Report as of FY2009 for 2007DE100B: "Graduate Fellowship: Modeling Hydrologic and Geochemical Effects of Land-Based Wastewater Disposal"

Publications

- Other Publications:
    - Pautler, M., ed., 2009, Delaware Water Resources Center WATER NEWS Vol. 9 Issue 2 DWRC Spotlight on Graduate Research, http://ag.udel.edu/dwrc/newsletters/Winter08Spring09/WATERNEWSco-Spring2009.pdf , p. 6.
- Water Resources Research Institute Reports:
    - Akhavan, M., P.T. Imhoff, and A.S. Andres, 2010, Modeling Hydrologic and Geochemical Effects of Land-Based Wastewater Disposal Progress Report, Delaware Water Resources Center, University of Delaware, Newark, Delaware, 13 pages.

Report Follows

Modeling Hydrologic and Geochemical Effects of Land-Based Wastewater Disposal

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1. Background

Land-based wastewater treatment is the controlled application of wastewater to soil to remove constituents in the wastewater. In this system physical, chemical, and biological mechanisms within the soil matrix are used to treat the wastewater. A Rapid Infiltration Basin System (RIBS), also known as a Soil Aquifer Treatment system (SAT) or “infiltration-percolation” (Pound et al. 1973), is one of three major land treatment techniques commonly used for land-based wastewater treatment.

A RIBS typically treats a much larger volume of wastewater per unit area of land than other land-based methods. In this system, wastewater that is treated using primary, secondary, or advanced treatment techniques is applied to shallow basins constructed in permeable deposits of soil or sand. The wastewater is treated as it moves through the soil matrix by sorption, ion exchange, precipitation, and microbial degradation processes, if a RIBS is operated in a way appropriate for site conditions. Vegetation typically is not used for treatment in a RIBS, so no vegetation is planted in the basin. However, weeds and grasses may grow within the basins. Such vegetation may cause organic matter and fine-grained mineral matter to accumulate on the soil surface, altering soil porosity and interfering with soil aeration. These processes affect the hydraulic properties and the treatment performance of a RIBS; however, the impact of vegetation on a RIBS performance has not been previously investigated.

A RIBS is operated in repetitive cycles of flooding, infiltration, and drying. Key operational parameters include the ratio of wetting to drying time and the hydraulic loading rate, which affect pollutant residence time and nitrogen and phosphorus loads to the aquifer. They also alter water saturation and air content of the soil, which have an impact on nitrogen removal via denitrification (DNF). The optimum values of the wetting-drying cycle ratio and the hydraulic loading is expected to vary with the quality of applied wastewater, soil type, treatment objective, and climate.

Wastewater is typically distributed by surface spreading in a RIBS and basins are not usually completely flooded. They are only partially flooded because the discharge areas are typically designed larger than the areas required for treatment. Use of a low loading rate and overdesign of the required infiltration area in many RIBS causes non-homogeneous distribution of wastewater. In these cases, areas located farthest from the discharge valves are flooded only after the infiltration capacity of areas nearest the discharge valves is exceeded. Overland flow to more distant areas of the infiltration beds is determined by hydraulic loading, infiltration, subsurface percolation, and subsurface lateral flow. Hence, consideration of surface flow coupled with subsurface flow is essential for simulating water movement and contaminant transport under the basin.

Wastewater treatment system effluents contain a number of potential groundwater and surface water contaminants, with the types of contaminants dependent on the performance of the treatment system. These contaminants can include a complex mixture of organic compounds, suspended solids, nitrogen (N), phosphorus (P), and other substances. If a RIBS is not designed appropriately, these constituents may enter groundwater or surface water and contaminate them.

N and P compounds are usually enriched in applied wastewater and are of particular concern. These pollutants may accumulate in both the unsaturated and saturated zone and eventually contaminant groundwater and nearby surface water bodies.

