**Supplementary Material**

# Evaluation of costs and efficiencies of urban Low Impact Development (LID) practices on stormwater runoff and soil erosion in an urban watershed using the Water Erosion Prediction Project (WEPP) model

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**Data S1 Water balance simulation in WEPP**

The Green-Ampt Mein-Larson model is used for infiltration estimation in the WEPP for the existence of excess rainfall when the rainfall rate is higher than the infiltration rate. Infiltration first begins to saturate topsoil before saturating the lower layers of soil (Equation S1) [1].

$$K_e t_c = F_i - \Psi \Theta_d ln[1 + \frac{F_i}{\Psi \Theta_d}] \quad \text{Equation S1}$$

$K_e$= effective saturated hydraulic conductivity $(m/s)$
$t_c$= corrected time to account for the difference in instantaneous time to ponding and the actual time to ponding
$F_i =$ cumulative infiltration depth at time i (m)
$\Psi$= average capillary potential across the wetting front (m)
$\Theta_d$= soil moisture deficit $(m/m)$

The runoff calculation method from CREAMS is adopted in WEPP. When there is rainfall excess, runoff is calculated by the time intensity distribution of rainfall excess being converted to a peak discharge value. The two main components of runoff simulation are the peak discharge rate and the effective duration (Equation S2) [1,2].

$$q_p = v_c (\frac{D_v}{t_e})^m \qquad D_v < t_e$$
$$q_p = v_c \qquad D_v > t_e \quad \text{Equation S2}$$

$q_p$= peak discharge rate $(m/s)$
$v_c$= constant rainfall excess rate $(m/s)$
$D_v$= duration of rainfall excess (s)
$t_e$= time to kinematic equilibrium computed using constant rainfall s excess rate (s)
m = kinematic wave depth-discharge exponent

WEPP uses the Penman equation for calculating evapotranspiration (ET). The Penman equation has many different climate-based components that are either observed values or generated by CLIGEN. The Penman equation relies on daily air and dew point temperatures, relative humidity, radiation, and wind (Equation S3) [3,4].

$$E_u = \frac{\delta}{\delta + y}(R_n - G) + \frac{\gamma}{\gamma + \delta} 6.43(1.0 + 0.53u_z)(e_z^o - e_z) \quad \text{Equation S3}$$

$E_u$= daily potential evapotranspiration $(MJ/m^2/\text{d})$
$\delta$= slope of the saturated vapor pressure curve at mean air temperature
$\gamma$= psychrometric constant
G = soil heat flux $(MJ/m^2/\text{d})$
$R_n$= net radiation $(MJ/m^2/\text{d})$
$u_z$= wind speed $(m/\text{s})$
$e_z^o$= saturated vapor pressure (KPa)

$e_z$= vapor pressure (KPa)

The percolation component of WEPP is based on storage routing techniques to simulate water flow through each layer of soil. WEPP also simulates the subsurface lateral flow of the water. With each layer of soil, there is a corresponding field capacity of water, and when that capacity is passed, percolation will happen (Equation S4) [3].

$$pe_i = (\Theta_i - FC_i)[1 - e^{\frac{-\Delta t}{t_i}}] \qquad \Theta_i > FC_i$$
$$pe_i = 0 \qquad \Theta_i \le FC_i \qquad \text{Equation S4}$$

$pe_i$= percolation rate through layer i $(m/d)$
$FC_i$= field capacity water content for layer i (m)
$\Delta t$= travel interval (s)
$t_i$= travel time through layer i (s)

**Table S1**. Delineation of the watershed by the online WEPPcloud interface.

| Watershed | Brentwood |
|---|---|
| NCDC weather station | Austin WB airport, TX |
| Outlet (long, lat) | -97.73°, 30.33° |
| Area (ha) | 141.34 |
| Minimum source channel length (m) | 70.00 |
| Critical source area (ha) | 5.00 |
| Longest flowpath slope gradient (%) | 1.85 |
| Average watershed slope gradient (%) | 1.47 |
| No. of hillslopes | 22 |
| No. of channels | 9 |
| Channel width (m) | 1~2 |
| Channel slope gradient (%) | 0.95 |

