depressions, some of the runoff will remain in the small depressions, and some will exit, to be routed to the large depression and/or the outlet, depending on the location of the large depression. The large depression gatekeeps its inflows until it is filled; any further inflows will then be routed to the outlet.

HGDM linear hysteresis model

The model for the hysteresis between the fractional water storage and the connected/contributing fraction is based on the work of K. Shook, Papalexiou, and Pomeroy (2021), who demonstrated that the hysteresis loops produced by WDPM and PCM could be reproduced by sets of randomly generated depressions with the appropriate frequency distribution, and scaling relationships.

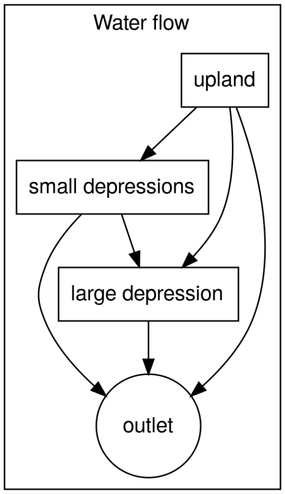

Figure 4: Diagram of flows among HGDM landscape units.

Figure 5 plots the connected fraction computed from 10,000 realizations of 1,000 depressions simulated from the relationships described in K. Shook, Papalexiou, and Pomeroy (2021). In each realization, the depressions were filled from their initial state, by repeated additions of water. In each addition, the water was applied evenly to the depression, and its basin, assuming a runoff coefficient of 1. With each addition of water, the connected fraction was computed based on the assumption of no gatekeeping - each depression is assumed to be connected directly to a stream channel. The curves in Figure 5a represent filling the simulated depressions from their being empty. The curves in Figure 5b were generated by filling all of the depressions, and remving 100 mm from each. This results in all of the ponds having surface elevations being below theier basins' outlets, which causes the connected fraction of the basin to be zero. Of course, all depressions with maximum depths smaller than 100 mm will have their water depth reduced to zero. Following the water removal, the simulated depressions were then filled iteratively as before. The process was repeated for removals of 200 mm and 300 mm, as plotted in Figure 5c and d.

Although there is some considerable scatter among the curves, the median curves are slightly sigmoidal, approximating lines. Very similar results were found by K. R. Shook and Pomeroy (2011) for applications and removals of water at Smith Creek Research basin using the WDPM.

It is important to note that K. Shook, Papalexiou, and Pomeroy (2021) demonstrated that the degree of scatter among realizations of this type is a function of the number of depressions being simulated. Only 1,000 depressions are used here; [] found over 2000 depressions with areas greater than 25 m^2 in a Prairie basin of only 11 km^2. Therefore, in a large basin, the degree of scatter, and therefore the degree of uncertainty in the filling trajectories, is reduced.

The median filling curves plotted in are quite linear, which is the genesis of the HGDM linear hysteresis model. The model is demonstrated by the diagram plotted in Figure 6, which demonstrates the changes in the state of the model as water is subtracted and added. Point a defines the initial state of the system. As water is removed from the system, the connected/contributing fraction immediately drops to zero, as all depressions are no-longer filled to their sill elevations, leading to point b. As more water is removed, the connected/contributing fraction remains at zero, while the fractional water volume decreases, causing the system state to move to point c. At this point, water is added to the system. The connected/contributing fraction, and the fractional water volume increase, in a trajectory toward (1,1). Because the fractional water volume and the connected fraction are inter-related, calculation of the location of point d will likely be solved iteratively.