2. Objectives

This study will elucidate the effect of different wastewater application rates and soil parameters on the hydraulic performance and treatment efficiency of RIBS. The results should provide important information that can lead to improved guidelines for the design and operation of RIBS. The overall objectives of this study are to evaluate the role of 1) soil development on RIBS performance, 2) subsurface porous media properties on RIBS performance, and 3) RIBS operating conditions on RIBS performance. For these objectives, the following hypotheses will be tested:

1-1) Soil development under vegetation for most permeable soils including coarse-grained soils leads to a low-permeable surface layer that reduces the infiltrability of a RIBS significantly.

1-2) Soil development under vegetation enhances DNF by providing a source of degradable carbon and interfering with soil aeration.

1-3) Soil development under vegetation enhances P removal by lowering the pore water velocity and increasing detention time.

2-1) Wastewater discharge in a heterogeneous media increases the probability of groundwater contamination by N and P since preferential flow may occur and allow wastewater to reach groundwater quickly.

2-2) Discharging wastewater on sandy soil (high permeable soil) leads to higher basin capacity and less contaminant removal, because water is quickly drained and pore water velocities are high. Conversely, discharging wastewater on loamy sand soil (less permeable soil) leads to less basin capacity and higher contaminant removal.

3-1) Discharging a fully nitrified effluent at the basin would have a counterproductive effect on DNF reactions; the presence of some amount of ammonia N is a required source of reductant for DNF.

3-2) DNF and N removal efficiency are higher in summers than winters because of greater microbial activity at higher temperatures.

3-3) Hydraulic loading rates as well as flooding duration can be designed to achieve optimal N and P removal rates. For example, the effluent discharge rate directly effects pore water velocities, and the flooding period has a direct impact on the saturation time. Both factors influence N and P removal.

3. Methodology

This study uses several different computer programs in conjunction with field data from a recently completed Delaware Geological Survey (DGS) study. Water and gas flow simulations are conducted using TOUGH2 (Pruess et al. 1999) and iTOUGH2 (Finsterle 1999). TOUGHREACT (Xu et al. 2004) and TOUGHREACT-N ((Maggi et al. 2008) (Gu et al. 2009)) will be used for modeling transport of N and P. The process-based TOUGHREACT-N incorporates environmental factors including soil temperature, soil moisture, and soil pH on microbial activity and N transformation to model its fate and transport. Field data from the DGS project are being used as input data for the simulations and for comparison to simulation results.

A two dimensional, axisymmetric, radial flow domain has been used as the model domain for most simulations to date. Soil development under vegetation is represented in the model as a thin surface layer with hydraulic properties specified for surface soils. Critical input data needed for these simulations are model parameters describing the pressure-saturation-permeability relationship for both gas and water in the surface soil and underlying porous media. Two approaches are used for obtaining these data: using data from the DGS field study or literature-reported data from field studies conducted at sites having similar soils, or using pedotransfer functions (PTF) to predict soil hydraulic properties. For understanding the effects of soil development under vegetation in different soil types, the PTF approach is applied. Properties of 12 USDA soil textural classes are provided using the Rossetta database (Schaap et al. 2001). The hydraulic properties of the sandy loam textural class are used for the soil layer that develops under vegetation.

A key task in the last year has been to modify iTOUGH2 to include surface water flow. A diffusion wave (non-inertial wave) form of the Saint-venant equations was used to describe surface water flow. In this form of the Saint-venant equations, the inertial terms are neglected. This approach is more precise than the kinematic wave approximation, where inertial terms and the hydraulic head gradient are both neglected. For coupling the surface flow model to the subsurface flow model, a full coupling (simultaneous) scheme is used, the same approach employed in Weill et al. (2009). In this method, both systems –surface and subsurface– are solved together simultaneously.

Three test cases are used for validation of the new coupled code. These are overland flow model validation (Test 1), subsurface flow model validation (Test 2), and integrated surface/subsurface flow validation (Test 3). In order to obtain the optimum values for the wetting and drying cycles and hydraulic loading rate, alternative loading cycles and application rates are tested for different soil types and conditions.

