

WDPM: the Wetland DEM Ponding Model

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Summary

The hydrography of the Canadian Prairies and adjacent northern US Great Plains is unusual in that the landscape is flat and recently formed due to the effects of pleistocene glaciation and a semi-arid climate since holocene deglaciation. Therefore, there has not been sufficient energy, time, or runoff water to carve typical dendritic surface water drainage networks in many locations. In these regions, runoff is often detented and sometimes stored by the millions of depressions (known locally as “potholes” or “sloughs”) that cover the landscape. Conventional hydrological models are unable to simulate the spatial distribution of ponded water in prairie basins dominated by depressional storage. When the depressions are filled, the detented water may overflow to another depression, through a process known as “fill and spill” ([Spence & Woo, 2003](#)). Therefore, the fraction of a depression-dominated prairie basin that contributes flow to the outlet changes dynamically with the state of water storage within the basin. This situation is difficult to simulate with conventional hydrological models.

Program description

The WDPM was developed to solve the problems described above. The model distributes simulated water over a digital elevation model (DEM), which is an array of land surface elevations. The program has three modules:

- **add**, which adds specified depth of water to the DEM. Addition of water can be caused by rainfall, but in the Canadian Prairies, it is dominantly due to the melt of snow trapped in depressions and from runoff from adjacent areas ([Hayashi et al., 1998](#)).
- **subtract**, which subtracts a specified depth of water from the DEM. Subtraction of water may be caused by infiltration to the soils, but in the Canadian Prairies, it is dominantly due to evaporation ([Hayashi et al., 1998](#)).
- **drain**, which drains water from the lowest point in the DEM.

WDPM does not attempt to compute the magnitudes of the additive or subtractive fluxes, which must be established by measurement or through the use of a physically based model of prairie hydrology such as the Cold Regions Hydrological Modelling platform (CRHM) ([Pomeroy et al., 2007](#)).

The model output is the depth of water over each cell of the DEM. WDPM is not a hydraulic model; it is a model of the state of the distribution of water in a landscape after the fluxes have been redistributed. FLUXOS-OVERFLOW is a 2-D hydrodynamic model capable of modelling overland flow rates in the prairies ([Costa et al., 2020](#)), but it is much slower than WDPM, and it requires more parameters and more forcing data.

All WDPM modules use the algorithm of [Shapiro & Westervelt \(1992\)](#) to redistribute the simulated water. This algorithm is iterative. In each iteration, the excess water, which is the

41 depth of water required to be removed to make the surface flat, is computed for each DEM
42 cell. As shown in Figure 1, water can be distributed to a lower cell or to a higher cell with
43 insufficient water. In each iteration, up to one-eighth of available water can be distributed to
44 any of the neighbouring cells. The algorithm is repeated until the water surface is flat, which
45 is determined by the maximum difference between successive values of the matrix every 1000
46 iterations. When the maximum cell difference is within a specified tolerance or the volume of
47 water draining in 1000 iterations is smaller than a specified value, then the program terminates
48 and the water depth is written to an ArcGIS .asc (ASCII) file.

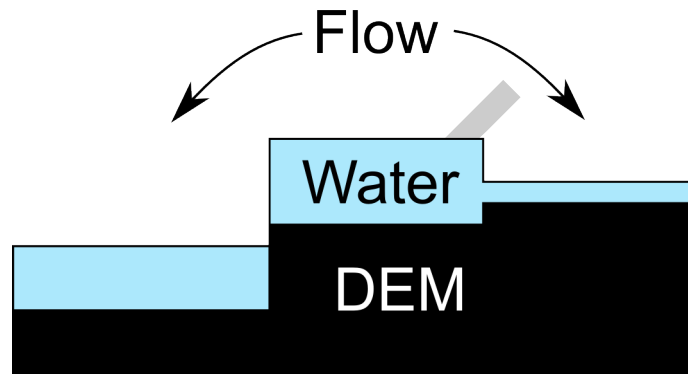


Figure 1: Schematic diagram of water flow from a DEM cell using WDPM.