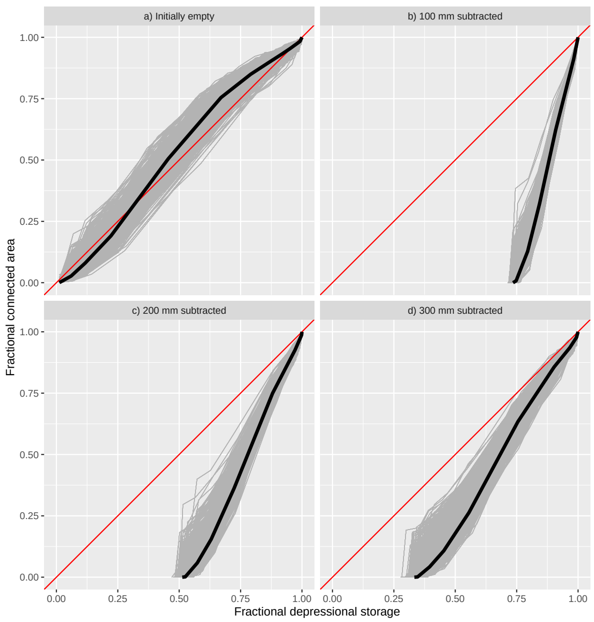

Figure 5: Connected/contributing fractions vs. fractional volume for 10,000 realizations of 1,000 depressions. The realizations are plotted in gray, the median of all realizations is plotted as the heavy black line. A 1:1 line is plotted in red.

HGDM water area fraction model

The existing physically-based hydrological models used for the Canadian Prairies, MESH and CRHM, are based on GRUs and HRUs, respectively. Incorporation of the parametic hystersis model would result in a single HRU/GRU being used to represent the water storage. Unfortunately, neither model currently simulates the relationship between the volume of water stored in a GRU/HRU and its area, which is important for calculating the actual evaporation. K. R. Shook and Pomeroy (2011) showed that the relationship between the fractional water-covered area and the fractional water storage is slightly hysteretic.

Figure 7 plots the fractional water cover (fraction of the maximum possible water-covered area) vs. the fractional depressional storage for simulated filling and emptying of a Prairie basin. The blue line plots the median of the filling curves from an initially-empty basin, the red line plots the median of the emptying curves, using the 10,000 realizations of 1,000 depressions discussed above. The green line plots the result that would be expected for a single depression using the relationship of Hayashi and van der Kamp (2000), with an exponent of 3.33. The purple line plots the same relationship using an exponent of 1.72. The two values were used by John W. Pomeroy et al. (2014) for depressions greater than or equal to and smaller than 10,000 m^2, respectively. The same values were used for all of the realizations.

The median filling curve lies midway between the single depression curves, for values of the fractional depressional storage smaller than about 0.5, becoming tangent to the p = 3.33 curve. As the depressions fill roughly in their size order (also affected by their basin areas), the small ponds are filled first, so the mdeian water area filling curve will come to resemble that of the large depressions. When the depressions are emptied, the ponds in small depressions are progressively elimiated. Thus the emptying curve lies below even the curve of the single depressions with exponent values of 1.72.

The original graphs of K. R. Shook and Pomeroy (2011) were derived from WDPM simulations at SCRB, and showed a greater degree of hysteresis than that of Figure 7, probably because of the actual values of the scaling exponents being more variable than the values used here. Nevertheless, as the degree of hysteresis is small, it is probably simplest to use the relation for a single depression, with a relatively small value of the scaling exponent, to represent the water area within a basin. The alternative of developing a set of hysteretic water area curves is left as an exercise for the reader.

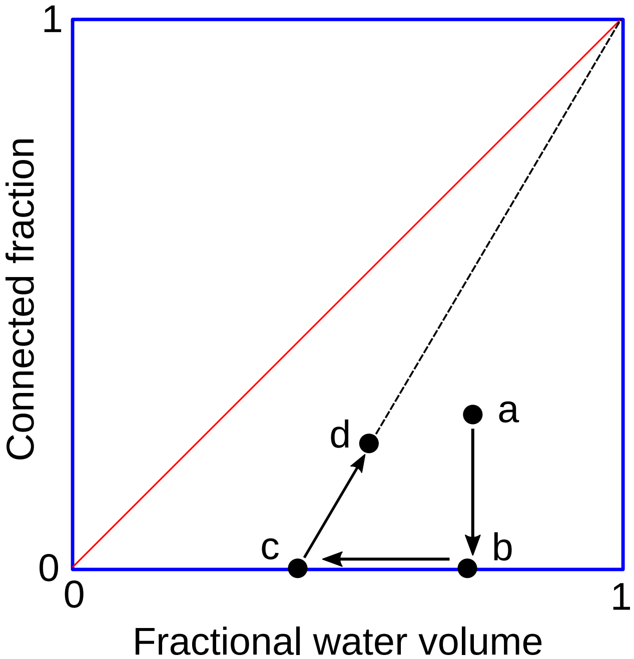

Figure 6: Operation of the parametric hysteresis model of the states of Prairie basins. The original state is shown at point a. Points b through d show the effects of removing, then adding water. All states exist below the 1:1 line plotted in red.

