Pollutant Treatment with Real-Time Control of Rain Gardens

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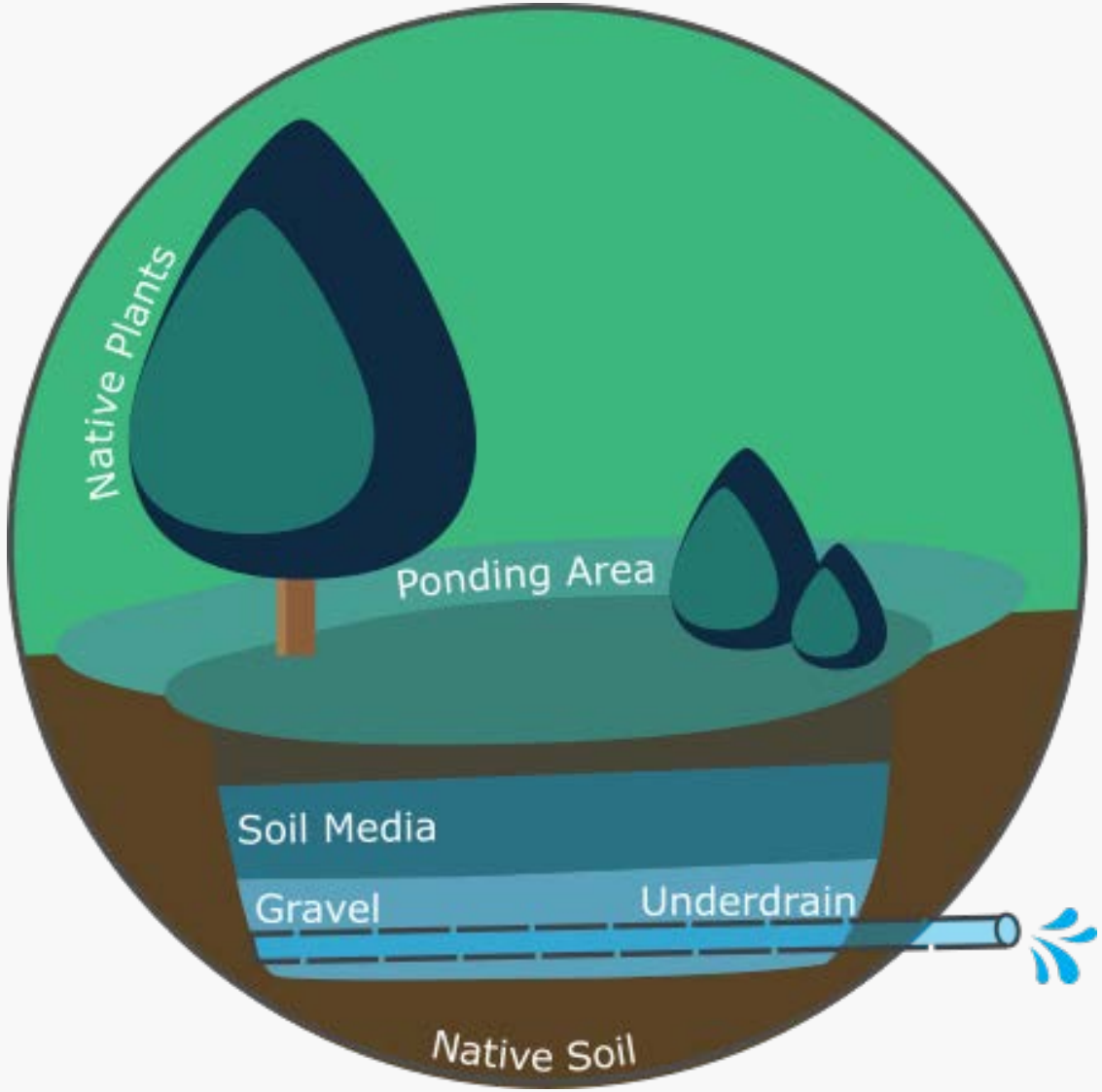
Sensors
Smart Covers
Smart Valves
Smart Rain Gardens

Objectives

- Quantify phosphorus removal of real-time controlled bioretention cells
- Compare these benefits to uncontrolled, passive approaches

