GSFLOWurban

An urban development water balance analysis expansion to GSFLOW[1]

GSFLOW, the coupled groundwater and surface-water flow model (Markstrom et. al., 2008) combines the Precipitation Runoff Modeling System (PRMS—Markstrom et. al., 2015) and MODFLOW-2005 (Harbaugh, 2005) as an open source groundwater-surface water modelling code offered by the U.S. Geologic Survey (USGS). The code has been adapted here to accommodate the hydrology of urban systems.

GSFLOWurban is the modified version that is also available open source and is maintained up to date with the native GSFLOW code. The adapted code will always remain backward compatible, meaning that any "native" GSFLOW model will run as is using GSFLOWurban. The adaptations were made with the intention that the new PRMS modules introduced here are to be applied in a grid-based fashion, as opposed to the sub-basin basis originally intended for PRMS. This is not a limitation, per se, as the model can still be applied on an sub-basin basis; however the reader should be aware that the developers of GSFLOWurban tend to use the model in this particular way.

The main addition to GSFLOW introduced here is the new PRMS module: `srunoff_urban`. This module has expanded the HRU into three (from two) distinct water balance features:

1. *Connected* impervious areas representative of on-grade impervious areas;
2. *Disconnected* impervious areas removed from the runon process meant to represent elevated structures such as roof tops; and,
3. Pervious areas.

From these water balance features, great flexibility is given to the modeller to simulate the impacts of common Green Infrastructure (GI)/Low Impact Development (LID)/Sustainable Drainage System (SuDS) mechanisms and strategies such as infiltration galleries, rooftop disconnection, bioswales, pervious paving, etc. In addition, the new water balance feature representation allows the explicit representation of building structures, and the hydrological processes specific to rooftops, which include a variety of logical pathways needed to route water from rooftops to various storage reservoirs and water management facilities.

GSFLOWurban also incorporates a conceptual "Sewershed" kept independent of overland and groundwater pathways used to simulate urban storm water drainage. Urban storm water drainage features (including sub-surface infiltration storage reservoirs) experience direct interaction with the modelled groundwater system such that the modeller can quantify long-term storage/retention potential of infiltration storage reservoirs and simulate groundwater infiltration (e.g., storm sewer I&I).

In addition to the new `srunoff_urban` module, a number of additional modules have been added to the original GSFLOW model code, these include:

`srunoff_scscn`	Soil Conservation Service Curve Number (CN) continuous runoff generation methodology.
`srunoff_grnampt`	An unsteady (and sub-daily) implementation of Green and Ampt (1911) infiltration theory.
`gw_topmodel`	The implementation of TOPMODEL as an alternative to the native (PRMS-only) groundwater reservoir mechanism.

The following is not a comprehensive instruction manual of GSFLOW, rather it is to serve as an addendum to the original manual of Markstrom et. al. (2008), describing only the modelling features that have been added to the original code.

[1]Draft version as of December, 2018

USGS Software User Rights Notice

Module Design

2.1 Module description

The PRMS/GSFLOW urban module was motivated by the need to better represent urban land cover at the watershed/regional scale. The conceptualization of the runoff modules native to PRMS (`srunoff_carea_casc` and `srunoff_smidx_casc`) were over-simplified when attempts were made to apply them at scales finer than the subwatershed scale. These native modules follow standard hydrologic response unit (HRU) based conceptualization of an area composed of a pervious region that allows for infiltration, and an impervious are that does not. When applied at the sub-catchment scale, this conceptualization sufficed in representing the interaction among urban, agriculture and natural land covers, especially when the objective is to predict runoff at a gauged location.

With the advent of GSFLOW, the HRU-based model design was commonly refocused to a rectilinear finite difference grid common to MODFLOW (Harbaugh, 2005), the groundwater flow model combined with PRMS in the development of GSFLOW (Markstrom et. al., 2008). In addition, with GSFLOW came the advent of a cascading runoff functionality which allowed for interaction among HRUs[1] in their treatment of overland flow. This re-conceptualization of the PRMS HRU posed conceptual problems with the native runoff modules, in that:

1. runoff originating from upslope HRUs arriving a downslope HRUs (i.e., runon) will equally cover the entire HRU, including rooftops.
2. PRMS modellers were forced to make two undesirable decisions regarding the handling of storm runoff:
   (a) storm water management mechanisms (e.g., storm sewers, tile drains) had to be implicitly represented as overland sheet flow, meaning that any quantity of water entering a storm sewer must be discharged onto adjacent HRUs, including rooftops; otherwise,
   (b) overland flow from urban HRUs had to be routed directly toward stream segments, lakes, or beyond the model domain, effectively sacrificing overland flow and interflow mechanisms built into the native PRMS model code.
3. many storm water management strategies, such as green infrastructure and low impact design (LID) that will greatly affect the water balance, could not be adequately implemented.
4. retention of water on top of roofs could not be isolated from water detained within micro-depressions on the land surface.
5. water collected on impervious areas commonly access adjacent pervious areas in many developed areas, a mechanism which is unavailable with the native versions of PRMS and GSFLOW.

2.1.1 Module dimensions

Two additional dimensions are required when implementing the urban module. `ndscn` instructs the model on the number of disconnected reservoirs to account for, and `ninfstor` instructs the model on the number of infiltration reservoirs to account for. Disconnected and infiltration reservoirs are optional but their dimensions must be specified. If either no disconnected or infiltration reservoir are to be modelled, the dimensions must be set to zero.

No more than one disconnected and/or infiltration reservoir can be specified for every HRU, however multiple HRUs can contribute to a single disconnected and/or infiltration reservoir

[1]note that in the grid cell based application of the "HRUs" no longer fits the established theory/intent of HRU-based hydrological modelling; this report will nonetheless continue to speak of model "cells" as "HRUs."

2.1.2 Storage types

The urban module separates the impervious area of a PRMS HRU into four main reservoirs:

1. Disconnected storage—storage that does not collect runoff from upslope source areas, its only source of water originates from direct precipitation. Example disconnected storage includes rooftops.

2. Connected storage—storage that will accept runoff from upslope source areas in the same way that "impervious areas" are treated in all other PRMS `srunoff` modules.

3. Infiltration storage—represents onsite storage reservoirs intended for storm water retention and infiltration enhancement. Examples being infiltration galleries...

4. Storm drains—a simplified representation of a storm sewer network.

Unique to this urban module is the ability for the model to account for hydrogeologic interactions with a infiltration facility. Through the infiltration storage reservoir implemented within the urban module, the modeller will be given the ability to quantify the long term efficacy of infiltration-based development strategies common to green stormwater management strategies and low impact design. The urban module built on top the integrated GSFLOW model will constrain infiltration capacity to local geology and seasonal watertable positions to better inform urban storm water design.

As the groundwater table rises, seepage into the infiltration storage facility is permitted and is restricted once the reservoir is at it's capacity or the watertable drops below the user-specified infiltration storage facility's invert elevation. As the model code currently stands, groundwater infiltration into storage reservoirs assume that the reservoirs extend across the entire HRU area.

