Basin Scale Concept Validation:
Newaukum Urban Approaches Draft 03/22/12

By: Olivia Wright and Erkan Istanbulluoglu

Approach 2: Landuse response to rainfall

The land use approach uses observed precipitation data to establish BMP scenarios and costs for rainfall and surface runoff storage. This approach will consider the response of different land cover types to precipitation across the basin. Figures 3 show the spatial distribution and total percent of 2009 impervious cover in the Newaukum Urban Basin.

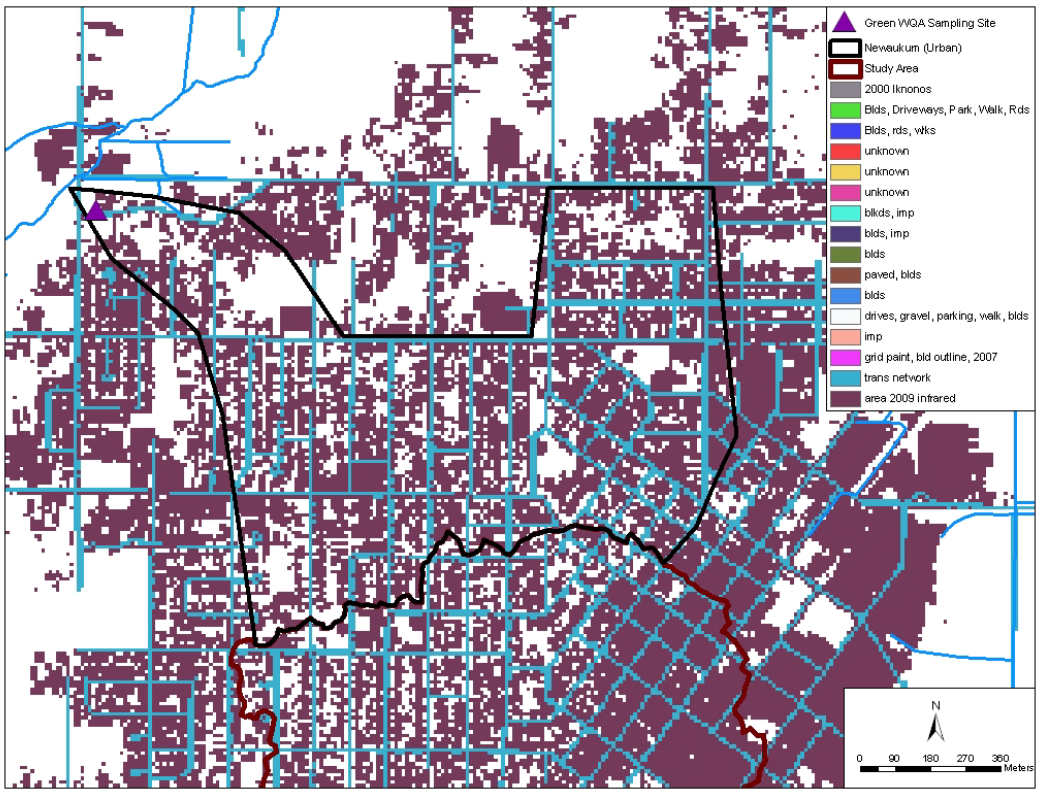


Figure 3. Newaukum (Urban) Basin 2009 Impervious Coverage

2009 Impervious cover:
15.45% Transportation Network
54.22% Impervious Area 2009 Infrared
30.33% Pervious

The landuse cover is divided into impervious rooftop area, impervious road area, and other impervious area. Rainfall generated surface runoff will be forced through an initial natural drainage treatment train as shown in Figure 4.