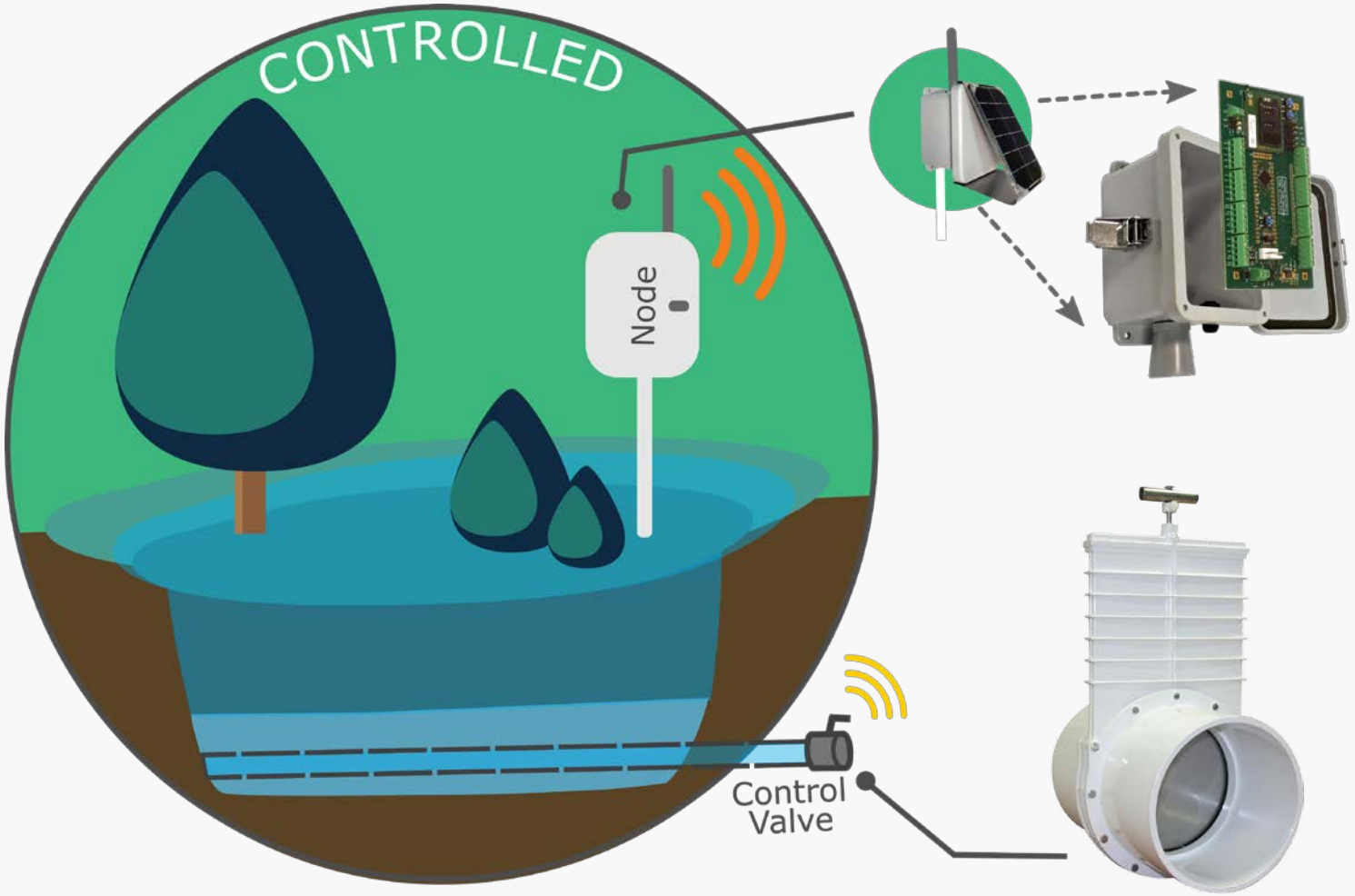
Main Message

- We can build smaller rain gardens without compromising performance!



Bioretention Cell

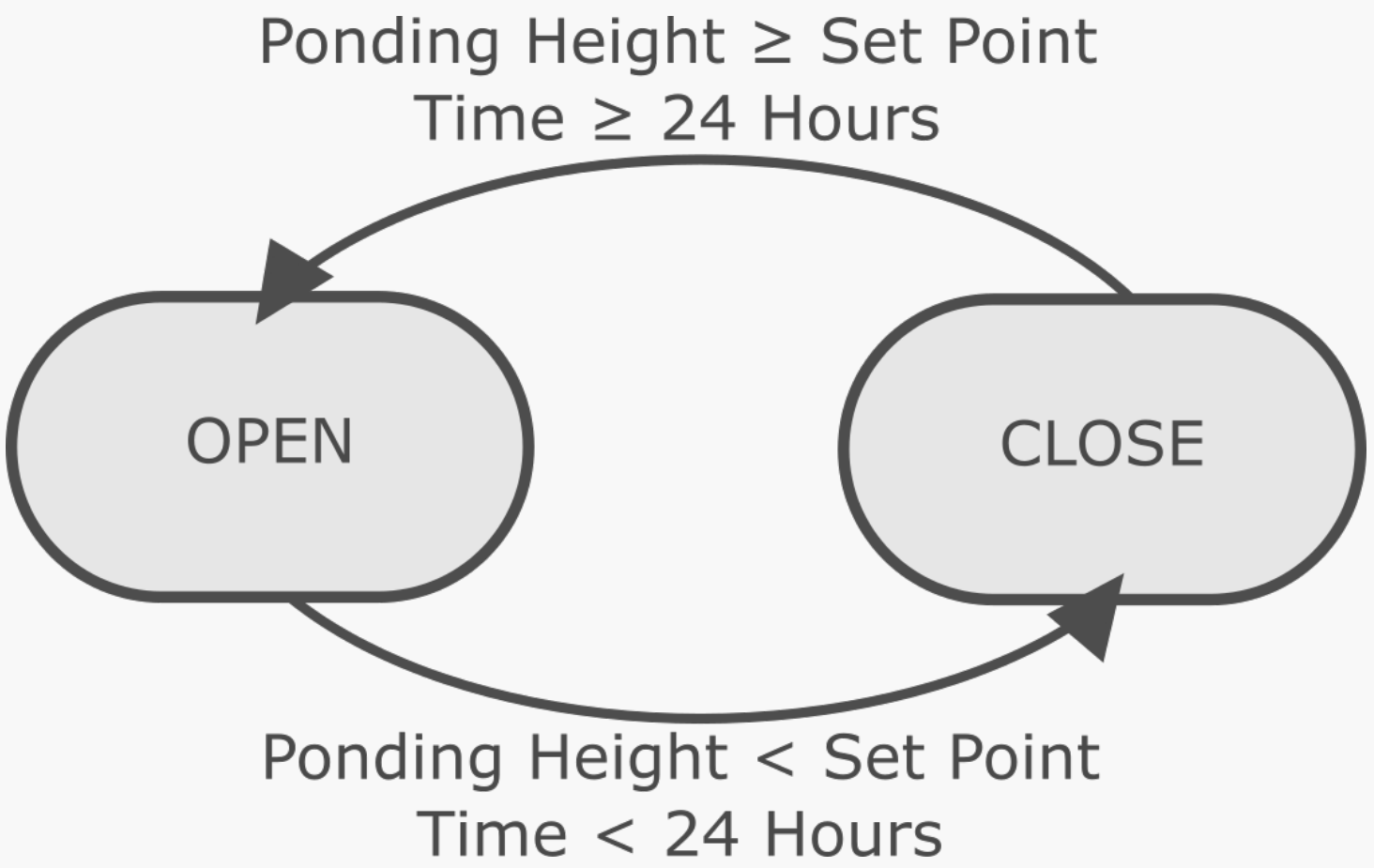
- Retains runoff quantity
- Improves water quality
- Small drainage areas (< 2 acres)