4. Results and discussion

Validation of code for coupled overland-subsurface flow

Three test cases were used to validate the coupled overland-subsurface flow changes made in the iTOUGH2 code. In Test 1, a 30-min rainfall with 1.4×10^{-5} m/s intensity was simulated over a 183 m long parking lot (Figure 1). This test case examined only the utility of the surface water flow portion of the code. The discharge rates at the outlet at different times were compared with a 1D analytical solution of the kinematic wave approximation for surface water flow and the results of another code that used the same method for integration of surface and subsurface flow (Weill et al. 2009). There was good agreement between the iTOUGH2 and the Weill model predictions, which is shown in Figure 2. The diffusive wave approach, used in both codes, resulted in a smoother rise to the maximum outflow rate than the analytical solution. This occurred because of the diffusive term, which was absent in the more approximate analytical solution but included in both iTOUGH2 and the Weill code.

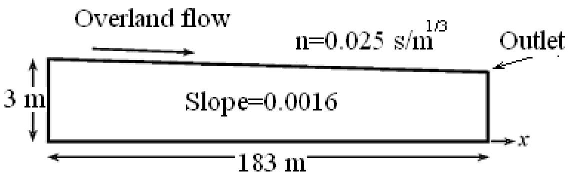


Figure 1. Schematic of the test case.

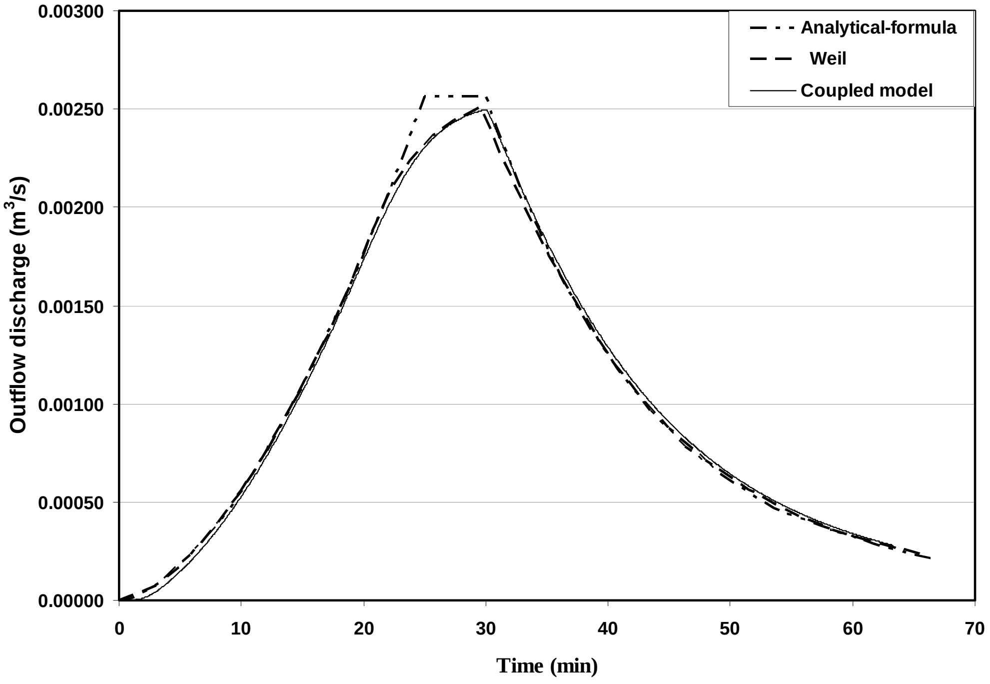


Figure 2. Comparison between the modified iTOUGH2 code, Weil (Weill et al. 2009), and the analytical solution