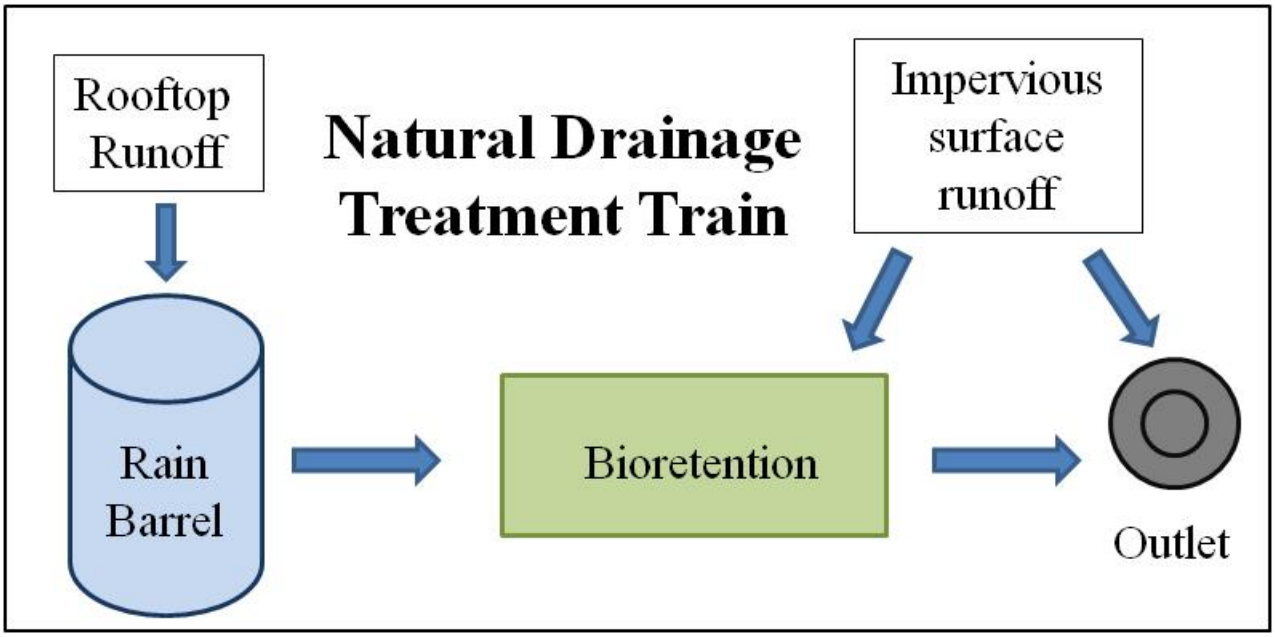


Figure 4. Natural Drainage Treatment Train

Rainbarrel Model

The rainbarrels in the treatment train are modeled to capture storm water runoff from rooftops within the basin. Figure 5 shows a conceptual diagram of the rainbarrel (*EPA SUSTAIN*, 2009).

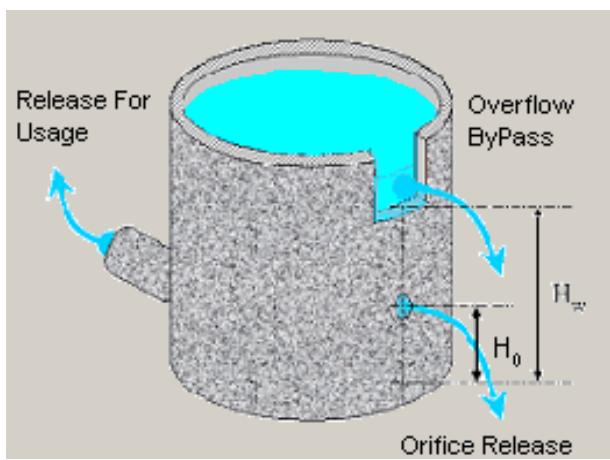


Figure . Rainbarrel Model

The storage in the rainbarrel varies with the rainfall volume coming into the rainbarrel and the resulting outflow of the rainbarrel. The change is volume is calculated as:

$$\frac{\Delta V}{\Delta t} = I - O$$

ΔV is the change in storage

Δt is the time interval

I is the inflow volume
O is the outflow volume

The Bernouli equation was applied to the rainbarrel to calculate the orifice outflow as follows:

$$Q_o = C_o A_o \sqrt{2gH}$$

C_o is the orifice coefficient of discharge
A_o is the area of the orifice
g is the acceleration due to gravity
H is the depth of the water level above the orifice

Our rainbarrel model assumes the rainbarrel is initially empty and the orifice is closed at the start of the simulation. As soon as the rain event begins, the rainbarrel fills until the rain stops. The owner opens the orifice as soon as the rain event ends, allowing the barrel to drain until empty or until the next storm events occurs, where the owner plugs the orifice again. The closing of the orifice causes the rainbarrel to fill and during large enough storm events, overflow. The rainbarrel overflow is calculated as:

$$Q_w(i) = \begin{cases} Vin(i) - Vrb(i-1) & Vrb(i) \geq V\max \\ 0 & Vrb(i) < V\max \end{cases}$$

Vin is the volume coming into the rainbarrel
Vrb is the volume of water in the rainbarrel
Vmax is the maximum volume of water the rainbarrel can hold

The total outflow of the rainbarrel is calculated by:

$$Q_t = \frac{V_o}{\Delta t} + Q_w$$

V_o is volume out

Roof area was calculated from building footprint information assigned to King County parcel data. The total roof area in the basin is approximately 100,839.28 m^2, or 24.92 acres. Our model evenly distributes the roof area runoff to rainbarrels in the basin. For the initial runs, one rainbarrel was assumed to treat approximately 100 m^2 of roof area , resulting in 1,009 rainbarrels distributed throughout the Newaukum Urban Basin. Figures 6 and 7 show preliminary results of the rainbarrel model.