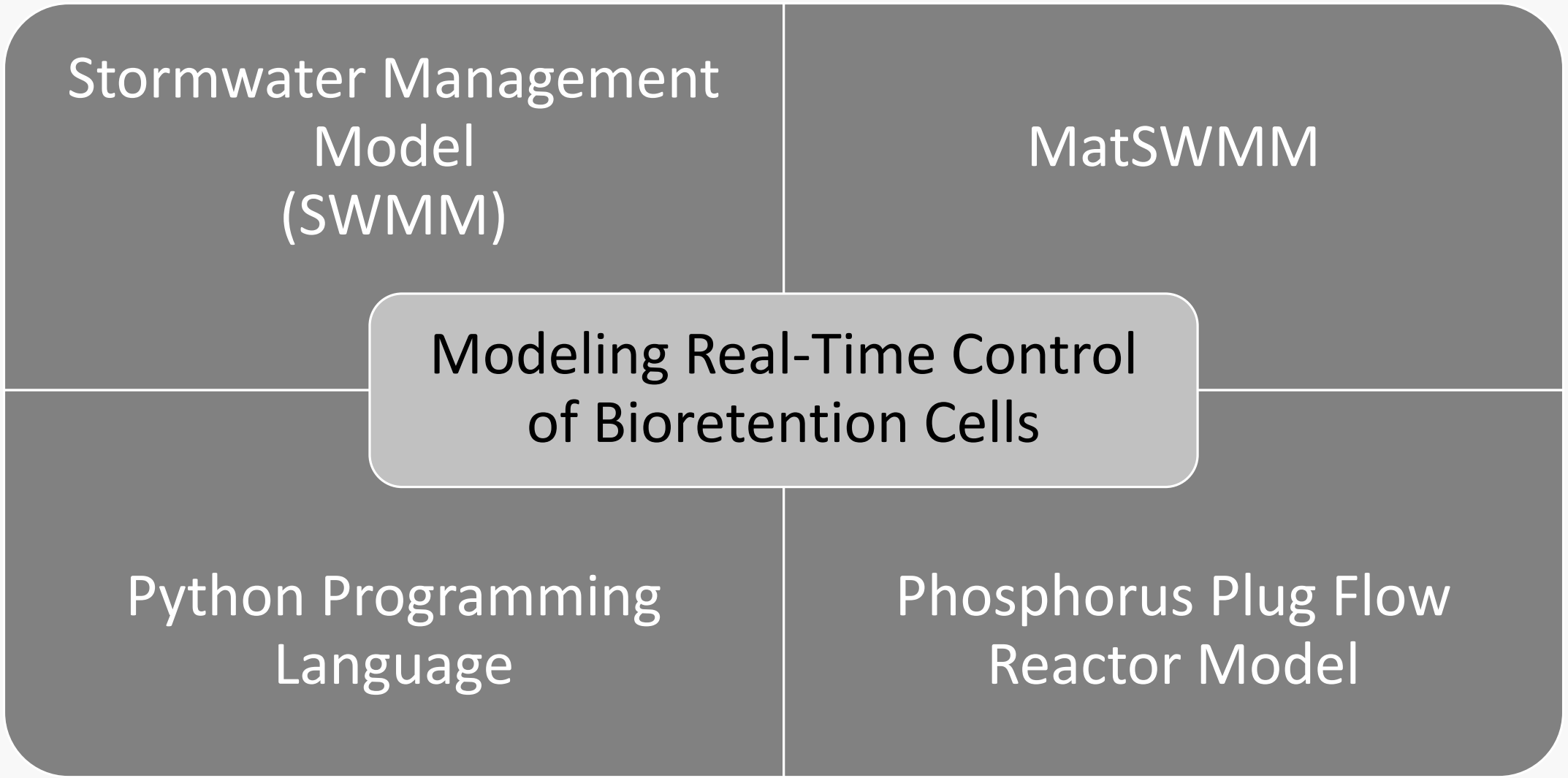
Real-Time Control

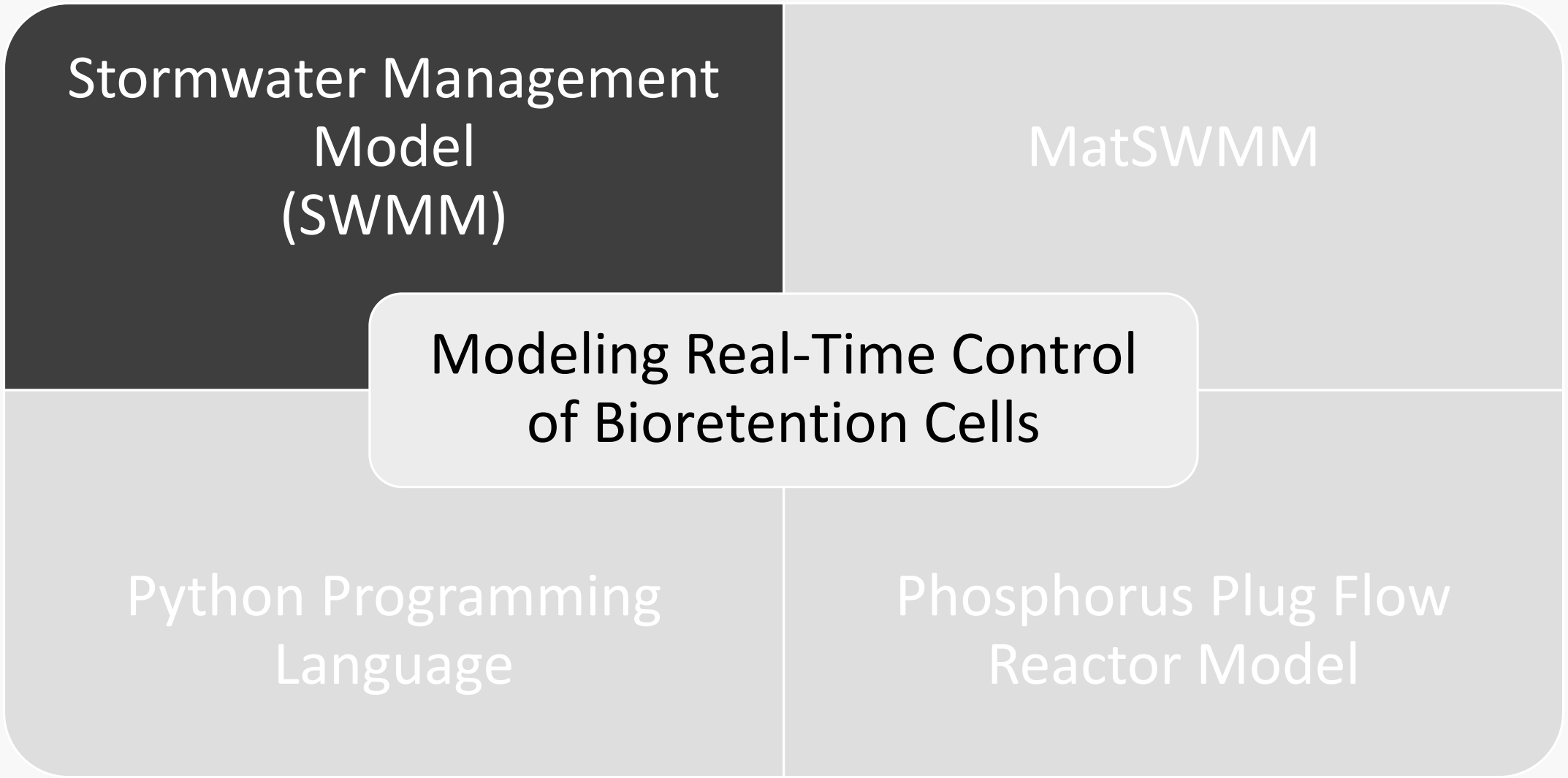
- Actuated valve
- Water level sensor
- Fully automated and internet-connected control system for $1,000 USD using open-source solutions