To verify that the subsurface flow portion of the modified code was correct, in Test 2 groundwater flow through a one-dimensional saturated soil column was simulated. Data from the model results were then used to compute the saturated hydraulic conductivity of the soil, K_s, which was known. Equation 1 was used to calculate the saturated hydraulic conductivity of the soil from the simulation.

$$K_s = \frac{L}{t_1} ln\left(\frac{b_0 + L}{b_1 + L}\right) \qquad (1)$$

where b_0 is ponding depth at the initial time, b_1 is the ponding depth at $t = t_1$, and L is the soil column length. The results at different times were in excellent agreement with the known K_s, which was defined as an input parameter in the model.

In Test 3 the experiment conducted by (Abdul and Gillham, 1984) was used to verify the integrated surface/subsurface flow code. Weill et al. (2009) also used this experiment to verify their code. The experiment was conducted in a Plexiglas sandbox 140 cm long, 120 cm high and 8 cm wide (Figure 3). The outlet of the system was located at the toe of the slope, and the initial conditions were defined by an equilibrium head distribution with the water table located at the toe of the slope. A 1.2×10^{-5} m/s constant rainfall rate was applied for 20 min across the entire surface. For code verification, the outflow at the toe of the slope predicted by the code was compared with experimental measurements and Weil's simulation results (Figure 4). The fluxes presented in this figure were normalized by the rainfall flux imposed at the surface. Good agreement between the iTOUGH2 simulation and Weil's simulation was observed for this case too. There were some differences, though, between both simulations and the actual laboratory data, which is likely due to the approximations inherent in application of the diffusive wave form of the Saint-venant equations.

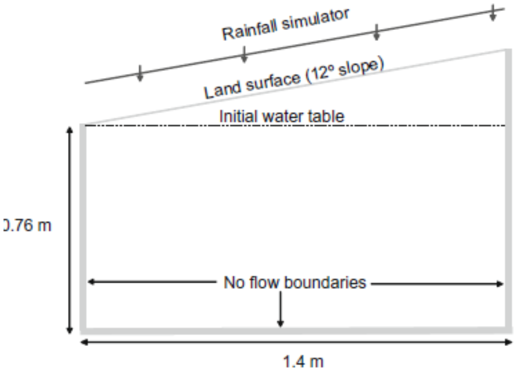


Figure 3. The Abdul and Gilham system. Figure taken from Weill, S., Mouche, E., and Patin, J., *Journal of Hydrology*, 366(1-4), 9-20, 2009.