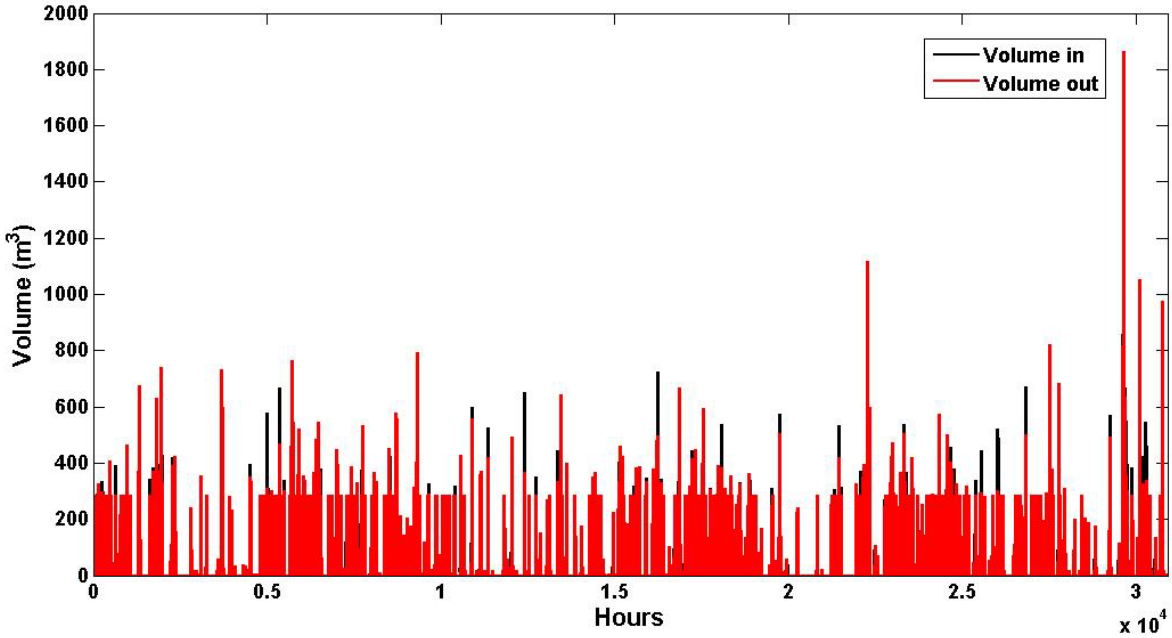


Figure 6. Modeled total volume in and out of all 1,009 rainbarrels in basin

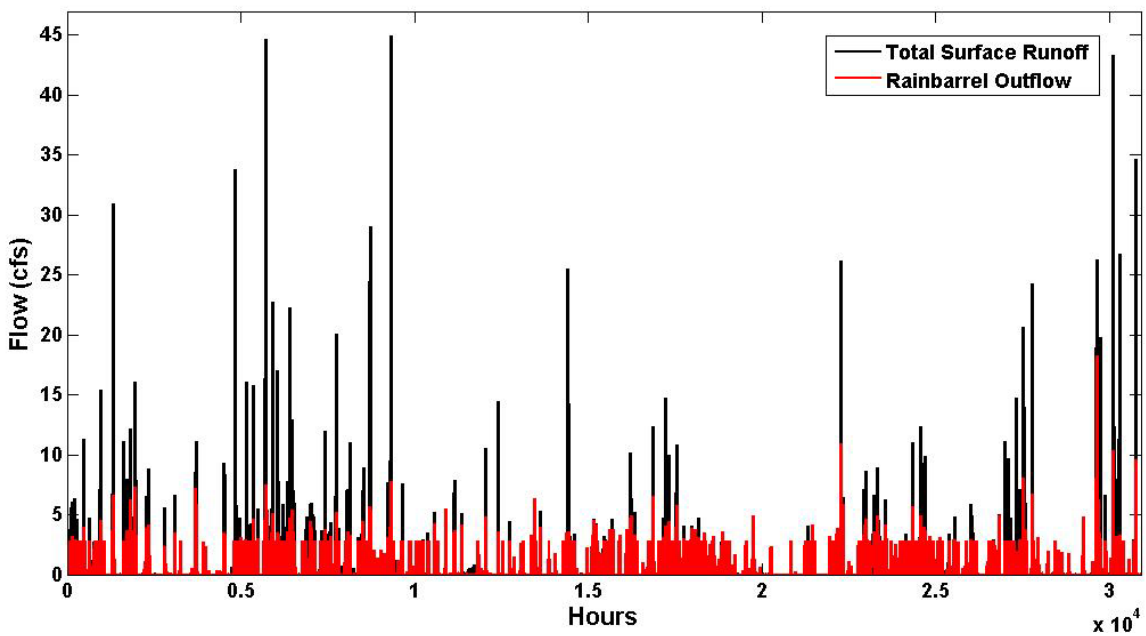


Figure 7. Modeled rainbarrel outflow for 1,009 rainbarrels and total surface runoff for the basin.