49 The original version of WDPM was written by in Fortran (Shook & Pomeroy, 2011) and
50 parallelized using OpenMP. Because the program was so slow to run (taking hours or days
51 to converge to a solution), the code was refactored. The program was converted to C,
52 and an optional python GUI was added. Because the program is typically run by end-users
53 on desktop computers, it was decided to use OpenCL to parallelise the code because this
54 framework permits the use of CPUs and GPUs. Using OpenCL, the matrix was subdivided
55 as shown in Figure 2, where each colour represents a separate thread. Because the matrix
56 locations of each thread are separated by 3 rows and columns, the points are independent, and
57 race conditions are avoided. The refactoring of the WDPM was successful in greatly reducing
58 execution time.

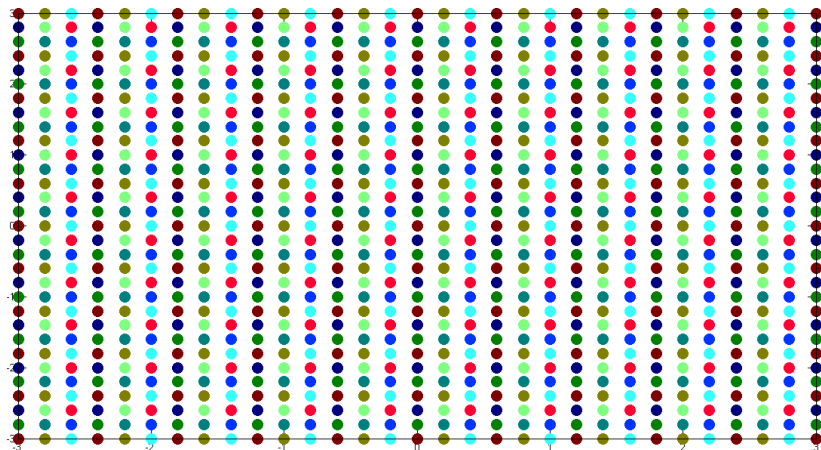


Figure 2: Schematic diagram of WDPM matrix subdivision for OpenCL. Each colour represents a separate thread.

59 Examples

60 The WDPM is distributed with a sample DEM data set, which represents a small ($\sim 10 \text{ km}^2$)
61 sub-basin in southeastern Saskatchewan. The sub-basin (Smith Creek sub-basin 5) is described
62 fully in [Shook et al. \(2013\)](#). The sample DEM measures 471×483 elements with a horizontal
63 resolution of 10 m and a vertical precision of less than 1 mm.

64 In the first step, 300 mm of water was added, using the **add** module, distributed evenly over
65 the basin. All of the water was allowed to run off the uplands, accumulating in the depressions.
66 Prior to the addition of water, the basin was empty. [Figure 3](#) shows the extent of water (depths
67 greater than 1 mm) resulting from the WDPM simulation. The accumulation of water in the
68 depressions is clearly visible. Because the edge of the DEM acts like a dam, water in the
69 stream channel is unable to leave the basin, causing it to back up. This unrealistic behaviour
70 was the reason for the development of the **drain** module.

71 When the **drain** module was applied, the water in the stream channel was able to drain from
72 the lowest point in basin, located at the basin outlet at the mouth of the stream. As shown
73 in [Figure 4](#), the resulting distribution of water is a more realistic representation of the state
74 of the basin after the cessation of runoff.

75 Following the addition and draining of water, 200 mm of water was removed using the **subtract**
76 module. As shown in [Figure 5](#), the ponds are reduced in size, and many of the smaller ones
77 have disappeared.

