**Table 1** Summary of recent numerical studies on bioretention columns with typical media structure. Typical media structure refers to planting soil on the top, engineered soil in the middle, and drainage layer at the bottom.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Study** | **Model** | **Modeling**  **Layer** | **Rain Events/Inflows** | **Hydraulics Outflows** | **Water**  **Quality Modeled** | **Ponding** | **Expt.**  **for Model Calibration** | **Comments** |
| This study | HYDRUS 1D | Ponding,  Plant soil,  Soil layer, Gravel | Design storms:  1:2, 1:5, 1:10, 1:25, 1:50, 1:100 yr  Rainfall depth:  24, 35, 43, 56, 69, 84 mm  Duration: 4 hrs, Chicago  Also snow melt &spring runoff events  CA/SA: 10 | Expt.: Free drainage & IWS (Internal water storage)  Model: Free drainage & IWS | NO2-N,  NO3-N,  NH3-N,  TP, Cl | Ponding observed. Simulated results close | Lab | 1. Accurate calibration & validation for summer rainfall  2. Also modeling for snowmelt & spring runoff events  3. HP1 was used for nutrient removal simulation |
|  |  |  |  |  |  |  |  |  |
| Li et al.,  2021 | HYDRUS 1D | Ponding,  Plant soil,  Soil layer, Gravel | Design storms: 1:2 & 1:5 yr  Rainfall depth: 25 & 34 mm  Duration: 120 min  CA/SA: 17 | Expt.: Free drainage & IWS  Model: Free drainage & IWS | COD,  NO3-N,  NH3-N,  TN, TP,  Cu, Zn, Cd | None | Lab | Able to simulate pollutants removal with adding amendments |
|  |  |  |  |  |  |  |  |  |
| Lisenbee et al., 2020 | DRAINMOD-Urban | Ponding,  Soil layer, Gravel | Local storms  Rainfall depth: 5 -97mm  Duration: N/A  CA/SA: 19.8 | Expt.: IWS  Model: Free drainage | None | None | Field | 1. Accurate calibration and validation for single event  2. Time scale: 1 min  3. Need manual calibration |
|  |  |  |  |  |  |  |  |  |
| Jiang et al.,  2019 | HYDRUS 1D | Ponding,  Plant soil,  Soil layer, Gravel | Design storms: 1:2 & 1:5 yr  Rainfall depth: 25 & 34 mm  Duration: 120 min  CA/SA: 17 | Expt.: Free drainage & IWS  Model: Free drainage | None | None | Field | No comprehensive calibration and validation |
|  |  |  |  |  |  |  |  |  |
| Li et al.,  2018 | HYDRUS 1D | Ponding,  Plant soil,  Soil layer, Gravel | Design storms: 1:2 & 1:5 yr  Rainfall depth: 25 & 34 mm  Duration: 120 min  CA/SA: 17 | Expt.: Free drainage & IWS  Model: Free drainage | COD,  NO3-N,  NH3-N,  TN, TP | None | Field | 1. Conduct nutrients removal simulation  2. No comprehensive calibration & validation |
|  |  |  |  |  |  |  |  |  |
| Gülbaz and Kazezyilmaz-Alhan, 2017 | RWB (Improved Green-Ampt method) & SWMM | Ponding,  Plant soil,  Soil layer, Gravel | Design storms  Rainfall depth: 4,8,11,17 mm  Duration: 15,20,25,30 min  CA/SA: 20 | Expt.: Free drainage  Model: Free drainage | None | Ponding observed. Simulated results close | Field | 1. RWB had better simulation results than SWMM  2. SWMM did not match peak flow  3. Both RWB and SWMM simulation did not match measured outflow after peak |
|  |  |  |  |  |  |  |  |  |
| Liu and Fassman-Beck, 2017a | SWMM | Ponding,  Soil layer, Gravel | Design storms: 1:2 yr  Rainfall depth: 13 mm  Duration: 1 hr  CA/SA: 43 | Expt.: Free drainage & IWS  Model: Free drainage | None | N/A | Lab | The simulation was not accurate |
|  |  |  |  |  |  |  |  |  |
| Liu and Fassman-Beck, 2017b | HYDRUS 1D | Ponding,  Soil layer, Gravel | Design storms: 1:2 yr  Rainfall depth: 13 mm  Duration: 1 hr  CA/SA: 20 | Expt.: Free drainage  Model: Free drainage | None | N/A | Lab | Accurate calibration & validation |
|  |  |  |  |  |  |  |  |  |
| Meng et al.,  2014 | HYDRUS 1D | Ponding,  Soil layer, Gravel | Local storms & Design storms  Rainfall depth: N/A  Duration: N/A  CA/SA: 10 | Expt.: Free drainage  Model: Free drainage | None | Ponding observed and simulated only for design storms  Duration: 180 mins  Max.: 12 cm | Field | Accurate calibration & validation |
|  |  |  |  |  |  |  |  |  |
| Brown et al.,  2013 | DRAINMOD | Ponding,  Soil layer, Gravel | Local storms  Rainfall depth: 2.5 ~ >38 mm  Duration: N/A  CA/SA: 14 & 16 | Expt.: Free drainage & IWS  Model: Free drainage & IWS | None | Ponding and overflow observed | Field | 1. Modelled long term hydrological performance  2. Not suitable for single rainfall event due to time scale limitation |
|  |  |  |  |  |  |  |  |  |
| He and Davis, 2011 | 2D variable saturated flow model (Richards equation) | Ponding,  Soil layer, surrounding gravel soil | Local storms  Rainfall depth: 2.5 - >25 mm  Duration: 2-24 hr  CA/SA: 20 | Expt.: Free drainage  Model: Free drainage | None | N/A | Field | 1. Discussed the influence of types of soil media & surrounding soil.  2. No validation. |