**Table S2**. Areas, slopes, land uses, runoff volumes, and sediment yields at hillslopes for the baseline.

| Hillslope | Area (ha) | Slope (%) | Land use | Runoff volume ($m^3$) | Sediment yield (kg) |
|---|---|---|---|---|---|
| 10 | 8.58 | 1.00 | Fallow (no vegetation) | 14643 | 16283 |
| 17 | 4.18 | 1.60 | Fallow (no vegetation) | 6765 | 7700 |
| 16 | 1.95 | 1.40 | Fallow (no vegetation) | 3342 | 3932 |
| 14 | 2.13 | 1.60 | Fallow (no vegetation) | 3496 | 3538 |
| 12 | 2.32 | 1.40 | Fallow (no vegetation) | 3807 | 3426 |
| 11 | 58.69 | 1.60 | Lawn | 80545 | 1625 |
| 13 | 0.33 | 1.10 | Fallow (no vegetation) | 576 | 720 |
| 9 | 0.14 | 0.90 | Fallow (no vegetation) | 249 | 331. |
| 4 | 6.02 | 1.60 | Lawn | 8252 | 197 |
| 7 | 7.54 | 1.50 | Lawn | 10336 | 214 |
| 8 | 5.91 | 1.60 | Lawn | 8125 | 184 |
| 20 | 5.12 | 1.80 | Lawn | 7024 | 151 |
| 15 | 1.02 | 1.00 | Lawn | 1420 | 28 |
| 3 | 0.96 | 1.30 | Lawn | 1323 | 27 |
| 21 | 0.95 | 0.80 | Lawn | 1322 | 22 |
| 22 | 0.80 | 1.00 | Lawn | 1114 | 20 |
| 5 | 0.76 | 1.20 | Fallow (no vegetation) | 1057 | 24 |
| 1 | 0.48 | 1.30 | Lawn | 668 | 14 |

| | | | | | |
|---|---|---|---|---|---|
| 19 | 0.28 | 0.90 | Lawn | 389 | 7 |
| 2 | 0.37 | 0.60 | Fallow (no vegetation) | 515 | 7 |
| 6 | 0.10 | 1.50 | Undeveloped Tall Grass | 139 | 3 |
| 18 | 0.08 | 1.30 | Undeveloped Tall Grass | 111 | 2 |

**Table S3.** The representation of LIDs in the WEPP model.

| LIDs | Parameter | Unit | Values with LIDs |
|---|---|---|---|
| **Native Planting** | Plant (.man) | - | Big Bluestem |
| | Initial residue cropping system (.man) | - | Perennial |
| | Initial canopy cover (.man) | % | 70 |
| | Initial rill and interrill cover (.man) | % | 80 |
| | Maximum root depth (.man) | m | 1 |
| | Maximum root mass for a perennial crop (.man) | $kg/m^2$ | 0.86 |
| | Biomass energy ratio (.man) | kg/MJ | 25 |
| | Use fragile or non-fragile mfo values (.man) | - | Non-Fragile |
| | Number of cut operations in year (.man) | - | 0 |
| **Rain Garden** | Plant (.man) | - | Big Bluestem |
| | Initial residue cropping system (.man) | - | Perennial |
| | Initial canopy cover (.man) | % | 70 |
| | Initial rill and interrill cover (.man) | % | 80 |
| | Maximum root depth (.man) | m | 1 |
| | Maximum root mass for a perennial crop (.man) | $kg/m^2$ | 0.86 |
| | Biomass energy ratio (.man) | kg/MJ | 25 |
| | Use fragile or non-fragile mfo values (.man) | - | Non-Fragile |
| | Number of cut operations in year (.man) | - | 0 |
| | Number of soil layers (.sol) | - | 4 |
| | Baseline interrill erodibility parameter (.sol) | $kg*s/m^4$ | 100 |
| | Baseline rill erodibility parameter (.sol) | s/m | 0.01 |
| | Baseline critical shear parameter (.sol) | $N/m^2$ | 40 |
| **Permeable Pavement** | Plant (.man) | - | Bromegrass |
| | Initial residue cropping system (.man) | - | Perennial |
| | Initial canopy cover (.man) | % | 15 |
| | Initial rill and interrill cover (.man) | % | 50 |
| | Maximum root depth (.man) | m | 0.03 |
| | Maximum root mass for a perennial crop (.man) | $kg/m^2$ | 0.34 |
| | Biomass energy ratio (.man) | kg/MJ | 15 |
| | Use fragile or non-fragile mfo values (.man) | - | Non-Fragile |
| | Number of cut operations in year (.man) | - | 15 |
| | Number of soil layers (.sol) | - | 4 |
| | Baseline interrill erodibility parameter (.sol) | $kg*s/m^4$ | 100 |
| | Baseline rill erodibility parameter (.sol) | s/m | 0.01 |
| | Baseline critical shear parameter (.sol) | $N/m^2$ | 40 |