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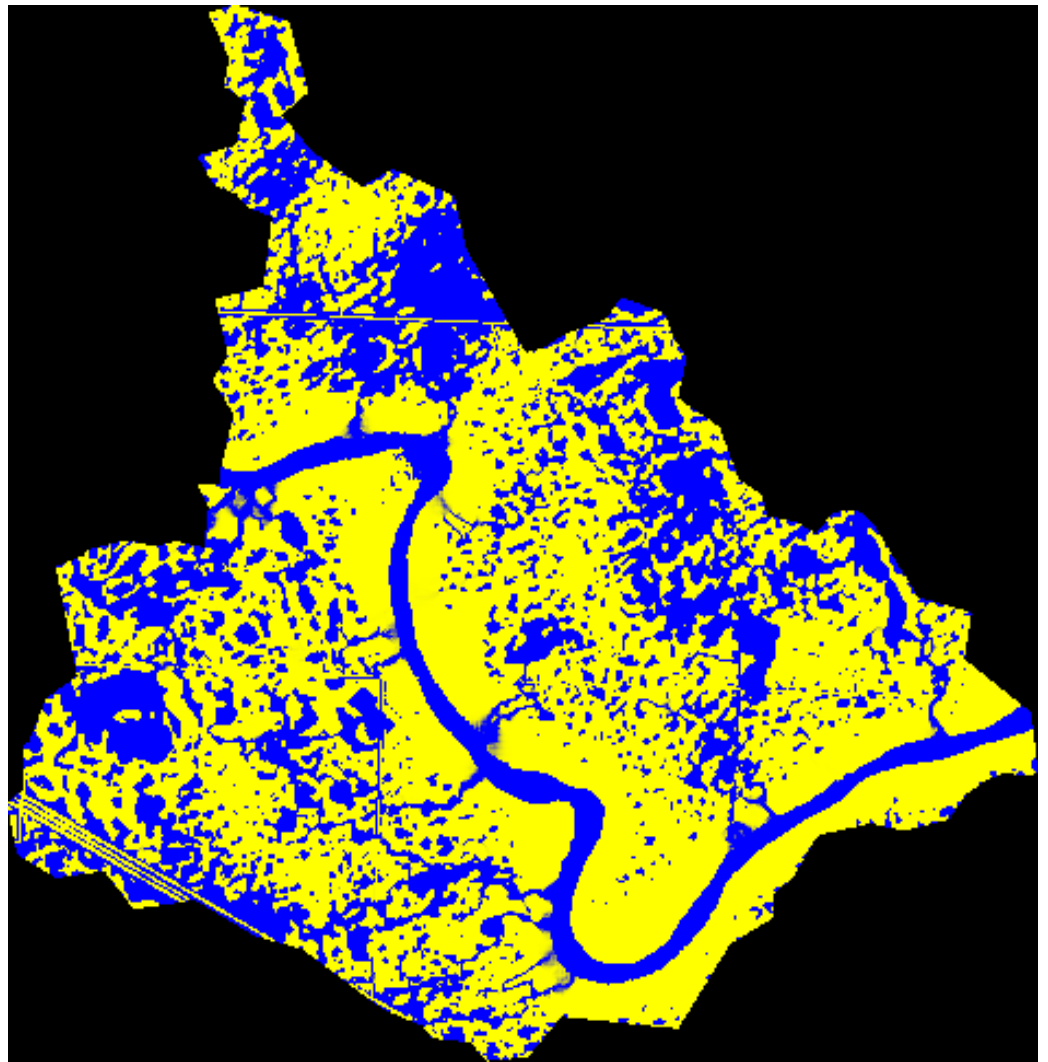


Figure 3: Plot of WDPM simulation of water (blue) and dry ground (yellow) for addition of 300 mm of water. The region outside the basin is shown in black. Smith Creek sub-basin 5.