Bioretention Model: Bucket Grassland Model (BGM)

We model bioretention cells by modifying a lumped bucket hydrology model, the Bucket Grassland Model (BGM) (*Istanbulluoglu et al.*, 2012), Figure 8. Our modifications include an underdrain storage layer below the unsaturated root zone and a ponding layer above the soil layer.

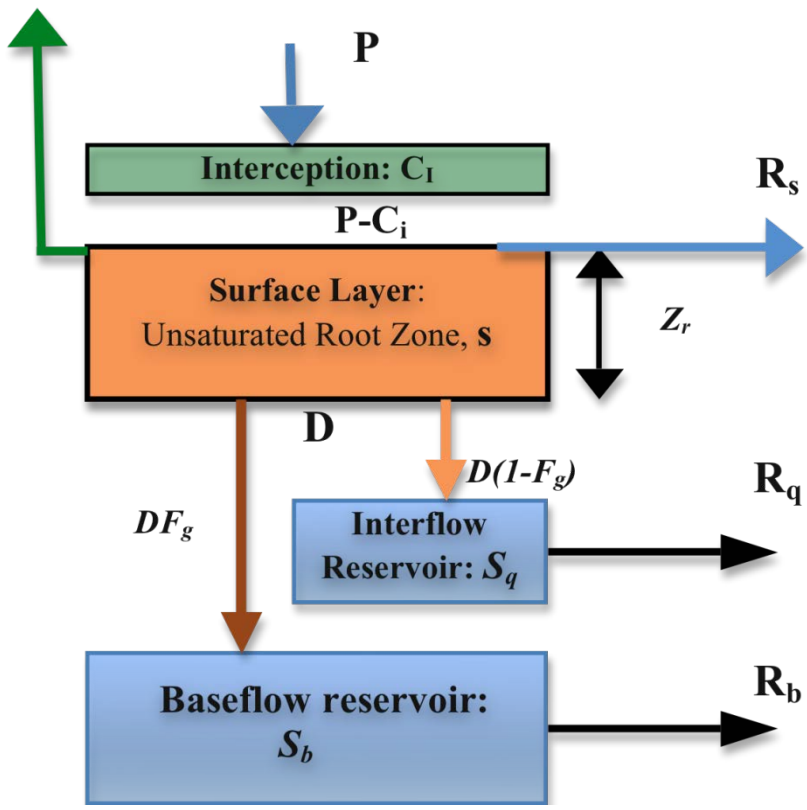


Figure 8. Conceptual representation of the processes in the BGM model

The depth averaged soil moisture in the root zone layer is calculated by the mass balance equation (*Istanbulluoglu*, 2012)

$$nZ_r \frac{ds}{dt} = I_a - ET_a(s) - D(s)$$

n is porosity
Z_r is effective rooting depth
s is soil moisture
t is time
I_a is infiltration rate
ET_a is actual evapotranspiration rate
D is drainage

Interception from the canopy is calculated by:

$$C_I = \min(I_{\max} V_t, P V_t)$$

I_{max} is a maximum hourly interception
V_t is the fraction of vegetation cover on the land surface (includes dry and live biomass)
P is depth of rainfall

When P is larger than C_I, throughfall occurs at the same rate as precipitation. The precipitation duration reaching the ground is reduced to account for initial filling of the canopy storage during the early part of the rain event. When the soil is unsaturated, the infiltration rate is determined by the minimum of the precipitation rate and the infiltration capacity. After soil saturation, the infiltration rate is reduced to the drainage rate:

$$I_a = \begin{cases} \min[p, I_c] & 0 \le s < 1 \quad P > C_I \\ D & s = 1 \quad P > C_I \end{cases}$$

p is average precipitation rate

I_c is infiltration capacity

Surface runoff occurs when p exceeds I_a and is approximated by:

$$R = \begin{cases} (p - I_a) & p > I_a \\ 0 & p \le I_a \end{cases}$$

** Currently being modified to represent more realistic bioretention conditions

The root zone layer is assumed to have uniform soil texture, porosity, and hydraulic conductivity. The drainage of the soil column by gravity is modeled to occur at the lowest boundary of the soil layer. At soil saturation, the drainage is at its maximum and is calculated as the saturated hydraulic conductivity (K_s) and decays exponentially to a value of zero at field capacity, s_{fc}.