Open-storm.org



Control Algorithm


Stormwater Management Model (SWMM)
MatSWMM
Modeling Real-Time Control of Bioretention Cells
Python Programming Language
Phosphorus Plug Flow Reactor Model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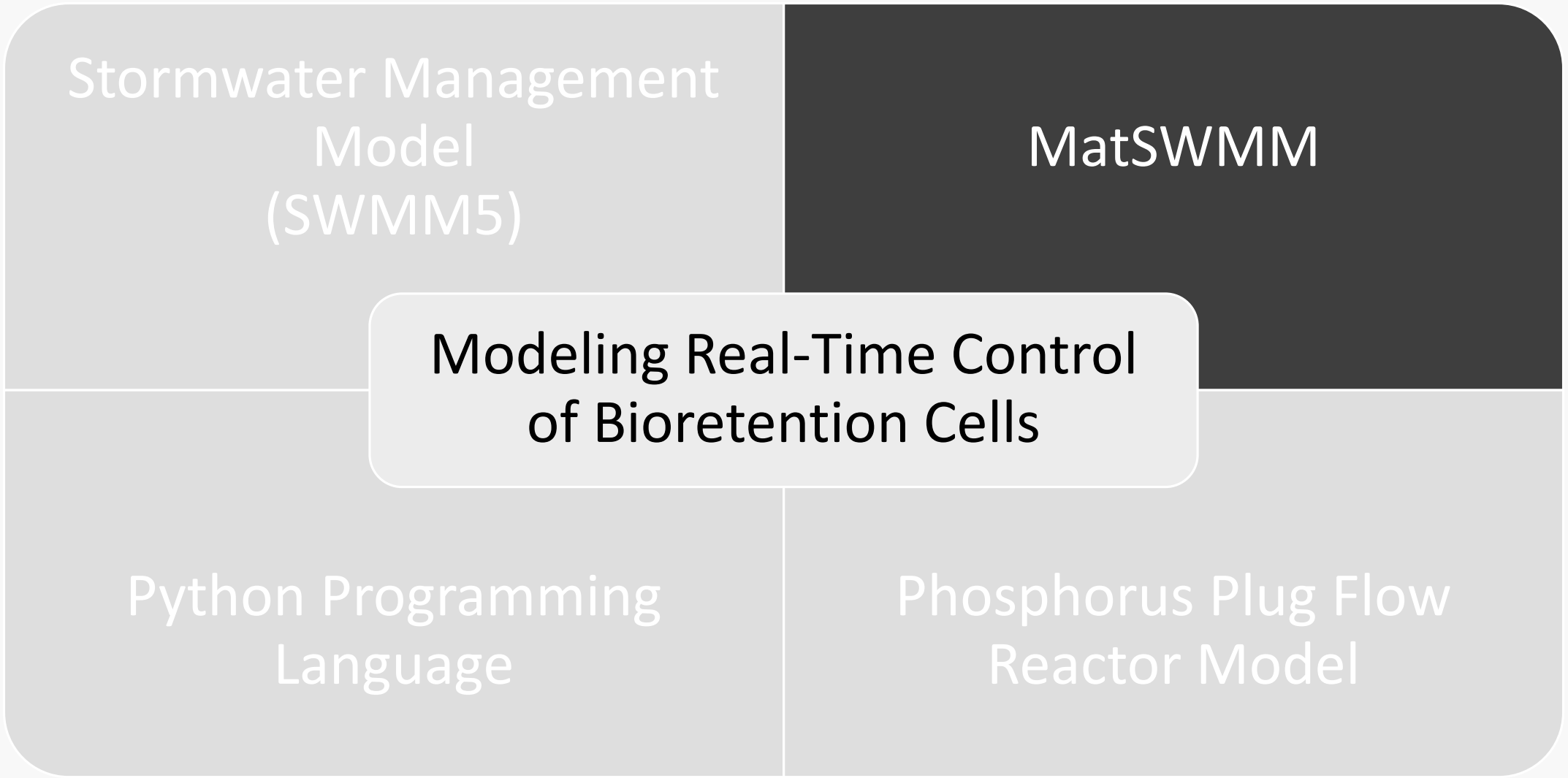
Stormwater Management Model (SWMM5)
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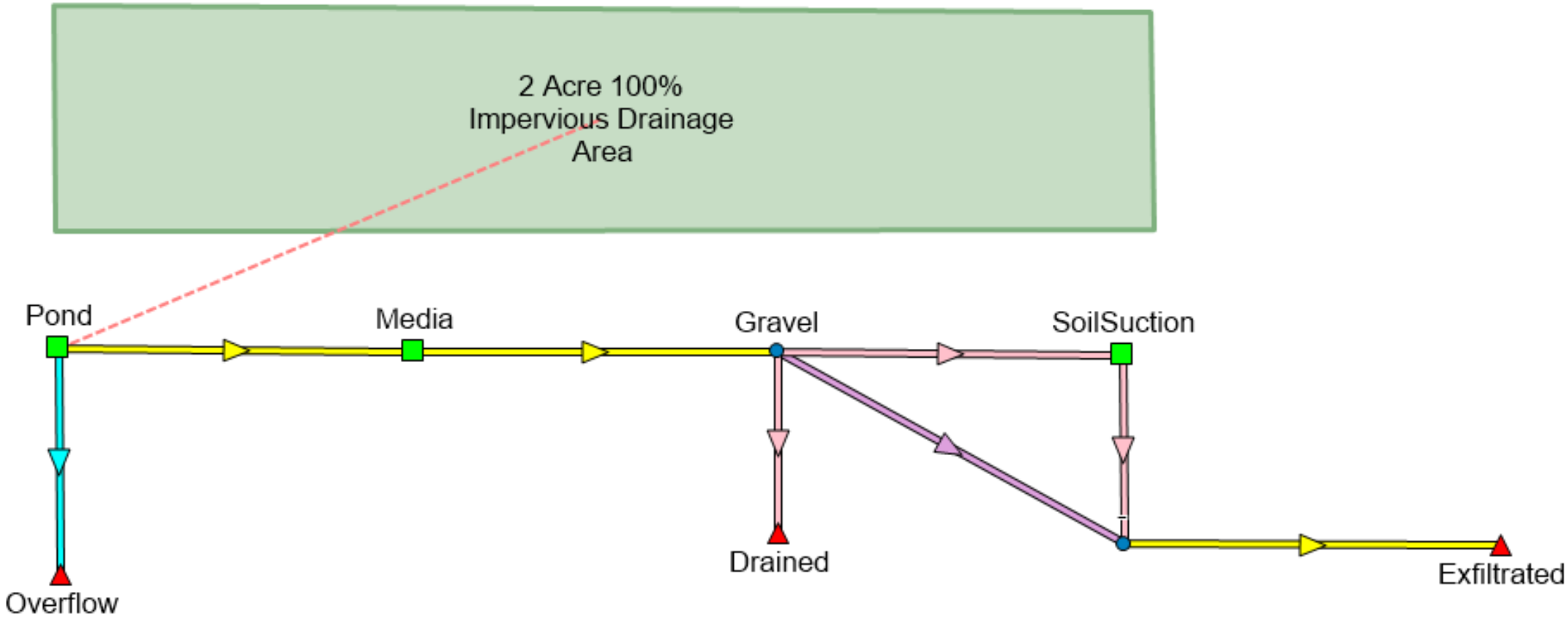
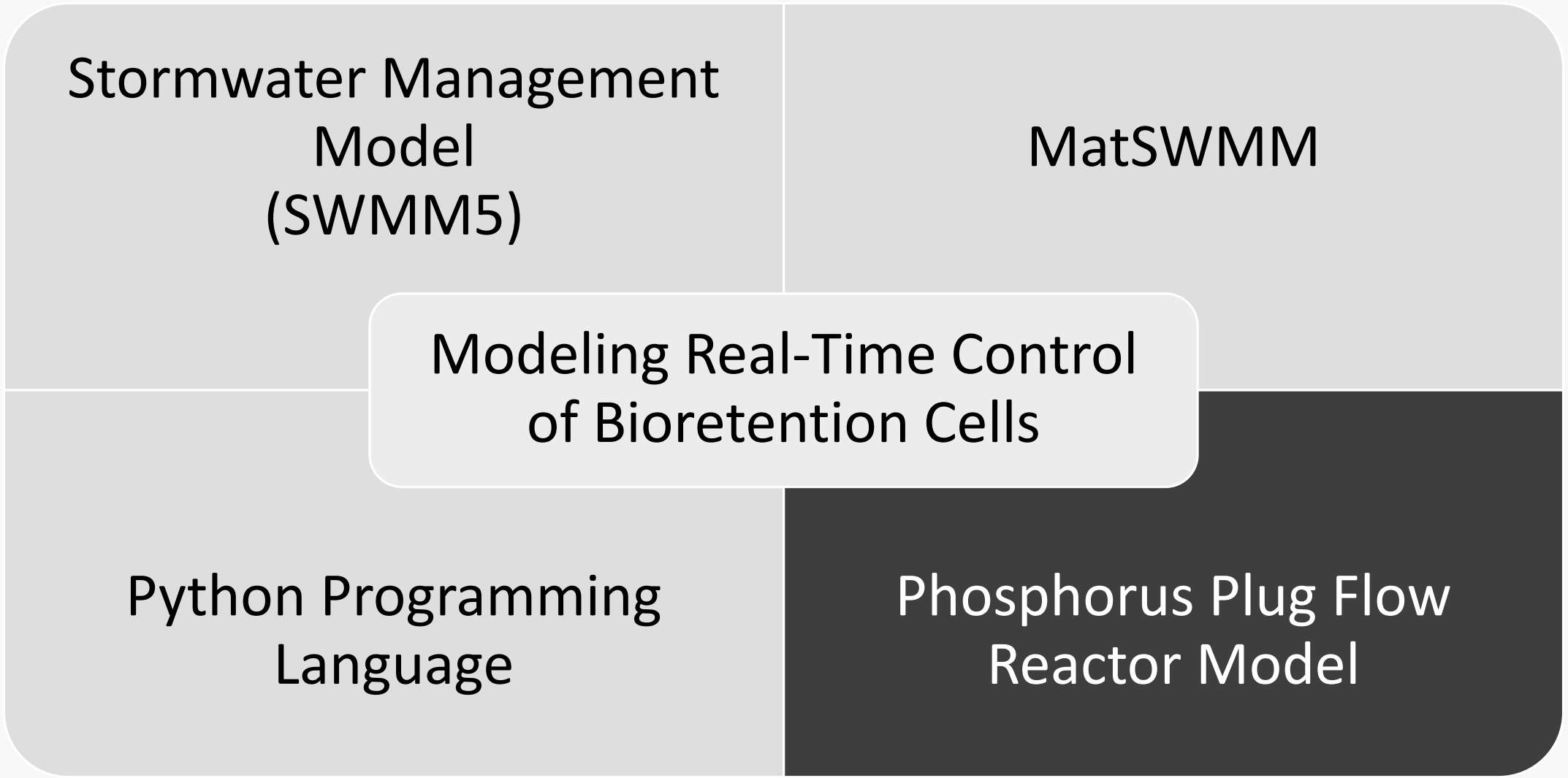