The conceptual storm drain also has the functionality to intercept groundwater, giving GSFLOWurban the ability to estimate groundwater "inflow and infiltration" (I&I). The principles behind the storm drain's interaction with the groundwater table is identical to the infiltration storage reservoir. Seepage out of a storm drain (Q_{SD}) is given by:

$$Q_{\mathrm{SD}} = \begin{cases} C_{\mathrm{SD}} \cdot h_{\mathrm{SD}} & h_{\mathrm{wt}} < h_{\mathrm{inv}} \\ C_{\mathrm{SD}} \cdot (h_{\mathrm{SD}} - h_{\mathrm{wt}} + h_{\mathrm{inv}}) & \text{otherwise} \end{cases}, \tag{2.1}$$

where the conductance term (C_{SD}) is given by:

$$C_{\mathrm{SD}} = \frac{K_{\mathrm{SDW}} \cdot L_{\mathrm{SD}} \cdot W_{\mathrm{SD}}}{Th_{\mathrm{SD}}} \tag{2.2}$$

and

h_{SD}	is the depth of flow within the HRU storm drain;
h_{inv}	is the height of the HRU storm drain invert (`stdrn_invert`), in `elev_units`;
h_{wt}	is the height of the watertable;
K_{SDW}	is the hydraulic conductivity of the storm drain walls;
L_{SD}	is the total length of the storm drains within an HRU;
W_{SD}	is the average width of storm drains within an HRU; and,
Th_{SD}	is the average thickness of storm drain walls within an HRU.

When applying storm drains in PRMS-only mode, the conductance term (C_{SD}), when set to a range of 0 to 1.0, can also be interpreted as a linear drainage coefficient in a similar fashion to the infiltration storage seepage coefficient (`infstor_seep_coef`).

2.1.3 Sewershed

Storm drainage networks are defined by the ultimate destination of overland flow collection, which can either be a lake, stream segment or outside of the model (farfield). These drainage networks currently have an unlimited capacity and thus do not simulate flow hydraulics. It is assumed that all water flowing through the network meets its destination within a model time step with perfect efficiency and zero back-water effects.

It must also be noted that water quality is not being considered anywhere within the urban module, consistent with PRMS and GSFLOW.

As PRMS and GSFLOW currently operated on daily timesteps intended for long term continuous water budgeting operation, the storm drainage networks were intentionally simplified for runtime efficiency. There are many storm water management model codes available that are purpose-built to investigate runoff through a network of pipes, channels, treatment units and diversion structures (see, for example Rossman and Huber, 2016). Rather, the motivation for the drainage networks implementation to the urban module is manyfold, allowing the modeller to:

- access additional flow pathways from urban areas when modelling at the region scale.
- investigate losses from and/or infiltration into storm sewers do to cracked or broken pipe.
- make indirect assessments of inflow and infiltration gains into a sanitary system do to misdirected storm water management design and/or high groundwater tables on a long-term/seasonal basis.
- allow for the analysis of low impact development strategies incorporating perforated pipe systems.

2.1.4 Storage pathways and formulation

The urban module introduces 11 sub-HRU flow pathways that enable (in various combinations) the simulation of the hydrological function of many stormwater management strategies while preserving function of overland flow and interflow common to the native distribution of PRMS/GSFLOW (2.1).

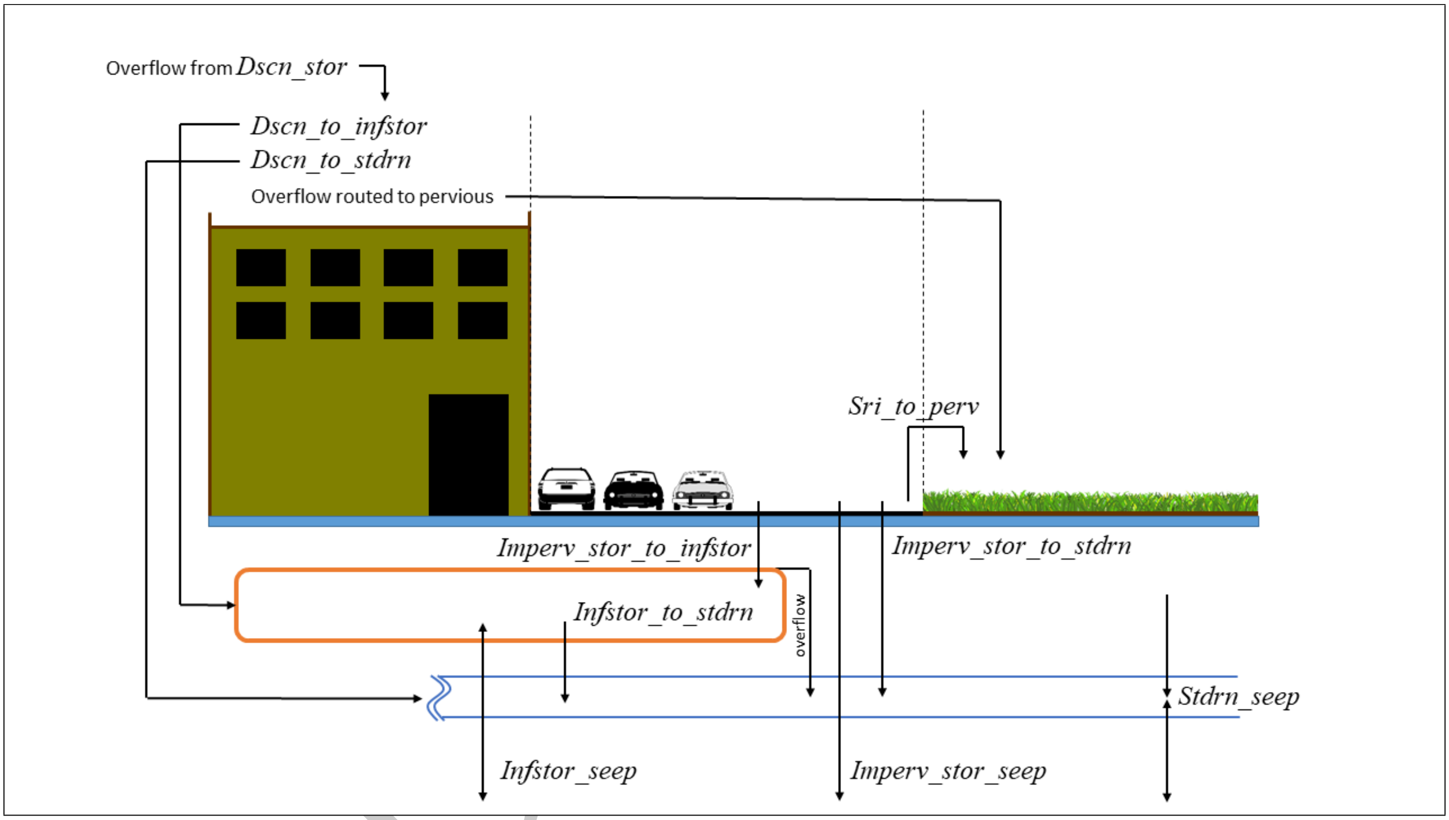

Figure 2.1: A uniform sampling transformation.

From disconnected reservoirs

The disconnected and infiltration reservoirs follow the formulation of a simple linear reservoir with a maximum capacity S_{max}. When storage S exceeds S_{max}, excess water S_{excess} from disconnected and infiltration reservoirs is immediately routed to the impervious areas and storm drains, respectively.