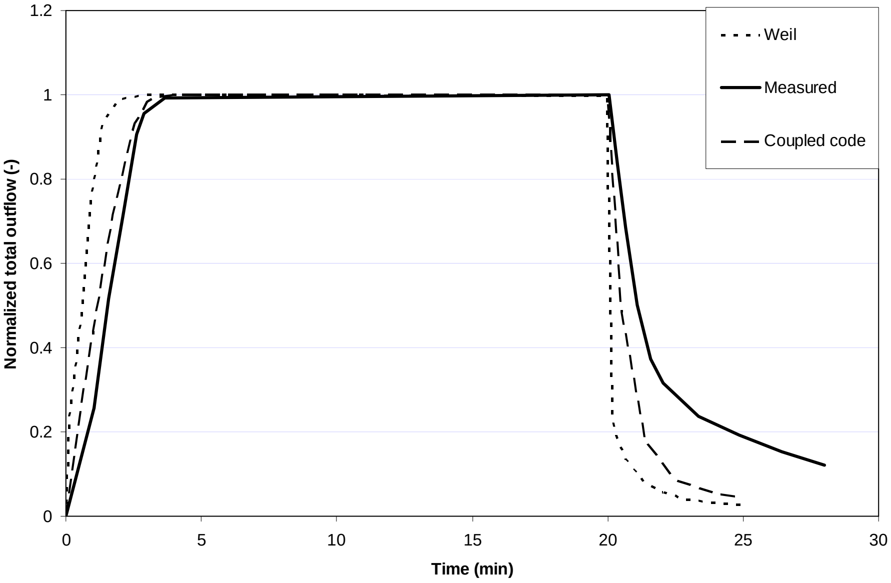


Figure 4. Simulated (Weil and iTOUGH2 codes) versus measured flow

Examination of alternative hydraulic loading cycles on a RIBS performance

The impact of alternative hydraulic loading cycles on a RIBS performance was examined. Figure 5 shows the model domain considered for these simulations, a two dimensional, axisymmetric, radial domain that was 14 m in radius and 20 m in depth. The RIBS was assumed to be circular with the