$$D(s) = \begin{cases} Ks & s = 1 \\ K(s) = K_s s^{2b+3} & s_{fc} < s \le 1 \end{cases}$$

K(s) is unsaturated hydraulic conductivity
b is an empirical parameter in the Campbell soil moisture retention model (*Campbell*, 1974)

Actual evapotranspiration is calculated using a soil moisture limitation approach (*Laio et al.*, 2001; *Istanbulluoglu et al.*, 2011):

$$ET_a = PET \cdot \beta_s(s)$$

PET is the potential evapotranspiration

β_s is evapotranspiration efficiency term based on soil moisture

$$\beta_s(s) = \begin{cases} 0, & s_h < s \le s_w \\ \dfrac{s - s_w}{s^* - s_w}, & s_w < s \le s^* \\ 1 & s_* < s \end{cases}$$

s_h is soil hygroscopic capacity

s_w is soil moisture at wilting point

s^* is soil moisture at stomata closure

Hourly potential evapotranspiration is calculated using the Priestly Taylor method:

$$PET = \alpha \frac{\Delta}{\Delta + \gamma} \frac{(R_N - G)}{\rho_w \lambda_v}$$

Δ: slope of the saturation vapor pressure – temperature relationship (kPa $^oC^{-1}$);

R_N: net radiation at the evaporating surface (W/m^2)

G: ground heat flux (W/m^2);

$\lambda_v \rho_w$: [illegible] ^{2} mm^{-1}) or (680.16 Wh m^{-2} mm^{-1} for hourly);

γ : is the psychronometric constant (kPa $^oC^{-1}$)

$\alpha = 1.26$

As mentioned previously, additions to the BGM model include an underdrain layer and a ponding layer. The underdrain storage layer is a linear reservoir decaying with time that captures drainage from the root zone layer when the soil moisture is above field capacity. When the underdrain layer is saturated, drainage ceases causing the root zone to saturate and produce runoff. The ponding layer captures the surface runoff until the ponding volume exceeds the storage volume, resulting in surface overflow from the bioretention cell.

** Currently being modified to represent more realistic bioretention conditions

The model also includes a dynamic vegetation component that updates the amount of biomass and LAI below and above ground.

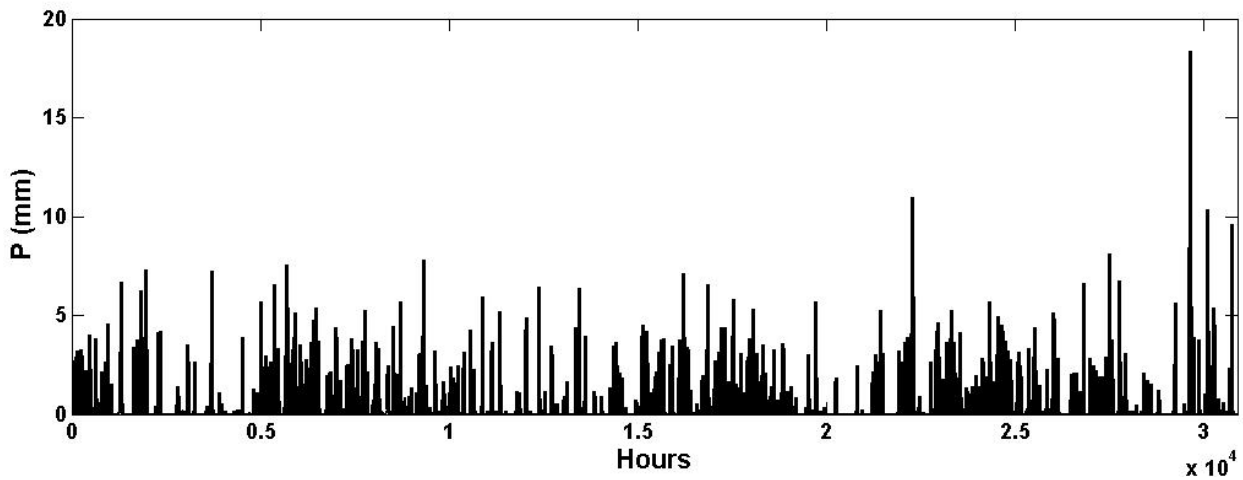
The total impervious area in the basin is 754,103.27 m^2, which includes roads, rooftops and all other impervious area in the basin (Table 1). For the initial model set up, the bioretention cells will treat surface runoff from the basin's impervious surfaces excluding the roads, or 586,877.79 m^2 of the basin.