Evaporation from the disconnected reservoir (e.g., rooftop) for each HRU is calculated according to:

$$S^m_{dscn} = \begin{cases} S^{m-1}_{dscn} - f_{dscn} \cdot PE^m_{HRU} & S^{m-1}_{dscn} > f_{dscn} \cdot PE^m_{HRU} \\ 0 & \text{otherwise} \end{cases}, \tag{2.3}$$

where

S^m_{dscn}	is the storage of the disconnected reservoir of the HRU during time step m, in inches;
f_{dscn}	is the fraction of the rooftop exposed to the atmosphere; and,
PE^m_{HRU}	is the maximum potential loss to evaporation from the disconnected reservoir.

TO COMPLETE

2.2 Module parameters

Table 2.1 provides the specifications for GSFLOWurban parameterization.

TO COMPLETE

2.2.1 Parameterization for common infrastructure

Through a combination of storage reservoirs and pathways, the urban module can be parameterized to simulate the hydrological function of a number of common infrastructure designs and LID strategies. This section provides examples of how the user would approach any number of designs. In general, the functionality of urban systems can be simulated on the basis of a simple water balance equation:

$$S^m = S^{m-1} - E - D - Q_{|S^m > S_{max}}, \tag{2.4}$$

where

S^m	is the storage of some HRU reservoir during time step m;
E	is the evaporative loss;
D	is loss due to drainage; and
$Q_{\lvert S^m > S_{max}}$	is the storage overflow given that storage will exceed its capacity S_{max}.

From this simple formulation, and the number of pathways defined in Figure 2.1 and parameters described in Table 2.1, GSFLOWurban parameters can be used to describe the hydrologic function of urban structure at the regional scale. In certain cases, parameters native to GSFLOW already provide the necessary mechanisms needed to simulate storm water management structures; in these cases, please refer to Markstrom et. al. (2008) for further details.

The following are examples of how the controlling functionality added to GSFLOWurban allow for the flexibility needed to simulate the mechanisms that regulate urban hydrology. Unless specified elsewhere, and in cases where there is more water than can be handled by user-specified drainage pathways, overflow ($Q_{|S^m > S_{max}}$) is either routed to pervious areas or to the conceptual storm drain system.

Storm water management

Much of the storm water management built into urban planning focuses on the removal of water ponded on the land surface and on rooftops via a stormwater drainage network. Surprisingly, it is rare to find regional-scale hydrological models that include this functionality. GSFLOWurban has a very simplified, yet effective means of handling such basic water management strategies. For instance, storm drain catch basins can be simulated by setting a non-zero value to `imperv_stor_to_stdrn` in all areas where urban drainage systems are anticipated.

Simulating roof collection to storm drains is where Equation 2.4 comes in to play. For example, each of S_{max}, E and D, which control the general functionality of water management, can each be associated with some the new parameters added to GSFLOWurban, for example for roof collection to storm drains, the user needs to set the parameters:

Component	Functionality	Controlling parameter(s)
S_{max}	rooftop capacity	`imperv_frac_dscn` > 0.0 `dscn_stor_max` > 0.0
E	rooftop exposure	`dscn_evap_coef` ≥ 0.0
D	redirecting of collected water	`dscn_to_stdrn` ≥ 0.0 `dscn_to_infstor` ≥ 0.0

2.2.2 Green infrastructure implementations

The functionality included in GSFLOWurban can easily be extended to accommodate green infrastructure and low impact design strategies. Again, Equation 2.4 and the suite of added parameters can be readily applied to represent the functionality of a variety of LID strategies.

Table 2.1: Input parameters required for PRMS Module: `srunoff_urban`.

[HRU: hydrologic response unit; **nhru**, number of HRUs; **ndscn**, number of disconnected storage reservoirs; **ninfstor**, number of infiltration storage reservoies; **nsegment**, number of stream-channel segments; **nlake**, number of lake HRUs]

Parameter name	Description	Dimension variable	Units	Type	Range	Default value
imperv_stor_seep	Fraction of impervious storage that is allowed to infiltrate	nhru	dimensionless	real	0.0 to 1.0	0.0
stdrn_hru_id	Identification number of the storm sewershed associated with an HRU	nhru	dimensionless	integer	-nlake to nsegment[a]	0
imperv_stor_to_stdrn	Fraction of impervious storage that is directed to storm drainage system	nhru	dimensionless	real	0.0 to 1.0	0.0
stdrn_invert	Invert elevation of HRU storm drain	nhru	elev_units	real	-1,000.0 to 30,000.0	9999.0[b]
stdrn_cond	Conductance of storm drain walls used to compute groundwater infiltration and leakage	nhru	inches/day	real	0.0 to 100.0	0.0
	Additional parameters for when ndscn > 0					
imperv_frac_dscn	Fraction of impervious area that is disconnected	nhru	dimensionless	real	0.0 to 1.0	0.0
dscn_hru_id	Identification number of the disconnected reservoir associated with an HRU	nhru	dimensionless	integer	0 to ndscn	0
dscn_stor_max	Maximum disconnected retention storage	ndscn	inches	real	0.0 to 40.0	0.05
dscn_evap_coef	Fraction of unsatisfied potential evapotranspiration to apply to disconnected storage	nhru	dimensionless	real	0.0 to 1.0	0.0
dscn_to_stdrn	Fraction of disconnected storage that is directed to storm drainage	nhru	dimensionless	real	0.0 to 1.0	0.0
	Additional parameters for when ninfstor > 0					
infstor_hru_id	Identification number of the infiltration reservoir associated with an HRU	nhru	dimensionless	integer	0 to ninfstor	0
infstor_max	Maximum infiltration detention storage	ninfstor	inches	real	0.0 to 500.0	10.0
imperv_stor_to_infstor	Fraction of impervious storage that is directed to infiltration storage system	nhru	dimensionless	real	0.0 to 1.0	0.0
infstor_invert	Invert elevation of infiltration detention storage reservoir	ninfstor	elev_units	real	-1,000.0 to 30,000.0	9999.0[b]
infstor_seep_coef	Coefficient used in linear drainage flow from infiltration storage for each HRU	nhru	dimensionless	real	0.0 to 1.0	0.02
infstor_to_stdrn_coef	Coefficient used in linear drainage flow from infiltration storage to storm drainage	nhru	dimensionless	real	0.0 to 1.0	0.05
	Additional parameters for when ndscn > 0 and ninfstor > 0					
dscn_to_infstor	Fraction of disconnected storage that is directed into infiltration storage	nhru	dimensionless	real	0.0 to 1.0	0.0

[a] sewershed ID: < 0 to (negative) lake ID; > 0 to stream segment ID; = 0 to farfield.

[b] for GSFLOW simulations only. Setting to 9999.0 essentially separates from the watertable, thus only losses can occur.

Green roofs

Green roofs are disconnected storage areas that "consist of a thin layer of vegetation and growing medium installed on top of a conventional flat or sloped roof" (TRCA & CVC, 2010).

Component	Factors	Controlling parameter(s)
S_{max}	depth of garden substrate; substrate porosity; proportion of land use area covered by roof; proportion of roof covered by garden.	`dscn_stor_max` > 0.0 `imperv_frac_dscn` > 0.0
E	proportion of roof covered by garden; proportion of garden exposed to the atmosphere	`dscn_evap_coef` ≥ 0.0
D	pathways identified for green roof drainage; rates of drainage	`dscn_to_stdrn` ≥ 0.0 `dscn_to_infstor` ≥ 0.0

Roof downspout disconnection

Roof downspout disconnection involves the re-directing of water from rooftops to a nearby pervious area that drains away from the building (TRCA & CVC, 2010). Note: the conceptual rooftop has many potential pathways that can allow drainage; by disabling all pathways, rooftop overflow is defaulted to route to the pervious area.