| | | | |
|---|---|---|---|
| | Effective hydraulic conductivity (.sol) | mm/h | 50 |
| **Detention Pond** | Flow length of the rock-fill check dam (.imp) | m | 5 |
| | Stage at which flow through the rock-fill check dam occurs (.imp) | m | 5 |
| | Overtopping stage (.imp) | m | 10 |
| | Cross-sectional width of the rock-fill check dam (.imp) | m | 50 |
| | Average diameter of the rocks forming the dam (.imp) | m | 0.01 |
| | Stage at which the overtop flag goes off (.imp) | m | 5 |
| | Stage at which the full of sediment flag goes off (.imp) | m | 0.4 |
| | Stage at the beginning of the simulation (.imp) | m | 2.438 |
| | Initial time step (.imp) | hr | 0.01 |
| | Infiltration rate (.imp) | m/d | 0.00864 |
| | Structure size (.imp) | - | Large |
| | Number of particle size subclass divisions (.imp) | - | 2 |

**Table S4**. Design and cost calculations of single LIDs in all suitable areas.

| LID | Rain garden | Permeable Pavement | Native planting | Detention Pond |
|---|---|---|---|---|
| **Operation 1** | Site Preparation, Mechanical | Excavation, common earth, large equipment, 46 m | Site Preparation, Mechanical | Excavation, common earth, large equipment, 15 m |
| **ID 1** | 944 | 1223 | 944 | 1222 |
| **Cost 1** | 24.88 | 2.75 | 24.88 | 1.15 |
| **Cost 1 Unit** | \$/ha | \$/m$^3$ | \$/ha | \$/m$^3$ |
| **Details 1** | Aerator, rolling drum chopper, etc. Includes equipment, power unit and labor costs. | Bulk excavation of common earth including sand and gravel with dozer >75 kW with average push distance of 46 m. Includes equipment and labor. | Aerator, rolling drum chopper, etc. Includes equipment, power unit and labor costs. | Bulk excavation of common earth including sand and gravel with dozer >75 kW with average push distance of 15 m. Includes equipment and labor. |
| **Operation 2** | Seeding Operation, Broadcast, 959 Ground | Aggregate, Gravel, Graded | General Labor | General Labor |
| **ID 2** | 959 | 46 | 231 | 231 |
| **Cost 2** | 4.65 | 28.02 | 21.65 | 21.65 |
| **Cost 2 Unit** | \$/ha | \$/m$^3$ | \$/hr | \$/hr |

| | | | | |
|---|---|---|---|---|
| **Details 2** | Broadcast seed via ground operation. May require post tillage operation to incorporate seed. Includes equipment, power unit and labor costs. | Gravel, includes materials, equipment and labor to transport and place. Includes washed and unwashed gravel. | Labor performed using basic tools such as power tool, shovels, and other tools that do not require extensive training. Ex. pipe layer, herder, concrete placement, materials spreader, flagger, etc. | Labor performed using basic tools such as power tool, shovels, and other tools that do not require extensive training. Ex. pipe layer, herder, concrete placement, materials spreader, flagger, etc. |
| **Operation 3** | General Labor | Introduced Perennial Grasses, Legumes and/or Forbs, Low Density | Straw | Rock Riprap, Placed with geotextile |
| **ID 3** | 231 | 2747 | 1237 | 44 |
| **Cost 3** | 21.65 | 12.44 | 65 | 38.14 |
| **Cost 3 Unit** | $/hr | $/ha | $/Mg | $/ha |
| **Details 3** | Labor performed using basic tools such as power tool, shovels, and other tools that do not require extensive training. Ex. pipe layer, herder, concrete placement, materials spreader, flagger, etc. | Introduced perennial grasses, legumes, and/or forbs, may include a small percentage of annual species for establishment purposes and/or if allowed by the CPS. Planted at lower to medium density (3.72 pure live seeds/$m^2$ and less). Includes material and shipping. | Small grain straw (non organic and certified organic). Includes materials only. | Rock Riprap, placed with geotextile, includes materials, equipment and labor to transport and place |
| **Operation 4** | Straw | | Native Perennial Grasses, Low 2750 Density | Mobilization, large equipment |
| **ID 4** | 1237 | | 2750 | 1140 |
| **Cost 4** | 65 | | 45.05 | 467.6 |
| **Cost 4 Unit** | $/Mg | | $/ha | $/machine |