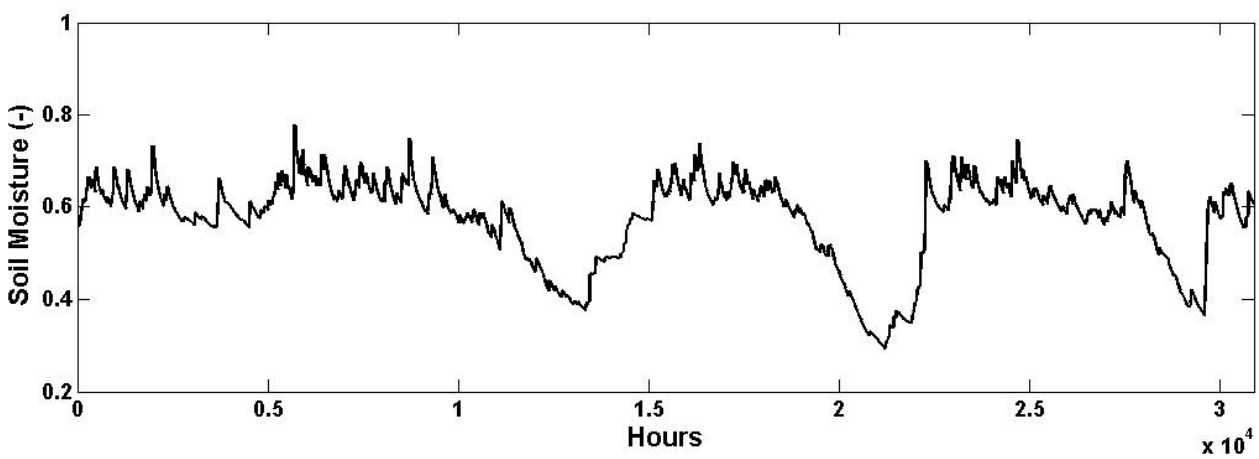
Impervious Category	Area (m^2)
Roads	167,225.47
Rooftop	100,839.28
Other	486,038.51
Total	**754,103.27**

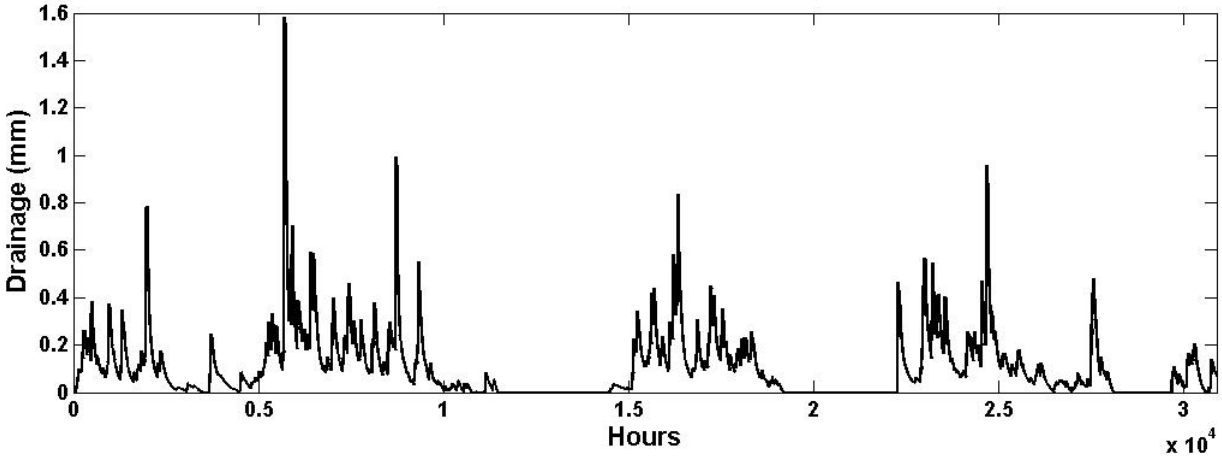
Table 1. Impervious area in Newaukum Urban Basin