**Table 2** Sensitivity test of hydraulic parameters, using Column 1 as an example. The objective was to evaluate the change in peak outflow due to the change of one parameter while maintaining all other parameters the same.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Soil** | **Index** | ***Qr*** | ***Qs*** | ***α***  **(1/cm)** | ***n*** | ***Ks* (cm/min)** |
|  | Increments | +0.01 | +0.1 | +0.01 | +0.1 | +0.01 |
| Topsoil | Change in peak outflow | 0.11% | -1.14% | -0.07% | -0.17% | 0.16% |
| Middle Layer | 0.03% | -0.34% | 3.71% | 2.34% | 20.03% |
|  |  |  |  |  |  |  |
|  | Increments | -10% | -10% | -10% | -10% | -10% |
| Topsoil | Change in peak outflow | -0.07% | 0.59% | 0.04% | 0.44% | -0.46% |
| Middle Layer | -0.01% | 0.13% | 0.80% | -5.10% | -9.13% |

**Table 3** Pollutant concentrations in the soils (based on the leaching test) and in the rainfall/inflow. The unit is mmol/kgw, except for CEC (Cation Exchange Capacity) that uses meq/100g) (Kratky, 2019)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Pollutants** | **Inflow** | **Compost** | **Soil A** | **Soil A with 20% compost** | **Soil B** | **Soil B with 20% compost** |
| NH4+ | 0.111 | 0.013 | 0.019 | 0.042 | 0.007 | 0.014 |
| NO3- | 0.024 | 0.045 | 0.740 | 3.518 | 0.034 | 0.731 |
| NO2- | 0.011 | 0.231 | 2.233 | 10.242 | 0.176 | 2.189 |
| PO4- | 0.021 | 0.001 | 0.070 | 0.348 | 0.001 | 0.070 |
| Cl- | 0.534 | 0.094 | 0.279 | 1.020 | 0.044 | 0.239 |
| K+ | 0.045 | 0.046 | 0.810 | 3.866 | 0.035 | 0.801 |
| Na+ | 0.434 | 0.311 | 2.493 | 11.220 | 0.213 | 2.415 |
| CEC | N/A | 16.0 | 12.0 | 25.0 | 17.8 | 14.6 |