Component	Factors	Controlling parameter(s)
S_{max}	depth of rooftop storage; proportion of land use area covered by roof.	`dscn_stor_max` > 0.0 `imperv_frac_dscn` > 0.0
E	proportion of roof exposed to the atmosphere	`dscn_evap_coef` ≥ 0.0
D	enable roof-to-pervious pathway by disabling all other potential pathways.	`dscn_to_stdrn` $= 0.0$ `dscn_to_infstor` $= 0.0$

Bioretention, bioswales, etc.

Class of LID strategies that retain stormwater above a pervious surface where the substrate may (or may not) is pre-treated to maximize its storage capacity and/or enhance infiltration. The conceptual sewershed can be applied here to capture a proportion of infiltrated water by setting `stdrn_cond` > 0.0. Routing overland impervious runoff to these features can be accomplished using the `sri_to_perv` parameter (see Table 4.1).

Other similar terminology/mechanisms (in term of their hydrologic function) may include: vegetated/grassed/bio filter strips, buffer strips, grass/dry swales, infiltration swales/basins/trenches, sand filters, dry wells, rain gardens, etc.

Component	Factors	Controlling parameter(s)
S_{max}	total storage of soil substrate matrix and surface depression ponding.	`sat_threshold` > 0.0
E	interaction of soil zone with the atmosphere	see Markstrom et. al. (2008)
D	percolation from soil zone; enable seepage into the conceptual storm drain system.	`soil2gw_max` ≥ 0.0 `ssr2gw_rate` ≥ 0.0 `stdrn_cond` ≥ 0.0

Rainwater harvesting (rain barrels, cisterns, planters, etc.

These mechanisms are generally characterized as stormwater detention/retention mechanisms that hold water above grade and slowly release captured water back to pervious areas. Rain barrels differ only in that they're likely not to experience much evaporative loss (i.e., `dscn_evap_coef` $= 0.0$).

Component	Factors	Controlling parameter(s)
S_{max}	capacity of retention mechanism.	`dscn_stor_max` > 0.0 `imperv_frac_dscn` > 0.0
E	proportion retention mechanism exposed to the atmosphere	`dscn_evap_coef` ≥ 0.0
D	pathways identified drainage (otherwise overflow will be routed to pervious areas); rates of drainage	`dscn_to_stdrn` ≥ 0.0 `dscn_to_infstor` ≥ 0.0

Below-grade storage (soakaways, infiltration chambers, etc.)

Underground detention systems, also referred to as infiltration chambers/trenches/chambers/cisterns, soakaways, etc., have been given their own water budget mechanism in GSFLOWurban. These facilities can receive water from either impervious area (connected or disconnected), can be set to drain via enhanced infiltration and/or sent to the conceptual storm drain. Overflow is defaulted to be directed to the storm drain. The most important attribute to these below-grade systems is that its capacity and functionality can be affected by a high groundwater table.

Component	Factors	Controlling parameter(s)
S_{max}	capacity of below-grade storage facility.	`infstor_max` > 0.0
S	storage can originate from multiple sources	`dscn_to_infstor` > 0.0 `imperv_stor_to_infstor` > 0.0 `infstor_invert` $<$ water table `infstor_seep_coef` > 0.0
$E = 0$	here, assumed not exposed to atmosphere	*n/a*
D	pathways identified drainage; rates of drainage	`infstor_to_stdrn_coef` ≥ 0.0 `infstor_invert` $>$ water table `infstor_seep_coef` ≥ 0.0

Permeable paving

Permeable pavement is an alternative to traditional (impervious) pavement design that allows stormwater to drain through to the underlying soil zone or an engineered porous material reservoir where it is temporarily detained (TRCA & CVC, 2010). This differs from the above LID strategies in that does not utilized a dedicated storage reservoir, however it requires the user to specify non-zero values for both `imperv_stor_seep` and `imperv_stor_max`. This parameterization will also serve as an alternative mechanism for incorporating vegetation strips/buffers and gravel fringes.

Additional Modules

This section details some of the additional modules that have been added to the PRMS portion of the GSFLOW code. These modules were not added as part of the urban hydrology components of GSFLOWurban and thus can be used independently; nonetheless, they can still be used in conjunction with the urban processes described above.

3.1 Soil Conservation Service Curve Number method

An additional runoff generation scheme has been added to the collection of surface runoff modules. The Soil Conservation Service[1] (SCS) Curve Number (CN) methodology (USDA-SCS, 1972) has been added in a similar fashion to that used in the EPIC model specific to its treatment of antecedent moisture conditions (Williams et. al., 1984). The SCS-CN model is given as:

$$Q = \frac{(P - I_a)^2}{P - I_a + S}, \tag{3.1}$$

where, Q is generated runoff, P is precipitation and S is the potential maximum infiltration, which can also be considered as the maximum difference between P and Q for a given storm event (Mishra and Singh, 2003). In the current application, the PRMS model accounts for various forms of initial abstraction; therefore the above equation applied in this module is based on effective precipitation ($P_e = P - I_a$) only:

$$Q = \frac{P_e^2}{P_e + S}. \tag{3.2}$$

The Curve Number (CN) is a widely published value found in many hydrology textbooks (i.e., Chow, 1964) that is specified according to land use and hydrologic soil group. It should be noted that these numbers were derived empirically over level plot-scale land surfaces by comparing peak flow rates occurring during annual extreme precipitation events (Mishra and Singh, 2003). However, as acknowledged by Mishra and Singh (2003), the SCS-CN methodology has been widely applied to long-term continuous watershed models; see, for example, many models within Singh (1995). Potential maximum infiltration S [*inches*] is related to CN, which varies from 0 to 100, by:

$$S = \frac{1000}{CN} - 10 \tag{3.3}$$

Further modification to the SCS-CN methodology is commonly applied to account for antecedent moisture conditions (AMC). Antecedent moisture conditions are typically differentiated in three classes on the basis of total 5-day antecedent rainfall: $\mathrm{AMC_I}$ is representative of dry conditions prior to the onset of a precipitation event; $\mathrm{AMC_{III}}$ is representative of wet conditions; and, $\mathrm{AMC_{II}}$ is somewhere in between. Transformations among the three conditions can be computed using (Hawkins et. al., 1985):

$$\begin{aligned} CN_I &= \frac{CN_{II}}{2.281 - 0.01281 CN_{II}} \\ CN_{III} &= \frac{CN_{II}}{0.427 - 0.00573 CN_{II}}, \end{aligned} \tag{3.4}$$

where CN_I, CN_{II} and CN_{III} are the adjusted curve numbers for $\mathrm{AMC_I}$, $\mathrm{AMC_{II}}$ and $\mathrm{AMC_{III}}$, respectively. Note: CN_{II} values are those listed in the many published SCS-CN tables.

