Savannah River Site Mixed Waste Management Facility Southwest Plume Tritium Phytoremediation

Evaluating Irrigation Management Strategies Over 25 Years

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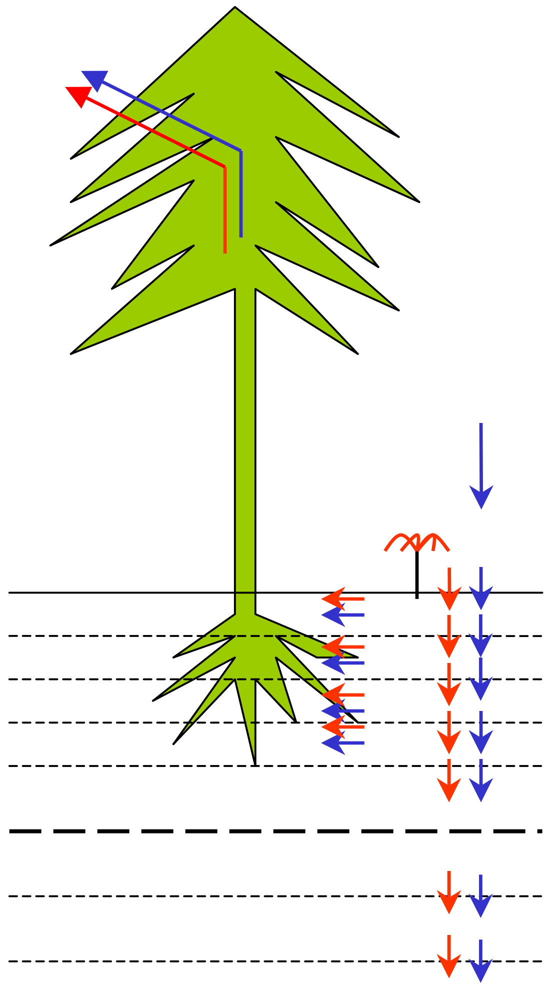

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Summary

To minimize movement of tritium into surface waters at the Mixed Waste Management Facility at the Savannah River Site, tritium contaminated seepage water is being retained in a constructed pond and used to irrigate forest acreage that lies above the pond and over the contaminated groundwater. Twenty five-year potential evapotranspiration and average precipitation are 1443 mm/year and 1127 mm/year, respectively, for the region in which the site is located. Management of the application of tritium contaminated irrigation water needs to be evaluated in the context of the large amount of rainfall relative to evapotranspiration, the strong seasonality in evapotranspiration, and intra-annual and inter-annual variability in precipitation.

A dynamic simulation model of water and tritium fluxes in the soil-plant-atmosphere continuum was developed to assess the efficiency (tritium transpired/tritium applied) of several irrigation management strategies. A one-dimensional multi-layer capacitance-based water model, where all applied tritium was completely mixed with soil water and moved as mass flow, was used to simulate water and tritium fluxes within soil, to roots and below the root zone. The model was parameterized for soils characteristic of the Coastal Plain, soils with a sandy layer of variable depth overlying clay, and for temperate hardwood and pine forest vegetation. Root density, and therefore water and tritium uptake, varies with soil depth. Potential evapotranspiration was calculated daily using data from the Savannah River Site meteorological tower for calibration of the model and from the Augusta, GA weather station for 25-year simulations. The model was parameterized using soil water content data measured at 18 sites for the first year of the project and validated using tritium activity measurements made over 2.5 years and water content measurements for two years.

The model was then used to test several irrigation strategies, including irrigating only when a critical water deficit was achieved and irrigating at a constant or varying percent of daily potential evapotranspiration. The 25-year efficiencies (tritium transpired/tritium applied) of the irrigation strategies were then related to the quantity of irrigation water applied. There was a strong (r^2=0.99), negative linear relationship between irrigation water applied and efficiency, indicating that, when assessed over long time periods, applying more irrigation water generally always results in lower efficiency. In addition, the simulations also demonstrated an increase in efficiency over the first one to two years, as tritium in the soil profile increases to a quasi steady state. When this state was reached, the annual efficiencies of all the irrigation strategies were negatively correlated with annual rainfall. Quantification of these relationships allows irrigation managers to choose irrigation strategies based on desired long-term system efficiency.

Problem Articulation

Tritium contaminated seepage water is being retained in a constructed pond and used to irrigate forest acreage that lies above the pond and over the contaminated groundwater in order to minimize movement of tritium into surface waters at the MWMF. A major goal of the remediation project is to maximize the movement of tritium to the atmosphere via the evapotranspiration pathway.

Tritium in the irrigation water can be
- Transpired by the vegetation and /or evaporated directly into the atmosphere
- Retained in the soil
- Leached below the root zone.