**Table 4** Calibrated hydraulic parameters of the four bioretention columns in summer. The five hydraulic parameters of the top layer and middle layer were calibrated (i.e., a total of 10 parameters), while the five parameters of the gravel layer were fixed.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Column** | **Soil Layer** | ***Qr*** | ***Qs*** | ***α***  **(1/cm)** | ***n*** | ***Ks* (cm/min)** |
| **1** | Top Layer | 0.067 | 0.519 | 0.051 | 1.902 | 0.247 |
| Middle Layer | 0.041 | 0.398 | 0.003 | 1.737 | 0.044 |
| Gravel | 0.005 | 0.42 | 0.12 | 2.5 | 750 |
|  |  |  |  |  |  |  |
| **2** | Top Layer | 0.09 | 0.52 | 0.029 | 1.726 | 0.282 |
| Middle Layer | 0.066 | 0.42 | 0.005 | 1.511 | 0.154 |
| Gravel | 0.005 | 0.42 | 0.12 | 2.5 | 750 |
|  |  |  |  |  |  |  |
| **3** | Top Layer | 0.033 | 0.526 | 0.06 | 1.917 | 0.224 |
| Middle Layer | 0.021 | 0.41 | 0.01 | 1.867 | 0.089 |
| Gravel | 0.005 | 0.42 | 0.12 | 2.5 | 750 |
|  |  |  |  |  |  |  |
| **4** | Top Layer | 0.045 | 0.5 | 0.028 | 1.844 | 0.219 |
| Middle Layer | 0.033 | 0.46 | 0.007 | 1.656 | 0.144 |
| Gravel | 0.005 | 0.42 | 0.12 | 2.5 | 750 |

**Table 5.** Summary of the fitness values (R2) for the model calibration and validation for the four bioretention columns during summer storm events

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | **R2** | |
| **Storm Event** | **Column** | **Q out** | **Ponding Depth** |
| **1:2 Year**  **(for calibration)** | 1 | 0.92 | 0.83 |
| 2 | 0.96 | / |
| 3 | 0.97 | 0.89 |
| 4 | 0.84 | 0.9 |
|  |  |  |  |
| **1:5 Year**  **(for validation)** | 1 | 0.8 | 0.97 |
| 2 | 0.92 | 0.47 |
| 3 | 0.83 | 0.81 |
| 4 | 0.62 | 0.79 |
|  |  |  |  |
| **1:10 Year**  **(for validation)** | 1 | 0.86 | 0.82 |
| 2 | 0.79 | 0.81 |
| 3 | 0.83 | 0.88 |
| 4 | 0.69 | 0.86 |

**Table 6** Calibrated hydraulic and heat transport parameters for bioretention Columns 1-2 during winter snowmelt and spring runoff events. The five hydraulic parameters of the top layer and middle layer were calibrated, and the five hydraulic parameters of the gravel layer were fixed. All the thermal parameters of the three layers were adopted from the literature review.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Column** | **Soil Medium** | ***Qr*** | ***Qs*** | ***α* (1/cm)** | ***n*** | ***Ks* (cm/min)** | ***F*** | ***b1***  **(W/m/℃）** | ***b2* (W/m/℃）** | ***b3* (W/m/℃）** |
| **1** | Top Layer | 0.067 | 0.519 | 0.051 | 1.9 | 0.121 | 0.112 | 0.243 | 0.39 | 1.53 |
| Middle Layer | 0.041 | 0.398 | 0.003 | 1.74 | 0.115 | 0.013 | 0.243 | 0.39 | 1.53 |
| Gravel | 0.005 | 0.42 | 0.120 | 2.5 | 500 | 0.005 | 0.228 | -2.40 | 4.92 |
|  |  |  |  |  |  |  |  |  |  |  |
| **2** | Top Layer | 0.09 | 0.55 | 0.029 | 1.73 | 0.120 | 0.216 | 0.228 | -2.40 | 4.92 |
| Middle Layer | 0.066 | 0.42 | 0.005 | 1.51 | 0.114 | 0.003 | 0.228 | -2.40 | 4.92 |
| Gravel | 0.005 | 0.42 | 0.113 | 2.5 | 500 | 0.005 | 0.228 | -2.40 | 4.92 |