2 Acre 100%
Impervious Drainage
Area
Pond
Media
Gravel
SoilSuction
Overflow
Drained
Exfiltrated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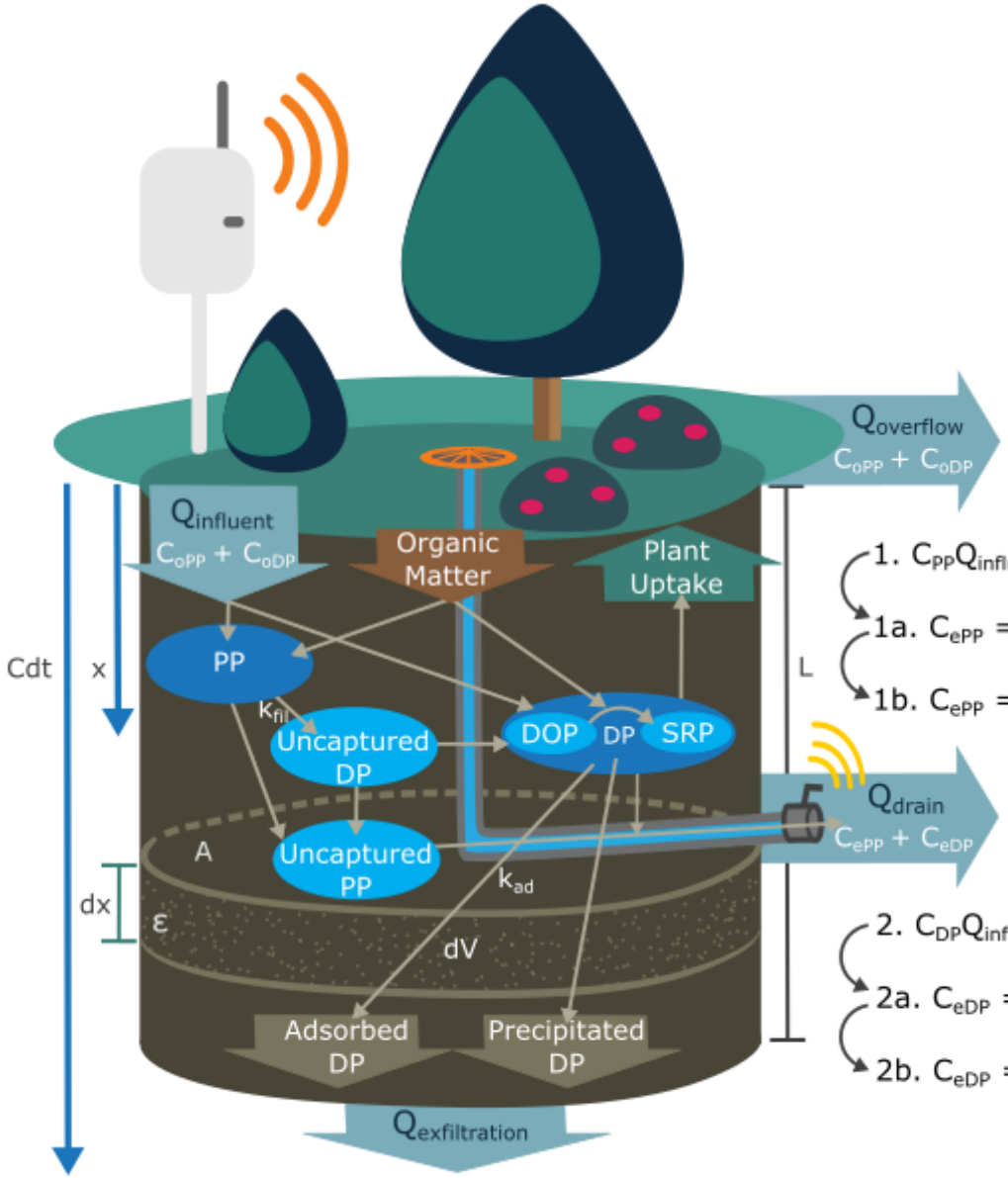