radius of 6 m, and wastewater was discharged through a discharge valve located at the centre of the basin. Atmospheric pressure and no-flow boundary conditions were applied to the top and bottom boundaries of the model, respectively. The boundary on the right hand side of the domain was specified as constant hydraulic head.

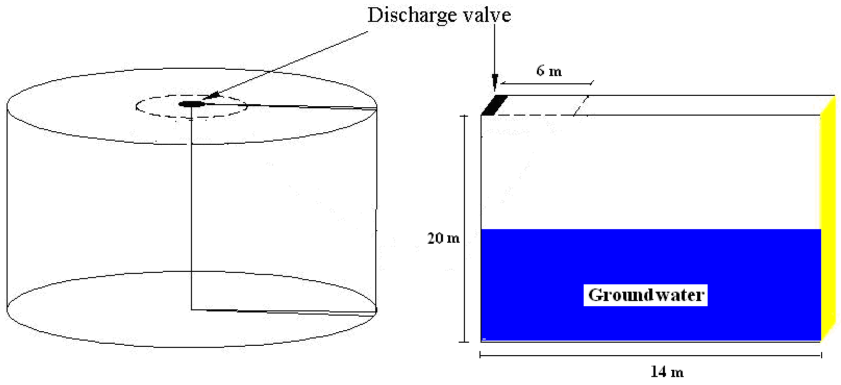


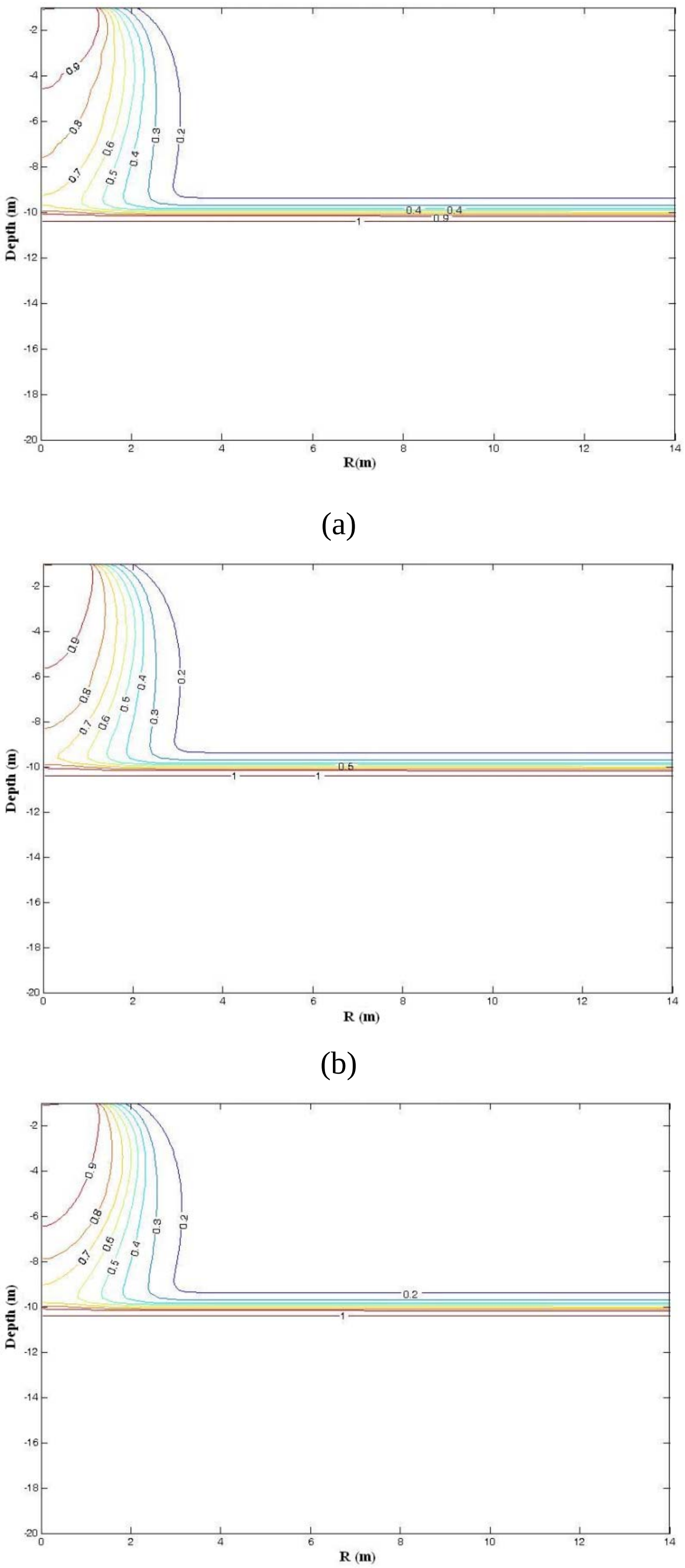
Figure 5. Schematic diagram of the conceptual radial model domain