**APPENDIX**

**Table A1** The stormwater pollutant concentrations to the bioretention columns in the experiments of Li (2019) and Kratky (2019)

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Source** | **Concentration**  **(mg/L)** |
| Ammonium (NH4+ - N) | NH4Cl | 2 |
| Nitrate (NO3--N) | KNO3 | 1.5 |
| Nitrite (NO2--N) | NaNO2 | 0.5 |
| Phosphate (PO43--P) | KH2PO4 | 2 |
| Chloride (Cl-) | NaCl | 15a |
| 320b |
| 1280c |

Note: a During summer operation including the 1:5 and 1:10 year storm events;

b During Year 1 winter operation and the second spring runoff event (major snow melt);

c During Year 1 the first spring runoff event (first flush).

**Table A2** The 4-hr design storm intensity in Chicago distribution. The 1:2, 1:5, and 1:10 year storms were modified from COE (2014) and used in Li (2019) and Kratky (2019)’s experiments, and 1:25, 1:50, and 1:100 year storms were from EPCOR (2018).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Time (min) | Return Frequency (mm/hr) | | | | | |
| 2-yr | 5-yr | 10-yr | 25-yr | 50-yr | 100-yr |
| 0 | 0.00 | 0.00 | 0.00 | 0 | 0 | 0 |
| 5 | 1.39 | 4.15 | 4.91 | 3.82 | 4.92 | 6.25 |
| 10 | 1.39 | 4.15 | 4.91 | 4.04 | 5.19 | 6.58 |
| 15 | 1.39 | 4.15 | 4.91 | 4.28 | 5.49 | 6.97 |
| 20 | 1.39 | 4.15 | 4.91 | 4.56 | 5.84 | 7.41 |
| 25 | 1.39 | 4.15 | 4.91 | 4.89 | 6.25 | 7.92 |
| 30 | 1.39 | 4.15 | 4.91 | 5.27 | 6.73 | 8.52 |
| 35 | 1.39 | 4.15 | 4.91 | 5.74 | 7.31 | 9.24 |
| 40 | 2.60 | 6.20 | 7.44 | 6.31 | 8.01 | 10.12 |
| 45 | 2.60 | 6.20 | 7.44 | 7.02 | 8.89 | 11.22 |
| 50 | 2.60 | 6.20 | 7.44 | 7.95 | 10.03 | 12.63 |
| 55 | 2.60 | 6.20 | 7.44 | 9.2 | 11.57 | 14.54 |
| 60 | 2.60 | 6.20 | 7.44 | 11 | 13.76 | 17.26 |
| 65 | 2.60 | 6.20 | 7.44 | 13.82 | 17.18 | 21.48 |
| 70 | 2.60 | 6.20 | 7.44 | 18.89 | 23.26 | 28.94 |
| 75 | 22.67 | 34.27 | 41.58 | 30.69 | 37.26 | 45.9 |
| 80 | 22.67 | 34.27 | 41.58 | 103.56 | 122.26 | 143.62 |
| 85 | 22.67 | 34.27 | 41.58 | 103.56 | 122.26 | 143.62 |
| 90 | 22.67 | 34.27 | 41.58 | 55.17 | 66.01 | 80 |
| 95 | 22.67 | 34.27 | 41.58 | 35.36 | 42.79 | 52.54 |
| 100 | 22.67 | 34.27 | 41.58 | 26.01 | 31.74 | 39.26 |
| 105 | 22.67 | 34.27 | 41.58 | 20.63 | 25.34 | 31.48 |
| 110 | 22.67 | 11.39 | 13.75 | 17.15 | 21.18 | 26.4 |
| 115 | 7.86 | 11.39 | 13.75 | 14.72 | 18.26 | 22.81 |
| 120 | 7.86 | 11.39 | 13.75 | 12.93 | 16.1 | 20.14 |
| 125 | 7.86 | 11.39 | 13.75 | 11.55 | 14.43 | 18.08 |
| 130 | 7.86 | 11.39 | 13.75 | 10.46 | 13.1 | 16.44 |
| 135 | 7.86 | 6.52 | 7.34 | 9.57 | 12.02 | 15.1 |
| 140 | 7.86 | 6.52 | 7.34 | 8.83 | 11.12 | 13.98 |
| 145 | 3.16 | 6.52 | 7.34 | 8.21 | 10.36 | 13.04 |
| 150 | 3.16 | 6.52 | 7.34 | 7.68 | 9.71 | 12.23 |
| 155 | 3.16 | 6.52 | 7.34 | 7.22 | 9.14 | 11.52 |
| 160 | 3.16 | 6.52 | 5.86 | 6.82 | 8.65 | 10.91 |
| 165 | 3.16 | 4.88 | 5.86 | 6.46 | 8.21 | 10.36 |
| 170 | 3.16 | 4.88 | 5.86 | 6.15 | 7.82 | 9.87 |
| 175 | 2.05 | 4.88 | 5.86 | 5.87 | 7.47 | 9.44 |
| 180 | 2.05 | 4.88 | 5.86 | 5.61 | 7.15 | 9.04 |
| 185 | 2.05 | 4.88 | 4.80 | 5.38 | 6.86 | 8.68 |
| 190 | 2.05 | 4.00 | 4.80 | 5.17 | 6.6 | 8.36 |
| 195 | 2.05 | 4.00 | 4.80 | 4.98 | 6.36 | 8.06 |
| 200 | 1.54 | 4.00 | 4.80 | 4.8 | 6.14 | 7.78 |
| 205 | 1.54 | 4.00 | 4.80 | 4.64 | 5.94 | 7.53 |
| 210 | 1.54 | 4.00 | 4.80 | 4.49 | 5.75 | 7.29 |
| 215 | 1.24 | 3.17 | 3.80 | 4.35 | 5.57 | 7.07 |
| 220 | 1.24 | 3.17 | 3.80 | 4.21 | 5.41 | 6.86 |
| 225 | 1.24 | 3.17 | 3.80 | 4.09 | 5.26 | 6.67 |
| 230 | 1.24 | 3.17 | 3.80 | 3.98 | 5.12 | 6.49 |
| 235 | 1.24 | 3.17 | 3.80 | 3.87 | 4.98 | 6.33 |
| 240 | 1.24 | 3.17 | 3.80 | 3.77 | 4.86 | 6.17 |