| | | | | |
|---|---|---|---|---|
| **Details 4** | Small grain straw (non organic and certified organic). Includes materials only. | | Native perennial grasses, may include a small percentage of annual species for establishment purposes and/or if allowed by the CPS. Planted at lower to medium density (3.72 pure live seeds/m$^2$ and less). Includes material and shipping. | Equipment >112 kW or typical weights greater than 13.61 Mg or loads requiring over width or over length permits. |
| **Operation 5** | Native Perennial Grasses, Low 2750 Density | | | |
| **ID 5** | 2750 | | | |
| **Cost 5** | 45.05 | | | |
| **Cost 5 Unit** | $/ha | | | |
| **Details 5** | Native perennial grasses, may include a small percentage of annual species for establishment purposes and/or if allowed by the CPS. Planted at lower to medium density (3.72 pure live seeds/m$^2$ and less). Includes material and shipping. | | | |
| **Operation 6** | Aggregate, Gravel, Graded | | | |
| **ID 6** | 46 | | | |
| **Cost 6** | 28.02 | | | |
| **Cost 6 Unit** | $/m$^3$ | | | |
| **Details 6** | Gravel, includes materials, equipment and labor to transport and place. Includes washed and | | | |

| | |
|---|---|
| | unwashed gravel. |

| | |
|---|---|
| **Operation 7** | Excavation, common earth, large equipment, 46 m |
| **ID 7** | 1223 |
| **Cost 7** | 2.74 |
| **Cost 7 Unit** | $/m$^3$ |
| **Details 7** | Bulk excavation of common earth including sand and gravel with dozer >75 kW with average push distance of 46 m. Includes equipment and labor. |