The impact of three different hydraulic loading cycles were examined, which are described in Table 1. Because of the impact of water saturation and air content of the soil on DNF reactions, water saturation contours and water content profiles of the soil through time were compared for these three cycles.

Figure 6 shows the maximum water saturations achieved at each point in the domain over a 7 day-period for each of the three loading cycles. Figure 7 shows the water saturation versus time at a section located 1m from the centre of the basin. The figures indicate that using a long flooding cycle (12h cycle) causes a higher-saturated water front to reach the greatest depth.

Table 1. Different cycles of flooding/drying

Simulation ID	Operation time		Discharge rate (kg/s)	Total discharged water (m^3)
	Day 1	Day 2-7		
12h-cycle	12h flooding 12h drying	Drying	0.393	16.96
8h- cycle	8h flooding-8h drying -8h flooding	Drying	0.294	16.96
2h- cycle	2h flooding-2h drying-… 2h flooding-2h drying	Drying	0.393	16.96

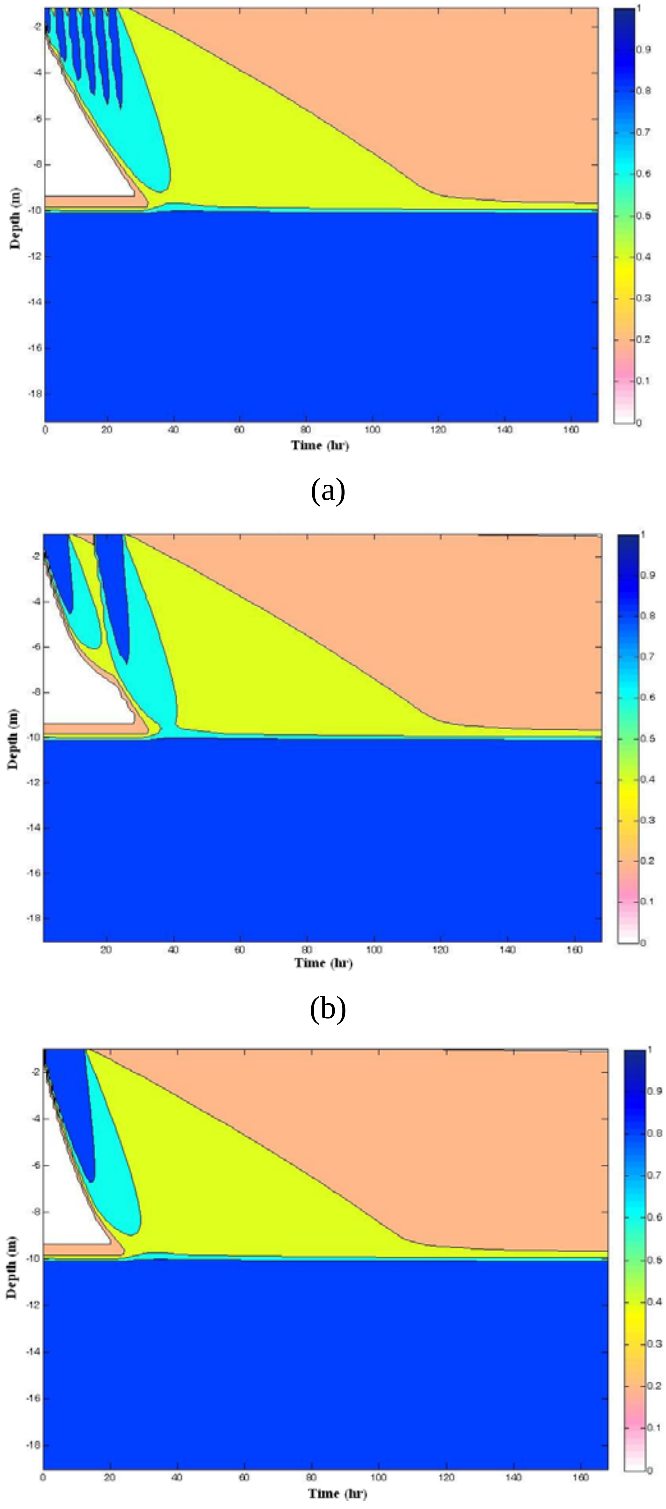


(a)

(b)

(c)

Figure 6. Maximum water saturation in 7 days a) 2h, b) 8h, and c) 12h cycles.



(a)

(b)

(c)

Figure 7. Water saturation profile at $r = 1$ m from the centre of the basin for a) 2h, b) 8h, and c) 12h cycles. Darker colors represent higher water saturations.

4. Conclusions and project implications (Accomplishments to Date)

1- After studying different approaches for coupling overland flow and subsurface flow, the most accurate one that was appropriate for RIBS was chosen and implemented in the iTOUGH2 code.

2- Three test cases were simulated to verify the modified code. The results demonstrated that the code changes were implemented properly.

3- Different groups of simulations were performed to assess the effect of vegetation, soil types, and operation methods on hydraulic aspect of RIBS.

- For simulating the effect of vegetation on hydraulic aspect of RIBS, water retention parameters predicted by PTF for sandy loam textural class were used. The results for this group of simulations were not presented in this report due to some ongoing convergence problems that have limited the duration of the simulations. Additional code modifications may be needed to simulate these cases for long time periods.

  The effect of vegetation was previously investigated without consideration of overland flow. In those simulations, a constant ponding depth was considered as a top boundary condition for the flooding period. These results indicated that vegetation growth in coarser sandy soil decreased the steady state infiltration rate, but did not have a significant effect on the infiltration rate in finer sandy soils.
- For understanding the effects of different operation methods on RIBS performance, three different cycles of flooding and drying were tested. The results indicate that using a long flooding cycle causes the saturated water front to extend to greater depth than shorter cycles.
- Although the effect of different cycles of wetting /drying on the DNF and P removal processes cannot be clearly understood from the water flow simulations alone, these results indicate that hydraulic loading will affect water distributions and most likely RIBS

treatment performance. Future work will simulate the fate of N and P using TOUGHREACT-N.

4. References

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