When applying the SCS-CN methodology to continuous models that have some form of a soil moisture accounting scheme, this procedure of adjusting to antecedent moisture conditions may be considered unsuitable since (a) the models

[1] now known as the Natural Resources Conservation Service (NRCS)

have sufficient information to determine antecedent moisture and need not rely 5-day antecedent rainfall, and (b) having three distinct antecedent moisture classes cause the application of the methodology to respond in a discontinuous manner. For these reasons, continuous models have adopted a modified approach to handling antecedent moisture conditions. The EPIC model (Williams et. al., 1984) was one of the earliest attempts to apply a continuous relationship between soil moisture and the S parameter, which was later refined by the SWAT model (Neitsch et. al., 2011) where:

$$S = S_I \left(1 - \frac{\theta}{\theta + \exp(w_1 - w_2\theta)} \right), \tag{3.5}$$

where S_I is the potential maximum infiltration during $\mathrm{AMC_I}$, θ is the current soil moisture content, and w_1 and w_2 are shape parameters, which can be determined by (Neitsch et. al., 2011):

$$\begin{aligned} w_1 &= \ln\left(\frac{\theta_{FC}}{1 - \frac{S_{III}}{S_I}} - \theta_{FC} \right) + w_2\theta_{FC} \\ w_2 &= \frac{1}{\theta_s - \theta_{FC}} \left[\ln\left(\frac{\theta_{FC}}{1 - \frac{S_{III}}{S_I}} - \theta_{FC} \right) - \ln\left(\frac{\theta_s}{1 - S_I^{-1}} - \theta_s \right) \right], \end{aligned} \tag{3.6}$$

where θ_s is the saturated soil moisture content and θ_{FC} is the soil moisture content at field capacity.

3.1.1 Numerical Implementation

The SWAT version of EPIC's continuous AMC formulation lends itself well to the PRMS code. Other than the user inputting CN values for every HRU (see Table 3.1), the model will internally correct for the appropriate S variable given the method outlined above. The soil moisture contents shown in Equations 3.5 and 3.6 relate to PRMS by:[2]

$$\begin{aligned} \theta &= \texttt{ssres\_stor} + \texttt{soil\_moist} \times \texttt{hru\_frac\_perv} \\ \theta_{FC} &= \texttt{soil\_moist\_max} \times \texttt{hru\_frac\_perv} \\ \theta_s &= \theta_{FC} + \texttt{sat\_threshold}. \end{aligned} \tag{3.7}$$

Note that `hru_frac_perv` $= 1 -$ `hru_percent_imperv`$/100$.

Table 3.1: Input parameters required for PRMS Module: `srunoff_scscn`.

[HRU: hydrologic response unit; `nhru`, number of HRUs]

Parameter name	Description	Dimension variable	Units	Type	Range	Default value
`scs_cn`	Soil Conservation Service Curve Number (CN) for each HRU	`nhru`	index from 0-100	real	0.0 to 100.0	75.0

Lastly, once the model has computed runoff Q, daily infiltration F at the HRU is determined by:

$$F = \begin{cases} P_e \left[1 - \frac{P_e}{P_e + S} \right] & 1 - \frac{P_e}{P_e+S} < \texttt{carea\_max} \\ P_e \cdot \texttt{carea\_max} & \text{otherwise.} \end{cases} \tag{3.8}$$

3.2 Green-Ampt Infiltration

The Green-Ampt infiltration model has been incorporated into the PRMS code following the method of Chu (1978). The Chu (1978) method allows for a time-distributed series of varying rainfall intensities to influence the rates of infiltration into the soil zone.[3] The module is expected to be utilized in areas where rainfall capacity (i.e., Hortonian) runoff patterns are dominant at time scales less than a day.

[2]Please refer to Markstrom et. al. (2008) for description of GSFLOW parameter names.

[3]In the current released version, only daily rainfall intensities are accepted. In future versions, there are plans to allow the user to input daily "intensity factors" to better realizes sub-daily storm patterns and rainfall intensities that impact the estimation of daily accumulated infiltration.

The Green-Ampt (1911) model is a one dimensional infiltration model that representes infiltration as a sharp "wetting front" coursing vertically downward through the soil zone driven by both capillary suction (i.e., matric potential) and gravity. Rates of infiltration are dependent on the cumulative volume of water infiltrated during past infiltration events. Over time, this cumulative volume of water percolates toward the watertable adding to groundwater recharge. The Green-Ampt (1911) model for vertical infiltration is commonly written as:

$$f_p = \frac{dF}{dt} = K_s \left[1 + \frac{\theta_d |\Psi_f|}{F} \right], \tag{3.9}$$

where, f_p is the infiltration capacity $[L/T]$, F is the cumulative infiltration $[L]$ at time t, K_s is the saturated hydraulic conductivity of the soil zone $[L/T]$, Ψ_f is the average difference in matric potential (or capillary suction/pressure) across the wetting front $[L]$, and θ_d is the soil moisture deficit ahead of the wetting front and is defined as $\theta_d = \theta_s - \theta$, where, θ_s is the volumetric soil moisture content when saturated, and θ is the current/initial soil moisture content $[-]$ at the onset of an infiltration event.

A drawback to common applications of the Green-Ampt equation to hydrological modelling is that the method is limited to the application to single events of steady rainfall (Mein and Larson, 1973). The Chu (1978) model was developed to overcome this limitation. For this reason, the Chu (1978) method was deemed ideal for inclusion into GSFLOWurban. The method is premised on the simple water budget:

$$P = F + G + R, \tag{3.10}$$

where P is the cumulative inputs (which can include rainfall, snowmelt and/or runoff from upslope sources), G is the cumulative ponding on the soil surface, and R is the cumulative runoff generated from the model cell. (In GSFLOWurban, these values are accumulated in daily time steps.) The above equation is best expressed in rate form:

$$i = f_p + \frac{dG}{dt} + r, \tag{3.11}$$

where, i is the rate of total inputs and r is rate of generated runoff; all $[L/T]$.

The procedure first determines whether ponding will occur at some time between t' to t, where t' represents a model time step prior to time step t. The module has been designed such that successive time step lengths ($\Delta t = t - t'$) can vary and can have shorter time spans than one day, which is the default time step for GSFLOW and PRMS. Thus, three conditions can exist for the t' to t:

1. No precipitation (or other inputs) are available (i.e., $i(t) = 0$)

$$\begin{aligned} P(t) &= P(t') \\ R(t) &= R(t') \\ F(t) &= 0 \qquad \text{(re-setting cumulative infiltration)} \\ f(t) &= 0 \\ r(t) &= 0 \end{aligned}$$

2. Surface ponding does <u>not</u> occur, but $0 < i(t) < f_p$:

$$\begin{aligned} P(t) &= P(t') + i(t)\Delta t \\ R(t) &= R(t') \\ F(t) &= P(t) - R(t') \\ f(t) &= i(t) \\ r(t) &= 0 \end{aligned}$$

3. Surface ponding does occur:

$$
\begin{aligned}
P(t) &= P(t') + i(t)\Delta t \\
F(t) &= F_p(t) \\
R(t) &= \begin{cases} P(t) - F_p(t) & P(t) - F_p > R(t') \\ R(t') & \text{otherwise} \end{cases} \\
f(t) &= f_p \\
r(t) &= \begin{cases} i(t) - f_p & i(t) > f_p \\ 0 & \text{otherwise} \end{cases}
\end{aligned}
$$