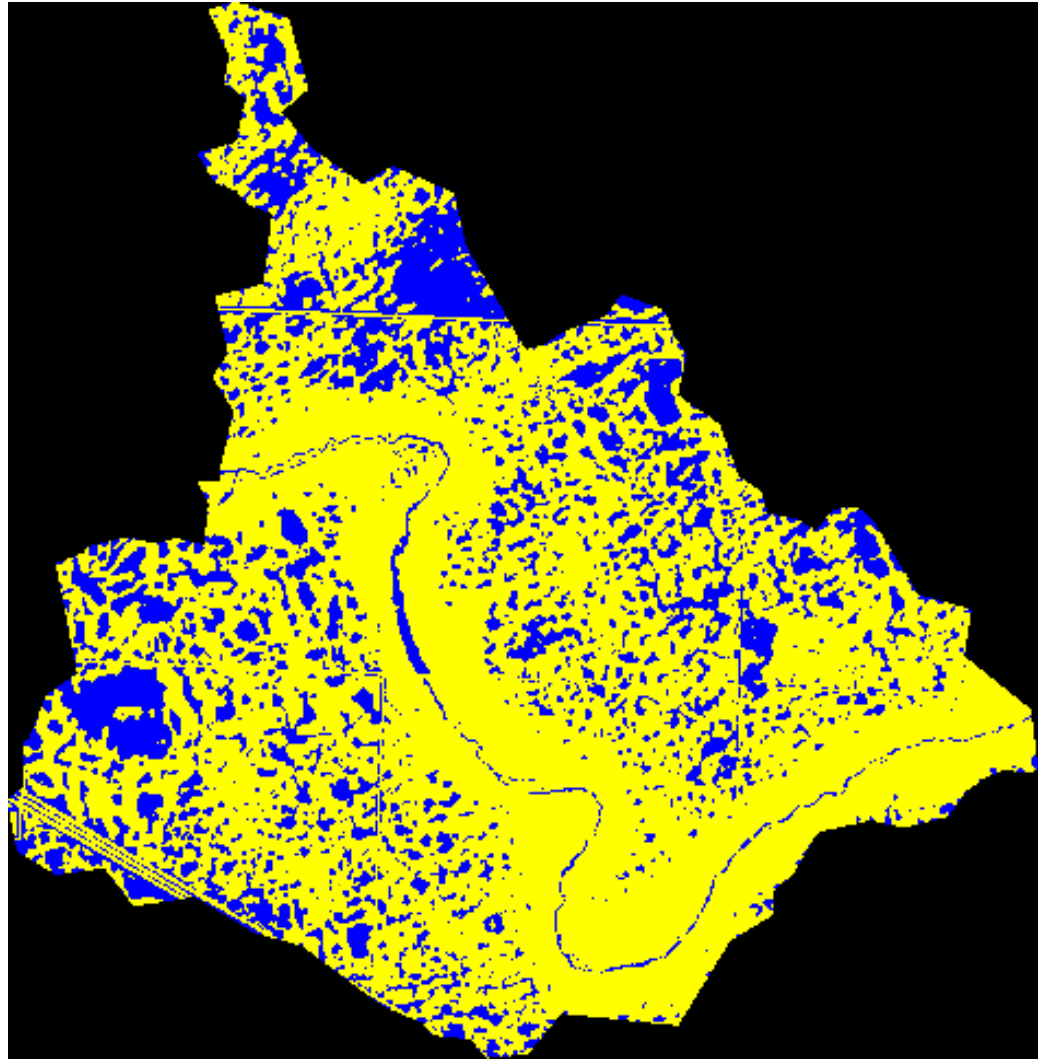


Figure 4: Plot of WDPM simulation of water (blue) and dry ground (yellow) for draining following the addition of 300 mm of water. The region outside the basin is shown in black. Smith Creek sub-basin 5.