The amount of tritium that is lost from the soil via evapotranspiration and leaching will depend on the climate, the rate and timing of tritium application, and soil and vegetation properties. Tritium transpired by vegetation and tritium leached below the root zone are not directly measured. A one-dimensional model of soil and tritium movement and storage has been parameterized for the site and used to predict how much tritium is transpired by the vegetation versus how much tritium is leached below the rooting zone and is retained in the soil over time. This model is used to determine the efficiency (tritium transpired / tritium applied) of several different irrigation management strategies when assessed over many years with varying weather.

Model description

Figure 1 is a simple conceptual representation of the model that is described below.

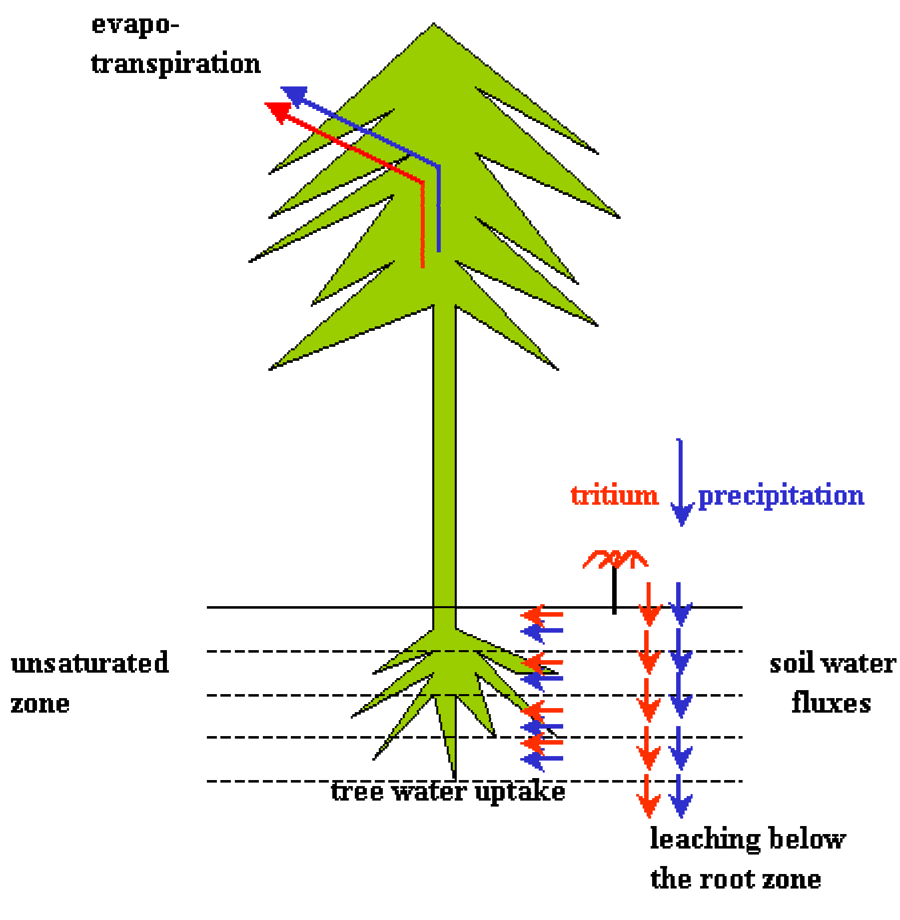
Soil water movement and storage were simulated using a capacitance approach. The soil is conceptualized as consisting of a series of layers, each having a specified capacity to hold water. Water is transferred downward from one layer to the next in the soil profile if the amount entering the layer exceeds the layer's water holding (field) capacity (FC). The capacity of each soil layer to hold water is calculated as the difference between the saturation water content and the current volumetric water content. This method is not iterative; the capacities at the beginning of the time step are used to estimate the redistribution of water during that time step.

Soil water uptake is simulated using an absorption approach. The maximum amount of soil water uptake is the potential evapotranspiration (calculated from daily weather data) multiplied by a “crop factor” to obtain potential transpiration. This vegetation factor is used to decrease potential transpiration below potential evapotranspiration due to incomplete canopy cover . The potential transpiration is partitioned among the soil layers based on the relative root density distribution in the soil profile, which is specified in the soil input file. As the soil water content in a layer decreases and approaches minimal soil water content, called the permanent wilting point (PWP), the demand for water uptake that is not met in a layer can be transferred to deeper layers. Thus root densities do not directly limit water uptake in this simple representation, but serve solely to partition transpiration demand in the soil profile. When demand can no longer be transferred to deeper layers (because the limit of rooting depth has been reached or all deeper layers are at the permanent wilting point) then actual transpiration will be less than potential.