1. $C_{PP}Q_{influent} - (C_{PP} + dC_{PP})Q_{influent} + r_{fil}dV + r_{pp*}dV + r_{om*}dV = 0$

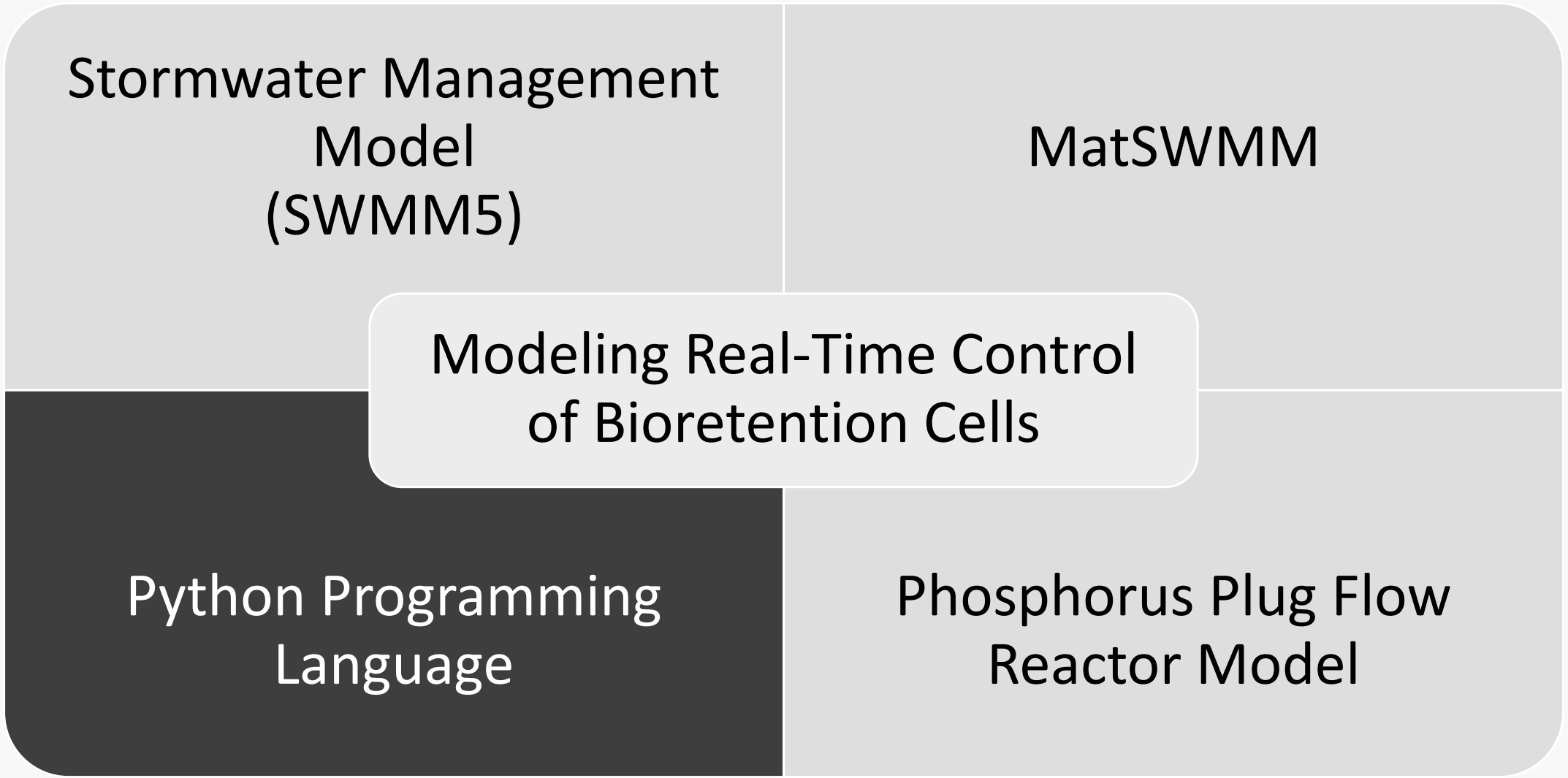
1a. $C_{ePP} = C_{oPP}\exp^{-k_{fil}LεA/Q_{influent}} + C_{eqPP}(1 - \exp^{-k_{fil}LεA/Q_{influent}})$

1b. $C_{ePP} = C_{oPP}\exp^{-\beta_2/Q_{influent}} + (C^0_{eqPP}\exp^{\beta_1 t})(1 - \exp^{-\beta_2/Q_{influent}})$

2. $C_{DP}Q_{influent} - (C_{DP} + dC_{DP})Q_{influent} + r_{ad}dV + r_{pp}dV + r_{om}dV = 0$

2a. $C_{eDP} = C_{oDP}\exp^{-k_{ad}LεA/Q_{influent}} + C_{eqDP}(1-\exp^{-k_{ad}LAε/Q_{influent}})$

2b. $C_{eDP} = C_{oDP}\exp^{-\beta_2/Q_{influent}} + (C^0_{eqDP}\exp^{\beta_1 t})(1 - \exp^{-\beta_2/Q_{influent}})$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Cell Size