F_p is defined as the cumulative infiltration under surface ponding, which, as can be seen in the Green-Ampt formula (Equation 3.9, is an implicit function of F. Chu (1978) introduces a modified integrated form of the Green-Ampt equation that describes infiltration under ponded conditions with added inputs $i(t)$:

$$\frac{F_p}{\theta_d|\Psi_f|} - \ln\left(1 + \frac{F_p}{\theta_d|\Psi_f|}\right) = \frac{K_s(t - t_p + t_s)}{\theta_d|\Psi_f|}, \tag{3.12}$$

where, t_s is termed "pseudotime" in Chu (1978) and is required to accommodate unsteady inputs, given by:

$$t_s = \frac{\theta_d|\Psi_f|}{K_s}\left[\frac{P(t_p) - R(t')}{\theta_d|\Psi_f|} - \ln\left(1 + \frac{P(t_p) - R(t')}{\theta_d|\Psi_f|}\right)\right], \tag{3.13}$$

and t_p is the time to surface ponding given by:

$$t_p = \frac{1}{i(t)}\left[\frac{K_s\theta_d|\Psi|}{i(t) - K_s} - P(t') + R(t')\right] + t' \qquad \text{for } i(t) > K_s. \tag{3.14}$$

Lastly, Chu (1978) offers a graphical means of solving for F_p in the implicit equation (3.12) by plotting $x = \log\frac{K_s(t-t_p+t_s)}{\theta_d|\Psi_f|}$ vs. $y = \log\frac{F_p}{\theta_d|\Psi_f|}$. After rebuilding this graph, a polynomial expression can been fitted with a coefficient of determination $R^2 = 1.0$ according to:

$$y = 0.0073x^3 + 0.063x^2 + 0.682x + 0.3369 \qquad \text{for } -4.3 < x < 0.9 \tag{3.15}$$

3.2.1 Numerical Implementation

Following Mein and Larson (1973), the Chu (1978) formulation takes the factor $\theta_d|\Psi_f|$ together as a single model parameter, which can be derived from infiltrometer data and published data, such as Rawls et. al. (1983). This factor, however, implies a constant soil moisture deficit, which is unnecessarily restrictive as PRMS continuously accounts for soil moisture as represented by effective degree of saturation (S_e), defined by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{\texttt{ssres\_stor} + \texttt{soil\_moist} \times \texttt{hru\_frac\_perv}}{\texttt{sat\_threshold} + \texttt{soil\_moist\_max} \times \texttt{hru\_frac\_perv}}, \tag{3.16}$$

where θ_r is the residual soil moisture content and `hru_frac_perv` $= 1 -$ `hru_percent_imperv`$/100$.[4] By expanding soil moisture deficit and combining equation 3.16, the Chu (1978) $\theta_d|\Psi_f|$ factor can be reduced to a new (and truly) constant factor now based on the average specific yield of the soil zone times the average difference in matric potential across the wetting front ($S_y|\Psi_f|$), where:

$$\theta_d|\Psi_f| = (\theta_s - \theta)|\Psi_f| = (1 - S_e)(\theta_s - \theta_r)|\Psi_f| = (1 - S_e)S_y|\Psi_f|. \tag{3.17}$$

The final solution to Equation 3.9 written in terms of Green-Ampt input parameters (the remaining terms are variables internal to the model code) is thus:

$$f_p = \texttt{ga\_ksat}\left[1 + \frac{(1 - S_e)\cdot\texttt{ga\_sypsi}}{F}\right], \tag{3.18}$$

and the calculation of infiltration follows the method of Chu (1978). In the end, the model returns $F(t) - F(t-1)$ as the sum of total daily infiltration, where $F(t-1)$ is the cumulative infiltration after the previous (daily) PRMS timestep.

[4]Please refer to Markstrom et. al. (2008) for description of GSFLOW parameter names.

3.2.2 Module Parameter Table

The `srunoff_grnampt` requires only two model parameters in addition to `carea_max`, namely `ga_ksat` and `ga_sypsi`. Like all `srunoff` modules, the GSFLOWurban parameter `sri_to_perv` can also be employed (Table 3.4).

Table 3.2: Input parameters required for PRMS Module: `srunoff_grnampt`.

[HRU: hydrologic response unit; `nhru`, number of HRUs]

Parameter name	Description	Dimension variable	Units	Type	Range	Default value
`ga_ksat`	Saturated hydraulic conductivity of the soil zone for each HRU	`nhru`	inches/day	real	0.0 to 100.0	0.1
`ga_sypsi`	The $S_y\|\Psi_f\|$ factor: Computed as the absolute value of matric potential[a] ahead of the wetting front × the specific yield of the soil zone for each HRU	`nhru`	inches	real	0.0 to 5.0	1.7

[a] matric potential must be inputted here as a positive (absolute) value (> 0.0).

The parameter `ga_sypsi` can be readily determined from published data should no other information be available. Table 3.3 shows a modification of the Rawls et. al. (1983) table of soil hydrologic characteristics according to soil type. The last column of the table computes the expected value for `ga_sypsi` on the basis of values found on original Rawls et. al. (1983) tables.

3.2.3 Model limitations and assumptions

The Green-Ampt model presented here is a simplified one-dimensional representation of infiltration processes. For this method to be applied, the soil zone is assumed as being a single homogenized layer of a porous medium. Pore spaces filled with air is assumed at atmospheric pressure and does not interfere with water movement. For infiltration to occur, ponding at the land surface has to first occur. Depth of ponding is assumed negligible and thus does add to the driving head potentials.

For the Green-Ampt model to work, infiltrating water is assumed representative as a sharp wetting front, which implies that diffusion of soil moisture during this period is disregarded.

Also note that, as discussed in Markstrom et. al., 2008, the parameter `sat_thresh` can be exaggerated in order to account for depression storage. Users must take this into consideration when parameterizing the Green-Ampt parameter `ga_sypsi`, which reflects only the maximum storage available within the soil zone pore spaces.

3.3 TOPMODEL

An additional groundwater modelling scheme available for PRMS-only simulations has been added. The TOPMODEL scheme of Beven and Quinn (1979) has been added as an alternative to `gwflow`, which is the sole option available for the groundwater flow module `gw_module`.

The handling of groundwater in `gwflow` PRMS module involves the typical use of a singular groundwater storage reservoir with a linear/exponential decay function. Calibrating models such as these to long-term stream flow records can be quite successful at matching baseflow recession measured at a gauge. Given its success and relative simplicity, the linear decay groundwater storage model is widely used and preferred for model calibration to stream flow gauging stations. Since PRMS-IV and GSFLOW, the module has incorporated an independent cascade mechanism identical to the soil zone cascade, which could, in theory, give the modeller the ability to impose time of concentration considerations into the groundwater decay term and the eventual groundwater discharge to streams.

The set of cascading groundwater reservoirs, however, have an unlimited capacity and thus never have an influence on the soil zone moisture balance as does MODFLOW when running in GSFLOW-mode. Consequently, the effects of catchment topography is neglected even though a cascade is imposed. Topography has a large role in distributing recharge, both in terms of focused recharge at overland flow convergences and rejected recharge at low-lying areas where the groundwater table is close to surface. For modeller who intend to project distributed recharge patterns using a grid-based PRMS, the linear decay groundwater storage model on its own will not suffice.

Table 3.3: Table of soil characteristics by soil type. *modified from:* Rawls et. al. (1983).