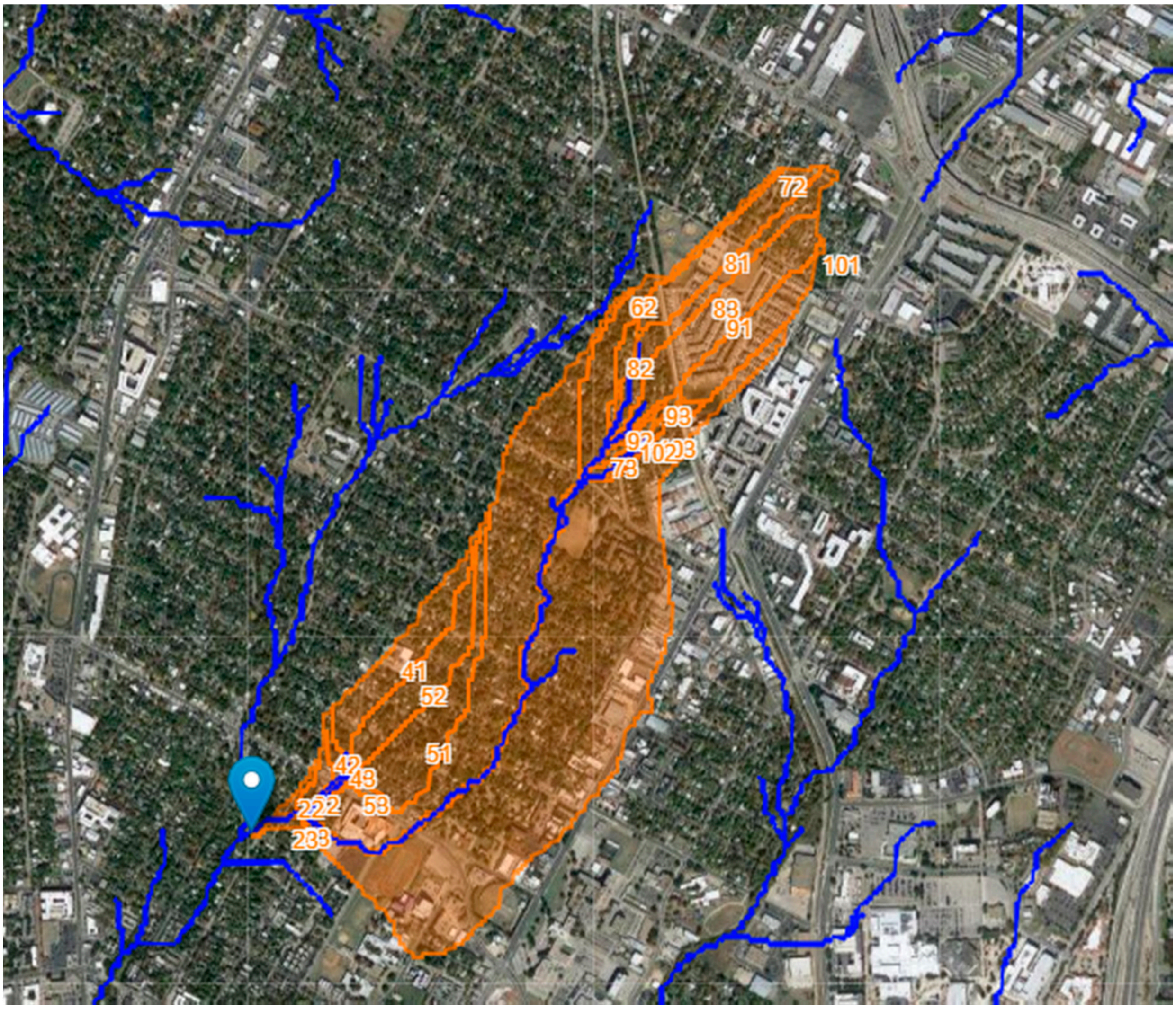


**Figure S1.** Watershed delineation for the Brentwood watershed from the WEPPcloud interface.

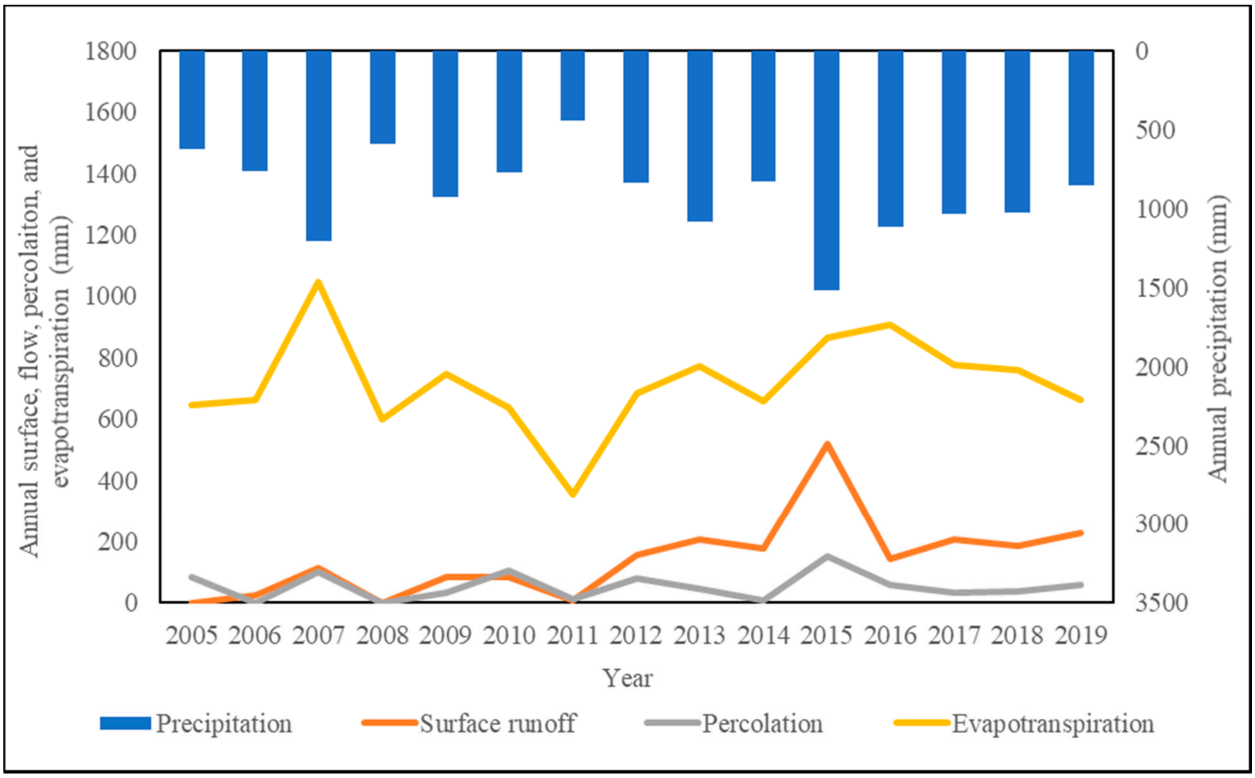


**Figure S2.** Annual flow components for the baseline in the watershed during the model simulation period (2005-2019).

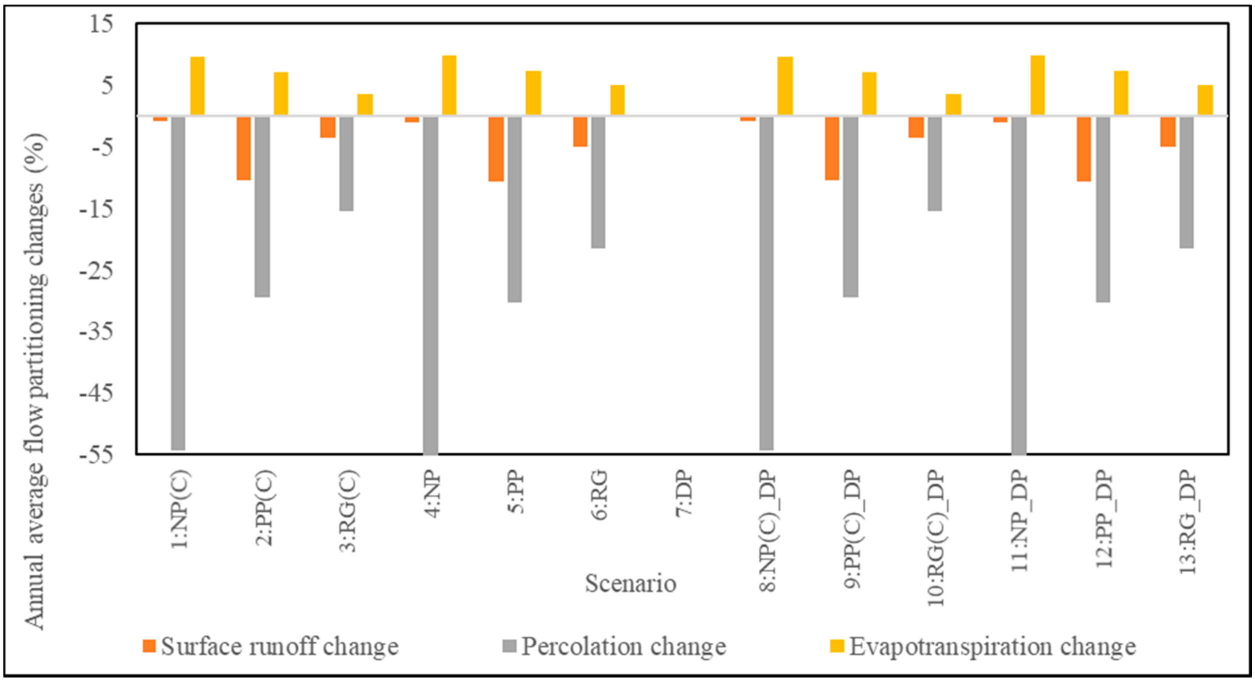


**Figure S3**. Average annual flow component changes to the baseline for the 13 scenarios in the watershed during the model simulation period (2005-2019).

**References:**


1. Stone, J.; Lane, L.; Shirley, E.; Hernandez, M. Chapter 4. Hillslope surface hydrology. In (Flanagan DC, Nearing MA, eds.) USDA-Water Erosion Prediction Project Hillslope Profile and Watershed Model Documentation. NSERL Report No. 10. USDA-ARS National Soil Erosion Research Laboratory West Lafayette, IN USA, 1995.
2. Chu, S.T. Infiltration during an unsteady rain. *Water Resour. Res.* **1978**, *14*, 461-466.
3. Savabi, M.; Williams, J. Chapter 5. Water balance and percolation. In (Flanagan DC, Nearing MA, eds.) USDA-Water Erosion Prediction Project Hillslope Profile and Watershed Model Documentation. NSERL Report No. 10. USDA-ARS National Soil Erosion Research Laboratory West Lafayette, IN USA, 1989.
4. Guo, T.; Srivastava, A.; Flanagan, D.C. Improving and calibrating channel erosion simulation in the Water Erosion Prediction Project (WEPP) model. *J. Environ. Manage* **2021**, *291*, 112616.