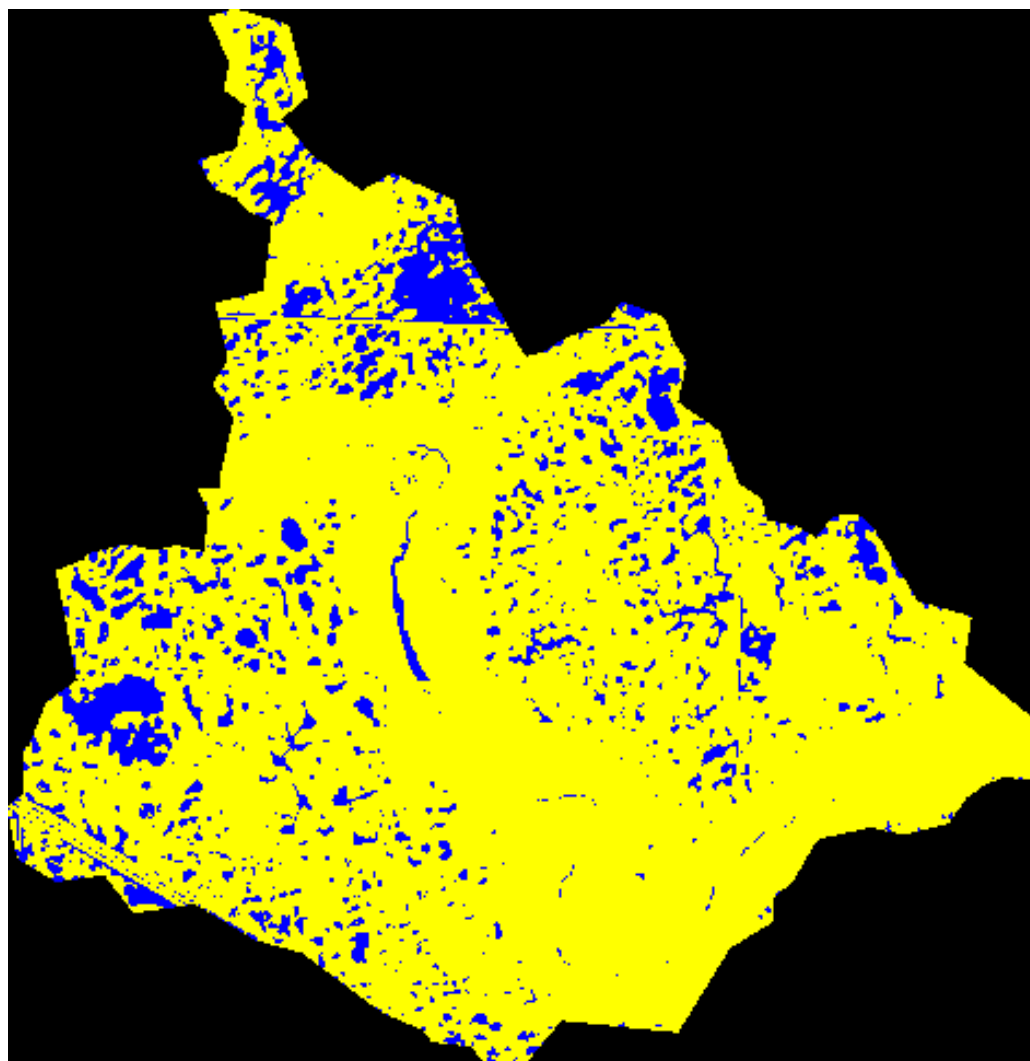


Figure 5: Plot of WDPM simulation of water (blue) and dry ground (yellow) for the removal of 200 mm of water following the addition of 300 mm of water and draining. The region outside the basin is shown in black. Smith Creek sub-basin 5.

78 The WDPM is computationally expensive, requiring many thousands or millions of iterations
79 to converge to a solution, depending on the DEM size, the depth of water used, and the toler-
80 ance(s) of the solution. In the examples above, the addition of 300 mm of water, smoothed to
81 a resolution of 10 mm, required 179,000 iterations, taking 145.23 s on a system with an Intel
82 i7 CPU (4 cores, 8 threads) running Linux Mint 20. Draining the water to a tolerance of 0.1
83 mm/0.1 m³ required 240,000 iterations and took 180.6 s on the same system. Removing the
84 water and smoothing to a tolerance of 1 mm required 1,000 iterations, which is the minimum
85 possible because the program tests every 1000 iterations, taking 0.85 s on the same system.

86 Despite the computational cost, the program's great advantage is that it can simulate any
87 storage state within a complex system of prairie depressions. This capability makes it useful
88 for mapping the floodplains from non-riverine floods in the Canadian Prairies. The program
89 outputs have been verified by remote sensing of recent floods in this region, and WDPM
90 has been used to develop a simpler parametric model that is more easily incorporated in
91 hydrological models (Shook et al., 2013). The program's floodplain mapping capabilities have
92 been used by researchers (Elboshy et al., 2019; Kiss, 2018; Schellenberg, 2017 ; Thapa et al.,
93 2019), for operational flood hazard mapping in the Canadian Prairies by government agencies

(Armstrong et al., 2013) and by private consultants (Venema, Henry David, 2020a, 2020b). As of July 2020, the program has been downloaded by at least 78 different users from 11 countries.

Licence

The WDPM is licensed under the GNU GPL v3.

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