Tritium fluxes within the soil are simulated using the simple assumption that all tritium entering a soil layer is completely mixed with the water in that layer and that tritium movement occurs only through mass flow. In other words, diffusion and dispersion are not simulated in this model. Tritium uptake in a layer is the product of the tritium activity in that layer and the water uptake by roots in that layer. Tritium transpired by the vegetation is the sum of tritium uptake in all soil layers with roots. Tritium that is leached is the flux of tritium out of the deepest soil layer containing roots.

This one-dimensional model runs on a daily time step.

Figure 1. Diagram of fluxes represented in 1-D model



Simulation parameters

Climate

We used 25 years of Augusta, GA weather data (1974-1999), using the rainfall directly and calculating potential evapotranspiration (ETP) using the Priestley-Taylor equation. Figure 2 shows the 25-year daily average ETP, which is significantly seasonal. Figure 3 shows the 25-year daily average rainfall, which does not show seasonal trends. Combining figures 2 and 3, it is clear that in winter precipitation is on most days much higher than ETP, while in summer precipitation is similar to ETP or less than ETP.

Figure 2. 25- year daily average potential evapotranspiration, calculated using the Priestly Taylor equation, for Augusta, GA.

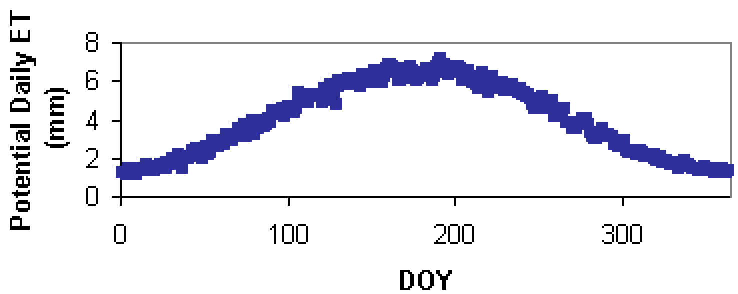
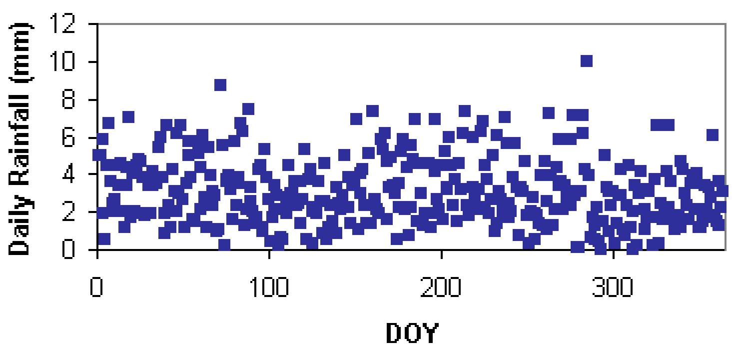


Figure 3. 25-year daily average precipitation for Augusta, GA.



Soil

The soil profile was divided in 9 layers, varying from 0.1 to 0.4 meter in thickness with the thin layers at the top where the system is more dynamic. A total depth of 3.1 meters of soil was simulated (Table 1).

Table 1. Soil variables of cluster 13-1, used for the 25-year model simulations

Layer	***Thickness (m)***	***Soil Depth (m)***	***FC ($m^3\ m^{-3}$)***	***PWP ($m^3\ m^{-3}$)***	***Relative root distribution***
1	0.1	0.1	0.12	0.05	0.3
2	0.3	0.4	0.15	0.05	0.2
3	0.35	0.75	0.15	0.05	0.2
4	0.4	1.15	0.26	0.18	0.1
5	0.4	1.55	0.26	0.18	0.1
6	0.35	1.9	0.2	0.13	0.1
7	0.4	2.3	0.2	0.13	
8	0.4	2.7	0.2	0.13	
9	0.4	3.1	0.2	0.13	

Vegetation

Roots occupy the first 6 layers of the soil profile to a depth of 1.9 m. Relative root density decreases with depth (Table 1). A 'crop factor' of 0.9 has been used for all the simulations and was constant over the year, representing a well-developed coniferous forest. This vegetation factor reduces potential transpiration to 90% of potential evapotranspiration.