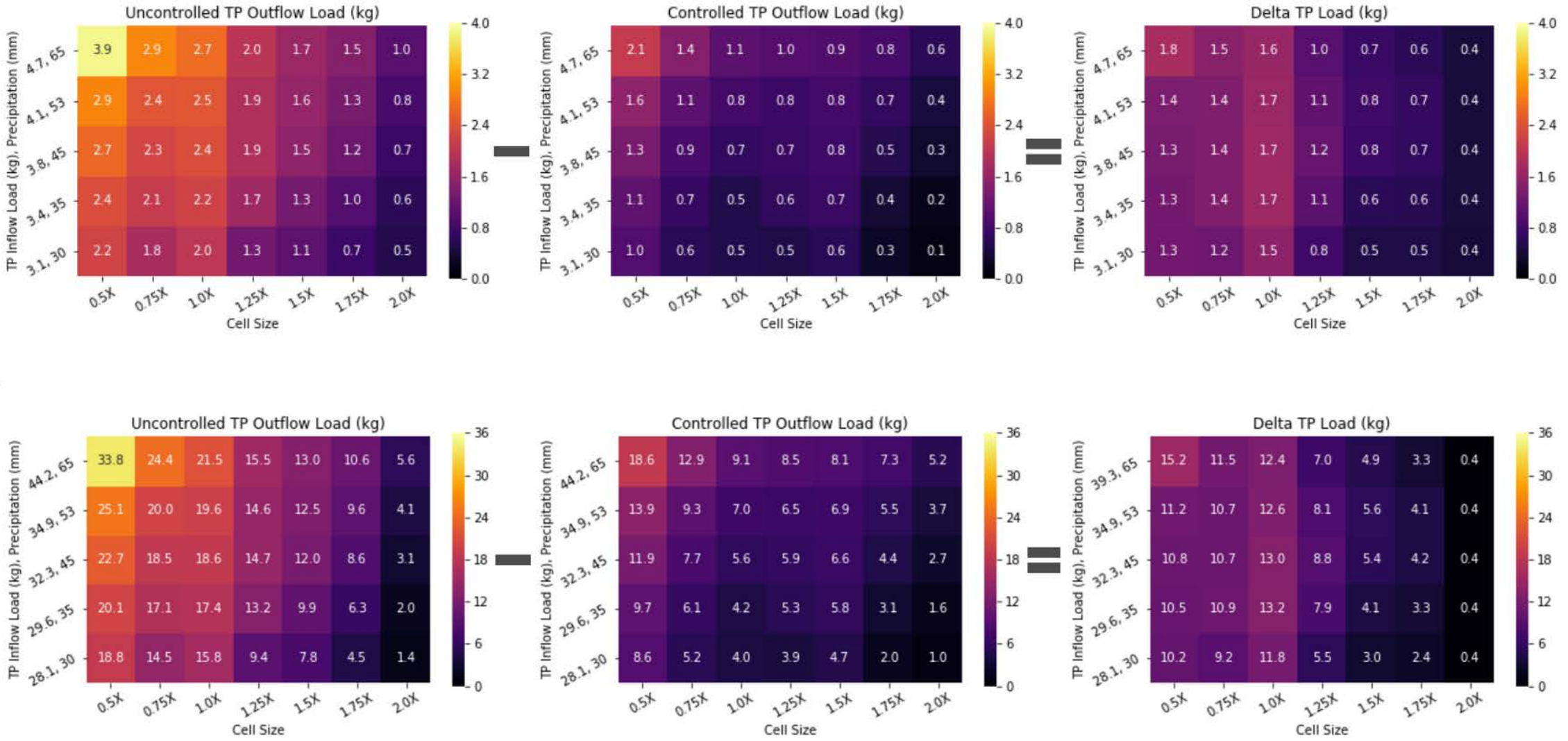
- 0.5X Ideal (0.05 acre)
- 0.75X Ideal
- 1.0X Ideal (0.1 acre)
- 1.25X Ideal
- 1.5X Ideal
- 1.75X Ideal
- 2.0X Ideal (0.2 acre)

Design Storm Size (2 hr)

- 1-yr: 30mm
- 2-yr: 35mm
- 5-yr: 45mm
- 10-yr: 53mm
- 25-yr: 65mm

TP Influent Concentration

- 200 ug/L
- 400 ug/L
- 600 ug/L
- 800 ug/L
- 1,000 ug/L
- 1,200 ug/L
- 1,400 ug/L
- 1,600 ug/L
- 1,800 ug/L