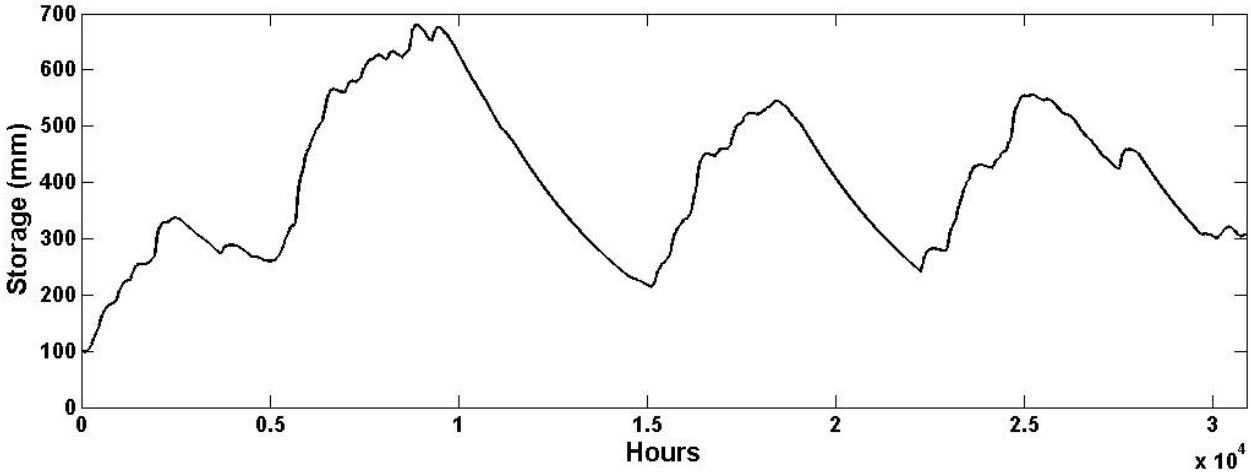
To understand the behavior of the unmodified BGM model, we initially ran two scenarios: observed precipitation input data only and calculated impervious surface runoff for the basin. Four figures for each scenario are plotted below: the precipitation or surface runoff model input, soil moisture, drainage and storage.