Soil Texture Class	**Specific Yield**[a] S_y $(-)$	**Wetting Front Capillary Pressure** Ψ_f $(-inches)$[b]	**Saturated Hydraulic Conductivity** K_s $(inches/day)$[c]	$S_y\|\Psi_f\|$ **factor** (ga_sypsi) *(inches)*
Sand	0.417	1.95	111.3	0.81
Loamy sand	0.401	2.41	28.3	0.97
Sandy loam	0.412	4.33	10.3	1.79
Loam	0.434	3.50	3.2	1.52
Silt loam	0.486	6.57	6.1	3.19
Sandy clay loam	0.330	8.60	1.4	2.84
Clay loam	0.309	8.22	0.9	2.54
Silty clay loam	0.432	10.75	0.9	4.64
Sandy clay	0.321	9.41	0.6	3.02
Silty clay	0.423	11.50	0.5	4.87
Clay	0.385	12.45	0.3	4.79

[a] originally termed "effective porosity"
[b] originally given as $(-cm)$ but converted here to remain consistent with PRMS input requirements
[c] originally given as (cm/hr) but converted here to remain consistent with the `ga_ksat` input requirements

TOPMODEL employs a distribution function that projects not only groundwater discharge to streams, but discharge in low-lying landscapes on the basis of a "soil-topological index" that considers the effects of both upslope surficial material properties and topographical pathways. TOPMODEL does not explicitly model integrated groundwater/surface water processes, however it does provide the ability, albeit an indirect one, to include the influence of near-surface watertables. Most importantly, low-lying areas close to drainage features will be prevented from accepting recharge resulting in saturated overland flow conditions.

Assumptions to TOPMODEL are that groundwater reservoirs are lumped, meaning that each reservoir is equivalently and instantaneously connected to all locations of the reservoirs' pre-specified groundwater basin delineations. Consequently "potential" recharge computed in the distributed sense is aggregated when added to the lumped reservoir, but the reservoir, in turn, will dictate the infiltrability of the landscape on the basis of topography. For additional discussion on theory and assumptions, please refer to Beven et. al. (1995) and Beven (2012).

3.3.1 Theory

TOPMODEL establishes that a sub-surface storage deficit at a given point i in the sub-watershed (D_i) can be approximated by:

$$D_i = \overline{D} + m\left[\gamma - \ln\frac{a}{T_o \tan\beta}\right], \tag{3.19}$$

where, T_o is the lateral transmissivity at model cell i when soils are saturated $[L^2/T]$, $\tan\beta$ is the cell slope angle, a is the unit contributing area to cell i $[L]$, defined here as the total contributing area to cell i divided by cell width, and m is a parameter controlling the exponential decline of transmissivity with depth. The expression $\ln(a/T_o \tan\beta)$ is referred to as the soil-topologic index. γ is the catchment average soil-topologic index and is given by:

$$\gamma = \frac{1}{A}\sum_i A_i \ln\left(\frac{a}{T_o \tan\beta}\right)_i, \tag{3.20}$$

where A and A_i is the sub-watershed and cell areas, respectively. Before every time step, basin-wide moisture deficit is updated by:

$$\overline{D}_t = \frac{1}{A}\sum_i A_i D_i + Q_{b,t-1} - G_{t-1}, \tag{3.21}$$

where G_{t-1} is the sub-watershed-wide groundwater recharge computed during the previous time step, and $Q_{b,t-1}$ is the baseflow computed during the previous time step, where:

$$Q_b = Q_o e^{-\overline{D}/m}. \tag{3.22}$$

It should be noted that the above equation is the equivalent to the linear groundwater storage model decay function, except here, TOPMODEL allows for an approximation of spatial soil moisture distribution, which will, in turn, determine spatial recharge patterns as $D_i \leq 0$ will prevent recharge from occurring at cell i. Q_o, defined as baseflow discharge when the sub-watershed is fully saturated (i.e., $\overline{D} = 0$) and is a model parameter entered by the user. The second parameter (m) can be determined from baseflow recession analysis (Beven et. al., 1995; Beven, 2012).

Initial watershed average soil moisture deficit can be determined by stream flow records by:

$$\overline{D} = -m \ln\left(\frac{Q_{t=0}}{Q_o}\right), \tag{3.23}$$

where $Q_{t=0}$ is the measured stream flow known at the beginning of the model run.

While TOPMODEL is theoretically allowed to have negative soil moisture deficits (i.e., $D_i < 0$), meaning that water has ponded and overland flow is occurring, the implementation of TOPMODEL to PRMS will prevent this and always move that negative portion back into the soil zone as infiltration, re-setting D_i back to zero. Under these conditions, potential recharge occurring at this cell will be rejected, and forced to runoff downslope.

An interesting aspect of TOPMODEL, is that given an effective porosity/specific yield (S_y) of the cell's soil zone material, positive D_i can be directly related to a depth to watertable z_i $[L]$ at cell i by:

$$z_i = \frac{D_i}{S_y}, \tag{3.24}$$

and Equation 3.19 can be in terms of a depth to watertable by:

$$z_i = \overline{z} + \frac{1}{f}\left[\gamma - \ln\frac{a}{T_o \tan\beta}\right], \tag{3.25}$$

where $\overline{z}$ is the basin-average depth to watertable and f is a parameter that relates to m by $S_y = \frac{m}{f}$.

Used in conjunction with the urban hydrology processes built into GSFLOWurban, groundwater limitations to urban infrastructure can be (loosely) assessed without explicitly modelling them. This has great advantages in cases where explicit groundwater modelling runtimes are too expensive.

3.3.2 Numerical Implementation

TODO The module also depends on `hru_slope`.

Table 3.4: Input parameters required for PRMS Module: `gw_topmodel`.

[GWR: ground-water reservoir associated with a hydrologic response unit (PRMS only); **ngw**, number of PRMS ground-water reservoirs; **ntop**, number of TOPMODEL basins]

Parameter name	Description	Dimension variable	Units	Type	Range	Default value
`topmodel_k`	Lateral conductivity of the soil zone for each GWR	`ngw`	inches/day	real	0.0000001 to 5000000.0	35.0
`topmodel_sy`	specific yield near surface for each GWR	`ngw`	dimensionless	real	0.01 to 0.9	0.3
`topmodel_f`	TOPMODEL parameter f, relating to the exponential decline of transmissivity with depth	`ntop`	dimensionless	real	0.0 to 1.0	1.0
`hru_topbasin`	Index of TOPMODEL basin assigned to each HRU	`ngw`	dimensionless	integer	0 to `ntop`	1
`hru_z_init`	Watertable depth at each GWR at the beginning of a simulation	`ngw`	elev_units	real	0.0 to 1000.0	0.0

[a] matric potential must be inputted here as a positive (absolute) value (> 0.0).

Testing of model code

TO COMPLETE

A rigorous test was simultaneously performed on all real (i.e., non-integer) parameters introduced in the urban module. The test was performed in such manner as to ensure that virtually any possible permutation and combination of model parameterization is tested to ensure that:

1. the module proved to be fail-safe, in that no combination caused the model code to crash;
2. parameter values were ignored in cases where they were specified, but not required;
3. parameter values outside of their feasible range were flagged and the user notified; and,
4. the model results failed to cause any water balance errors (i.e., no significant volume of water was either lost or gained during model operation, other than that due to numerical round-off error).

Parameter testing was accomplished using a Monte Carlo Latin Hypercube sampling (MCLHS) methodology that ensures a n samples of parameter choices are selected equally dispersed from a specified range and sampled randomly (Lemieux, 2009). The parameters and their specified feasible ranges sampled from are given in Table 4.1. Here, the term "feasible range" implies the minimum to maximum value a value is likely to take during any practical application.