Uncontrolled TP Outflow Load (kg)
TP Inflow Load (kg), Precipitation (mm)
4.7, 65
4.1, 53
3.8, 45
3.4, 35
3.1, 30
3.9 2.9 2.7 2.0 1.7 1.5 1.0
2.9 2.4 2.5 1.9 1.6 1.3 0.8
2.7 2.3 2.4 1.9 1.5 1.2 0.7
2.4 2.1 2.2 1.7 1.3 1.0 0.6
2.2 1.8 2.0 1.3 1.1 0.7 0.5
0.5X 0.75X 1.0X 1.25X 1.5X 1.75X 2.0X
Cell Size
4.0 3.2 2.4 1.6 0.8 0.0
Controlled TP Outflow Load (kg)
2.1 1.4 1.1 1.0 0.9 0.8 0.6
1.6 1.1 0.8 0.8 0.8 0.7 0.4
1.3 0.9 0.7 0.7 0.8 0.5 0.3
1.1 0.7 0.5 0.6 0.7 0.4 0.2
1.0 0.6 0.5 0.5 0.6 0.3 0.1
Delta TP Load (kg)
1.8 1.5 1.6 1.0 0.7 0.6 0.4
1.4 1.4 1.7 1.1 0.8 0.7 0.4
1.3 1.4 1.7 1.2 0.8 0.7 0.4
1.3 1.4 1.7 1.1 0.6 0.6 0.4
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Uncontrolled TP Outflow Load (kg)
44.2, 65
34.9, 53
32.3, 45
29.6, 35
28.1, 30
33.8 24.4 21.5 15.5 13.0 10.6 5.6
25.1 20.0 19.6 14.6 12.5 9.6 4.1
22.7 18.5 18.6 14.7 12.0 8.6 3.1
20.1 17.1 17.4 13.2 9.9 6.3 2.0
18.8 14.5 15.8 9.4 7.8 4.5 1.4
36 30 24 18 12 6 0
Controlled TP Outflow Load (kg)
18.6 12.9 9.1 8.5 8.1 7.3 5.2
13.9 9.3 7.0 6.5 6.9 5.5 3.7
11.9 7.7 5.6 5.9 6.6 4.4 2.7
9.7 6.1 4.2 5.3 5.8 3.1 1.6
8.6 5.2 4.0 3.9 4.7 2.0 1.0
Delta TP Load (kg)
39.3, 65
15.2 11.5 12.4 7.0 4.9 3.3 0.4
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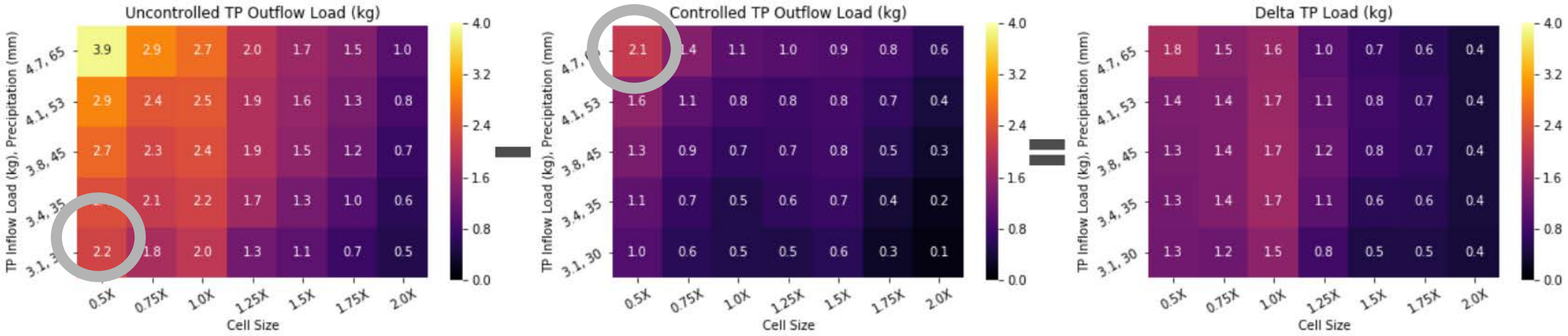
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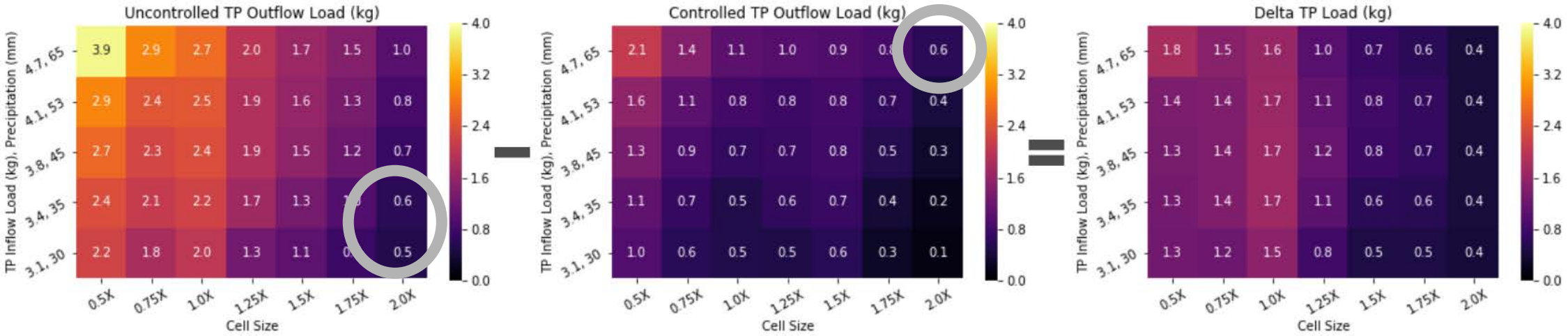
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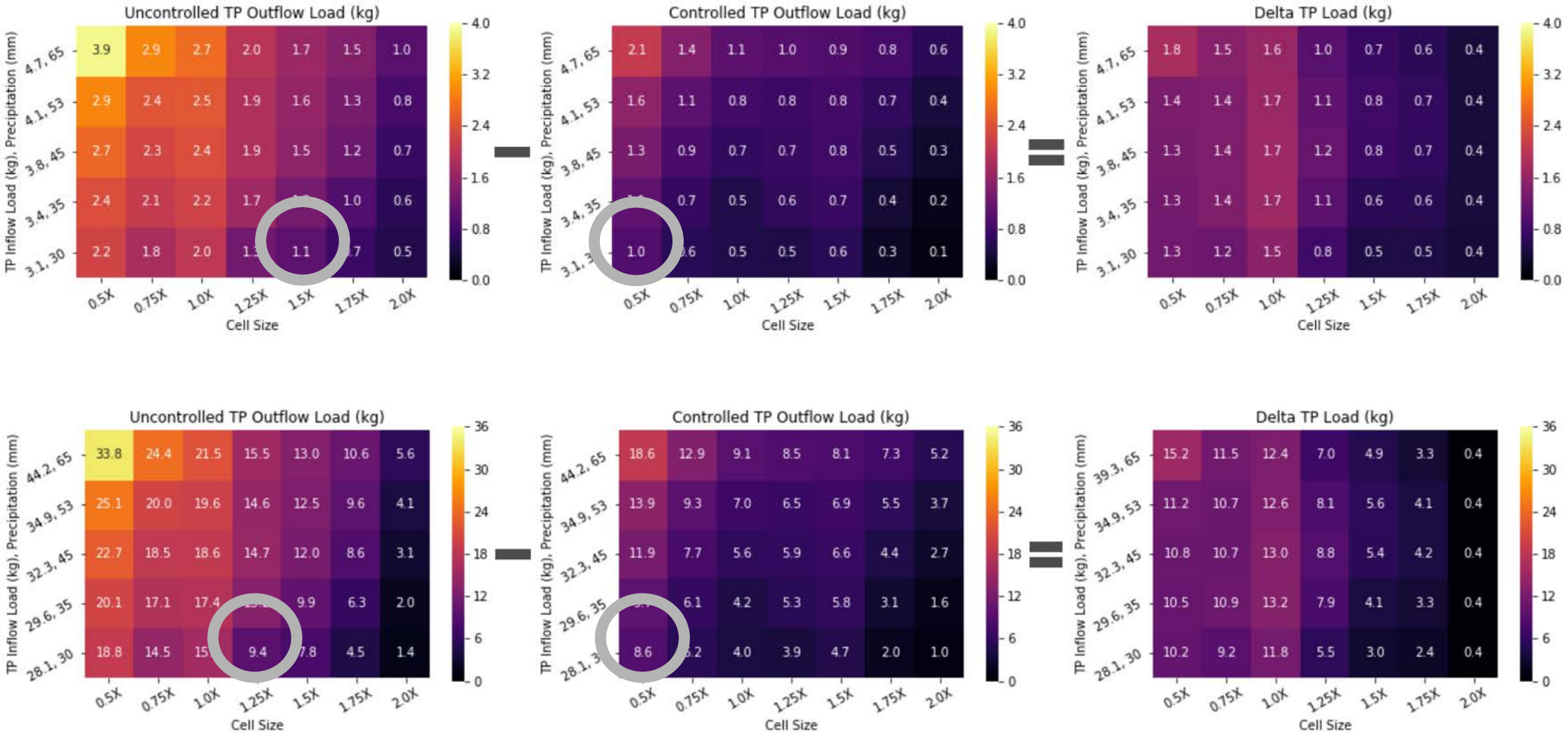
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Cost Comparison

1.25X IDEAL UNCONTROLLED CELL

Item	Cost/Item	Total Cost
Soil Media (506 m^2)	\$55/m^2	\$27,800
Controls	\$1,000	\$0
		\$27,800

greenvalues.cnt.org

0.5X IDEAL REAL-TIME CONTROLLED CELL

Item	Cost/Item	Cost
Soil Media (202 m^2)	\$55/m^2	\$11,100
Controls	\$1,000	\$1,000
		\$12,100

Open-storm.org

Conclusions

- Control enhances phosphorus removal!
- We can build smaller rain gardens without compromising performance!

Questions?

THANK YOU!

Phosphorus Equation Notes

- Refer to “A unified look at phosphorus treatment using bioretention” by Li and Davis (2016) for more details
- Mass balances for steady state PFR for dissolved and particulate phosphorus are shown in Equation 1 and 2
- Variables in Equations 1 and 2 were separated and integrated over the column depth, 0 to L, and the change in concentration, influent (C_o) to effluent (C_e), to create Equations 1a and 2a
- Rates of adsorption and filtration are assumed to be first order, dependent on the gradient resulting from the influent concentration and the equilibrium concentration at the surface of the absorbent/collector (C_{eq}) defined by the adsorption/attachment characteristics of the media
- Reaction rate constants, adsorption rate (k_{ad}) and filtration rate (k_{fil}), were substituted in for the reaction rates
- Equilibrium concentration will vary over the lifetime of the BRC’s soil media, observed as an exponential decay-shaped curve for effluent phosphorus concentrations with time
  - To account for this variability, $C_{eq}^{0} exp^{\beta_1 t}$, is substituted in for C_{eq} in Equations 1b and 2b
  - C_{eq}^{0} is the initial DP or PP equilibrium concentration for a rainfall event
  - β_1 is the coefficient related to the rate at which C_{eq} approaches C_o
  - t is the cumulative runtime corresponding to a rainfall event