Scenario 1: Observed precipitation input only

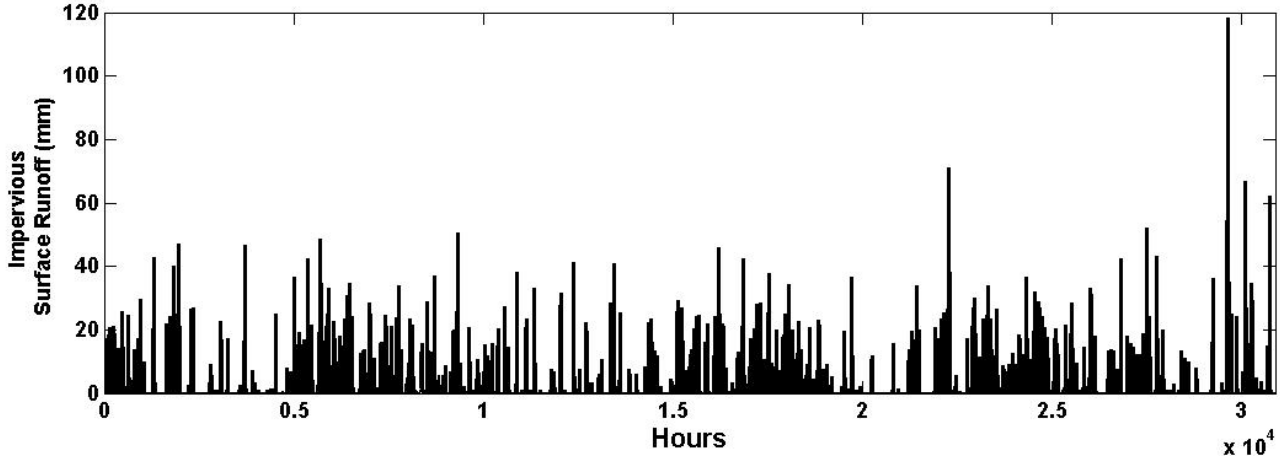


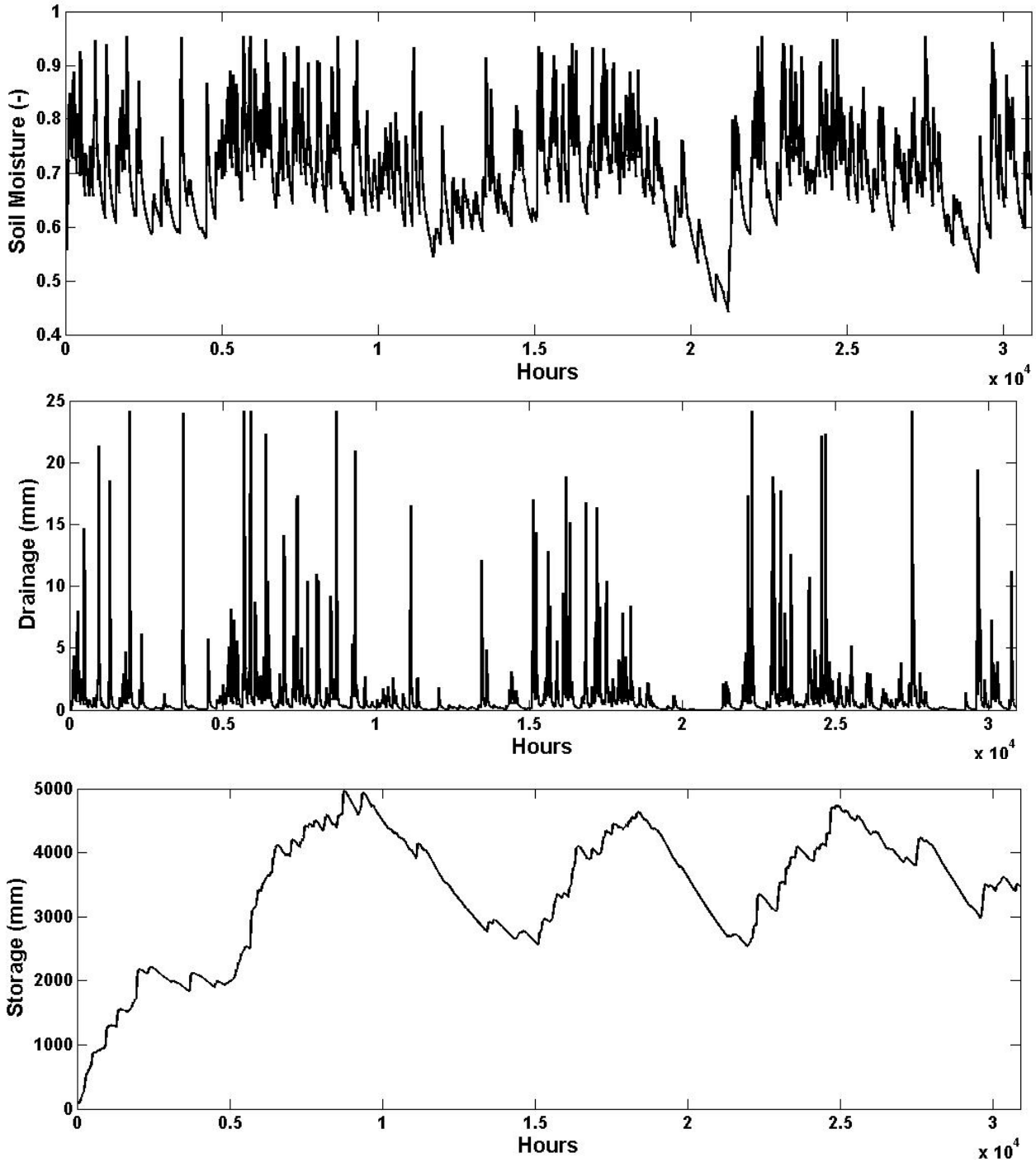






Scenario 2: Calculated impervious surface runoff input




Soil Moisture (-)
Hours
x 10^4
Drainage (mm)
Hours
x 10^4
Storage (mm)
Hours
x 10^4

References

Campbell, G. S. (1974), A simple method for determining unsaturated conductivity from moisture retention data, *Soil Sci.*, 117, 3311-314.

Chapman, T. (1991), Comment on ‘‘Evaluation of automated techniques for base flow and recession analyses’’ by R. J. Nathan and T. A. McMahon, *Water Resour. Res.*, 27, 1783– 1784.

Hino, M., and M. Hasabe (1984), Identification and prediction of nonlinear hydrologic systems by the filter-separation autoregressive (AR) method: extension to hourly hydrologic data, *J. Hydrol.*, 68, 181-210.

Istanbulluoglu, E., T. Wang, and D. A. Wedin (2012), Evaluation of ecohydrologic model parsimony at local and regional scales in a semiarid grassland ecosystem, *Ecohydrol.*, 5, 121-142.

Laio, F., A. Porporato, L. Ridolfi, I Rodriguez-Iturbe (2001), Plants in water controlled ecosystems: Active role in hydrologic processes and response to water stress II. Probabilistic soil moisture dynamics, *Adv. Water Resour.*, 24, 707-723.

Linsley et al. (1958), *Hydrology for Engineers*, McGraw-Hill, New York.

Nathan, R. J., and T. A. McMahon (1990), Evaluation of automated techniques for base flow and recession analyses, *Water Resour. Res.*, 26, 1465– 1473.

Smakhtin, V. U. (2001), Low flow hydrology: A review, *J. Hydrol.*, 240, 147– 186.

Sujono, J. et al. (2004), A comparison of techniques for hydrograph recession analysis, *Hydrol. Process.*, 18, 403-313.

Wang, T., E. Istanbulluoglu, J. Lenters, and D. Scott (2009a), On the role of groundwater and soil texture in the regional water balance: An investigation of the Nebraska Sand Hills, USA, *Water Resour. Res*., 45, W10413, doi:10.1029/2009WR007733.