**Table A3** The initial values and testing ranges of hydraulic parameters for model calibration

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Soil** | **Setting** | ***Qr*** | ***Qs*** | ***α***  **(1/cm)** | ***n*** | ***Ks* (cm/min)** |
| Soil Media A and Compost | Initial value | 0.08 | 0.5 | 0.05 | 2 | 0.25 |
| Range | 0 ~ 0.1 | 0.1 ~ 0.6 | 0 ~ 0.1 | 1 ~ 2 | 0 ~ 1 |
|  |  |  |  |  |  |  |
| Soil Media A (Loam) | Initial value | 0.078 | 0.43 | 0.036 | 1.56 | 0.0417 |
| Range | 0 ~ 0.1 | 0.1 ~ 0.6 | 0 ~ 0.1 | 1 ~ 2 | 0 ~ 1 |
|  |  |  |  |  |  |  |
| Soil Media B and Compost | Initial value | 0.08 | 0.5 | 0.08 | 2 | 0.25 |
| Range | 0 ~ 0.1 | 0.1 ~ 0.6 | 0 ~ 0.1 | 1 ~ 2 | 0 ~ 1 |
|  |  |  |  |  |  |  |
| Soil Media B (Sandy Loam) | Initial value | 0.065 | 0.41 | 0.075 | 1.89 | 0.208 |
| Range | 0 ~ 0.1 | 0.1 ~ 0.6 | 0 ~ 0.1 | 1 ~ 2 | 0 ~ 1 |