Hydrological models

CRHM

The Cold Regions Hydrological Modelling platform (CRHM) is a physically-based semi-distributed model developed for modelling the processes of cold regions, including the Canadian Prairies (J. W. Pomeroy et al. 2007).

CRHM uses hydrological response units (HRUs) to represent sub-basin heterogeneity. HRUs are used to represent the storage in individual large depressions and in the sets of small depressions. Because of the flexibility of CRHM, there can be any number of these HRUs, and they can be arranged in any manner.

One of CRHM's most unusual features is a built-in macro language. HGDM was implemented as a macro which intercepts the inflows to the small-depression HRU, and diverts a fraction of the value to the downstream HRU depending on the current contributing fraction. After each addition or removal of water from the small depressions, the connected/contributing fraction is re-computed. As CRHM does not allow are of the ponded water in a HRU to change with its depth, it was not necessary to implment the calculation of the water area as described above.

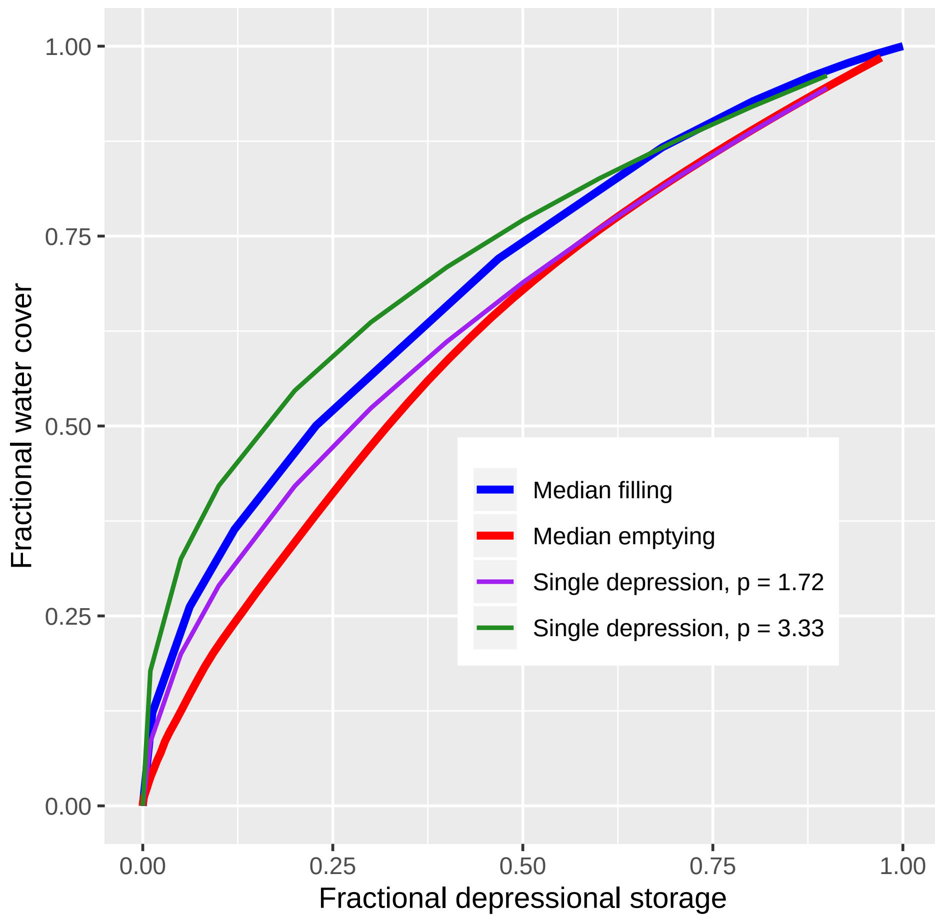

Figure 7: Fraction water cover vs. fractional volume for 10,000 realizations of 1,000 depressions. The median rising limb is plotted in blue, the median falling limb is plotted in red. Curves for a single depression, based on the Hayashi-van der Kamp equations are plotted in green, for p = 3.33, and purple for p = 1.72

Data

Results

Conclusions

Acknowledgments

The acknowledgments must list: A statement that indicates to the reader where the data supporting the conclusions can be obtained (for example, in the references, tables, supporting information, and other databases).

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AGU does not normally allow dedications.

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