The MCLHS test was performed using 10,000 samples under 36 separate conditions, for a total of 360,000 separate model runs. The 36 conditions are a result of any combination of:

- 0, 1, or 2 disconnected reservoirs spanning over multiple HRUs (`dscn_hru_id`)
- 0, 1, or 2 infiltration reservoirs spanning over multiple HRUs (`infstor_hru_id`)
- 4 sewershed options (`stdrn_hru_id`), including:
  - sewershed equivalent to watershed contributing areas directed to stream segments
  - a random selection of 162 HRUs (50
  - a random selection of 162 HRUs (50
  - all HRUs draining to the farfield

Each sample consisted of a 10-year model run for a 324-HRU model. Parameterization was implemented randomly and independently to each HRU, thus effectively totalling 116 million parameter permutations.

A second round of testing was performed using only 10 samples similar to the above method, except and additional 4,095 (2^{12}-1) runs were performed by forcing any of the 12 parameters to zero, which effectively deactivates the parameter. This was done to ensure that by setting any parameter to zero, the modeller is given added flexibility to customize model function without running into issues common to zero-values in a numerical code (i.e., division by zero). This procedure will effectively add another 1.5 million parameter permutations.

Although the parameter test described herein is rigorous, it still cannot guarantee that the model code will never crash or yield spurious results. Through the support of this code, should any potential user come across an issue with the module and its computations, please do not hesitate to the author.

4.0.1 In PRMS-only mode

Twelve of the fourteen parameters (see Table 2.1) plus the universal `sri_to_perv` can be utilized without the need for an integrated groundwater system.

Table 4.1: Feasible ranges sampled from the real parameters required for the `srunoff_urban` module.

Parameter name	**Description**	**Sample range**	**Units**
`sri_to_perv`	Fraction of impervious runoff that is redirected to the pervious area with the same HRU	0.0 to 1.0	dimensionless
`imperv_stor_seep`	Fraction of impervious storage that is allowed to infiltrate	0.0 to 1.0	dimensionless
`imperv_stor_to_stdrn`	Fraction of impervious storage that is directed to storm drainage system	0.0 to 1.0	dimensionless
`stdrn_cond`	Conductance of storm drain walls used to compute groundwater infiltration and leakage	0.0 to 8.0	inches/day
`imperv_frac_dscn`	Fraction of impervious area that is disconnected	0.0 to 1.0	dimensionless
`dscn_stor_max`	Maximum disconnected retention storage	0.0 to 8.0	inches
`dscn_evap_coef`	Fraction of unsatisfied potential evapotranspiration to apply to disconnected storage	0.0 to 1.0	dimensionless
`dscn_to_stdrn`	Fraction of disconnected storage that is directed to storm drainage	0.0 to 1.0	dimensionless
`infstor_max`	Maximum infiltration detention storage	0.0 to 40.0	inches
`imperv_stor_to_infstor`	Fraction of impervious storage that is directed to infiltration storage system	0.0 to 1.0	dimensionless
`infstor_seep_coef`	Coefficient used in linear drainage flow from infiltration storage for each HRU	0.0 to 1.0	dimensionless
`Infstor_to_stdrn_coef`	Coefficient used in linear drainage flow from infiltration storage to storm drainage	0.0 to 1.0	dimensionless
`dscn_to_infstor`	Fraction of disconnected storage that is directed into infiltration storage	0.0 to 1.0	dimensionless

4.0.2 In GSFLOW mode

As urban development continues to expand into limited available land areas, urban planning in certain situations may be faced with development in areas known for having a regionally high watertable. A prime motivator for the development of this urban module was the lack of numerical tools available to investigate the consequence of such planning.

When adding the influence of the water table, 4 of 14 parameters will affect the outcome of the model results, and they include:

1. `infstor_invert`—the elevation at which groundwater starts to infiltrate the infiltration storage reservoir and thus prohibits the function of the infiltration facility;
2. `infstor_seep_cond`—is the conductance specified at the base of the infiltration storage reservoir that determines the rate water drains when the water table is below `infstor_invert`, or is infiltrated when the water table is above `infstor_invert`.
3. `stdrn_invert`—the elevation at which groundwater starts to infiltrate the HRU storm drains; `stdrn_cond`—is the conductance rate at which the HRU storm drain leaks when the water table is below `stdrn_invert`, or is infiltrated when the water table is above `stdrn_invert`.

References

Beven, K.J., M.J. Kirkby, 1979. A physically based variable contributing area model of basin hydrology. Hydrological Science Bulleton 24(1):43–69.

Beven, K.J., R. Lamb, P.F. Quinn, R. Romanowicz, and J. Freer, 1995. TOPMODEL. In Singh V.P. editor, Computer Models of Watershed Hydrology. Water Resources Publications, Highland Ranch, CO: pp. 627–668.

Beven, K.J., 2012. Rainfall-Runoff modelling: the primer, 2nd ed. John Wiley & Sons, Ltd. 457pp.

Chu, S.T., 1978. Infiltration During an Unsteady Rain. Water Research Research 14(3). pp.461–466.

Chow, V.T. (ed.), 1964. Handbook of Applied Hydrology: A Compendium of Water-Resources Technology. McGraw-Hill Book Company, New York, 1418p.

Green, W.H., G. Ampt, 1911. Studies of soil physics, part I—the flow of air and water through soils. Journal of Agricultural Science 4. pp.1–24

Harbaugh, A.W., 2005. MODFLOW-2005, the U.S. Geological Survey modular ground-water model—the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.

Hawkins, R.H., A.T. Hjelmfelt, A.W. Zevenbergen, 1985. Runoff Probability, Storm Depth, and Curve Numbers. Journal of the Irrigation and Drainage Division, ASCE 111(4). pp.330-340.

Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., and Barlow, P.M., 2008. GSFLOW—Coupled Ground-water and Surface-water FLOW model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005): U.S. Geological Survey Techniques and Methods 6-D1, 240 p.

Markstrom, S.L., Regan, R.S., Hay, L.E., Viger, R.J., Webb, R.M.T., Payn, R.A., and LaFontaine, J.H., 2015. PRMS-IV, the precipitation-runoff modeling system, version 4: U.S. Geological Survey Techniques and Methods, book 6, chap. B7, 158 p.

Mein, R.G., C.L. Larson, 1973. Modeling infiltration during a steady rain. Water Resources Research 9(2). pp.384–394.

Lemieux, C., 2009. Monte Carlo and Quasi-Monte Carlo Sampling. Springer Science. 373pp.

Lewis A. Rossman, L.A., W.C. Huber, 2016. Storm Water Management Model Reference Manual Volume III–Water Quality. National Risk Management Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH. 159pp.

Mishra, S.K., V.P. Singh, 2003. Soil Conservation Service Curve Number (SCS-CN) Methodology. Kluwer Academic Publishers: Water Science and Technology Library 42. 513pp.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams, 2011. Soil and Water Assessment Tool: Theoretical Documentation, version 2009: TR-406. 647pp.

Rawls, W.J., D.L. Brakensiek, N. Miller, 1983. Green-Ampt Infiltration Parameters from Soils Data. Journal of Hydraulic Engineering, ASCE 109(1). pp.62–70.

Singh, V.P. (ed.), 1995. Computer Models of Watershed Hydrology. Water Resources Publications. 1130pp.

The Toronto and Region Conservation Authority (TRCA) and Credit Valley Conservation (CVC), 2010. Low Impact Development Stormwater Management Planning and Design Guide, version 1.0. 300pp.

United States Department of Agriculture: Soil Conservation Service, 1972. National Engineering Handbook, Section 4–Hydrology. USDA-SCS, Washington, D.C.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27:129-144.