Irrigation Algorithms

Irrigation managers have the ability to change both the timing and the rate of application of the pond water. Therefore, irrigation algorithms were devised that varied the timing of irrigation and the amount of irrigation water applied. The irrigation algorithms evaluated in this study can be divided in 4 general categories:

1. Irrigate daily as a constant percent of daily ETP or irrigate daily at a higher percent of ETP in summer (April 15 to October 15) and lower percent in winter (October 16 to April 14).
2. Irrigate daily at a constant rate or irrigate daily at a higher rate in summer (April 15 to October 15) and lower rate in winter (October 16 to April 14).
3. Irrigate if 6, 12 or 18 mm of deficit has accrued, restarting deficit accrual accounting after 10, 20, or 40 mm excess precipitation over ETP has accumulated. Deficit accrual has to be rezeroed periodically because precipitation exceeds ETP for much of the year.
4. Irrigate as a constant percent of ETP only if value is equal to or less than the soil water deficit on the previous day or at a higher percent of ETP in summer (April 15 to October 15) and lower percent in winter (October 16 to April 14).

The tritium activity in the irrigation water was assumed to be at a constant level of 16000 pCi/ml.

Results

Long-term Efficiency

Various irrigation algorithms summarized above were simulated for 25 years, using the 25-year weather data. Comparisons of the results of the different algorithms are presented in Table 2. The most important result of this study is that in general, **as more irrigation water is applied, more tritium is transpired (e.g. there is greater phytoremediation) but the system becomes less efficient (tritium transpired / tritium applied)**. This is because at higher application rates, more tritium is stored in and leached from the soil.

There is overall **a linear relationship (r^2=0.99) between the amount of irrigation water applied and the long-term efficiency of the tritium phytoremediation project** (Figure 4) using the range of irrigation algorithms described above. Some irrigation schemes are slightly more efficient than others, but over a 25-year simulation these differences in efficiencies are small. The **irrigation algorithms tested resulted in a range of annual average application of irrigation water from 220 to 1370 mm of water and efficiencies of 56 to 87%** (Table 2, Figure 4). **The simulations indicate that, in the long term, increasing the annual amount of irrigation water applied by 100 mm will decrease the efficiency of the system by 2.8%.**

Figure 4. Long-term efficiency of tritium remediation as a function of average annual irrigation water applied.

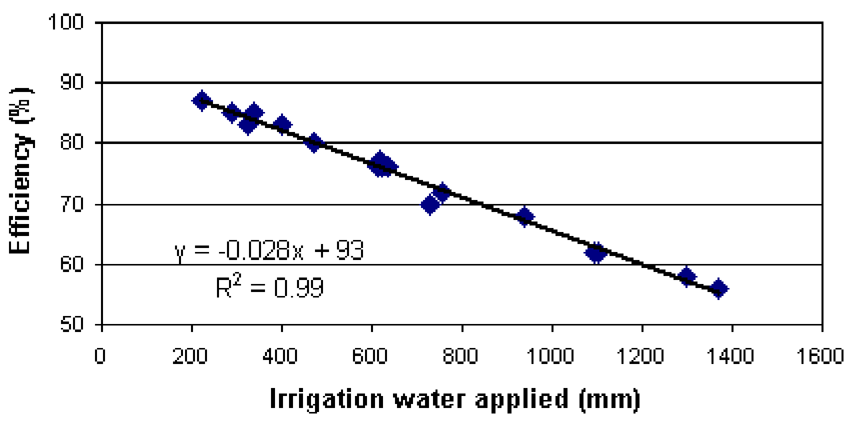


Table 2. Comparison of annual performance of different irrigation algorithms over a 25-year period. w = winter, s = summer

Irrigation Scheduling	Algorithm	Efficiency % (s.d.)	Irrigation water applied mm yr-1	Tritium applied μCi m-2 yr-1	Tritium transpired μCi m-2 yr-1
95% of daily ETP	1	56(3.8)	1370	21927	12292
90% of daily ETP	1	58(4.0)	1298	20773	12006
2 mm w, 4 mm s	2	62(5.4)	1092	17472	10846
45%w, 90%s of daily ETP	1	62(4.3)	1104	17658	10937
65% of daily ETP	1	68(5.1)	938	15002	10198
2 mm w, 2 mm s	2	70(5.3)	728	11648	8129
12 mm, if deficit, rezero after 10 mm excess.	3	72(8.6)	756	12104	8563
18 mm, if deficit, rezero after 20 mm excess.	3	76(9.6)	634	10149	7531
6 mm, if deficit, rezero after 20 mm excess.	3	76(9.2)	622	9953	7937
12 mm, if deficit, rezero after 20 mm excess.	3	76(9.0)	612	9792	7334
45% of daily ETP	1	77(5.3)	616	9852	8031
12 mm, if deficit, rezero after 40 mm excess.	3	80(9.1)	473	7565	5996
65% of daily ETP if deficit previous day	4	83(6.0)	402	6439	5294
90% of daily ETP if deficit previous day	4	83(8.9)	326	5215	4250
45% of daily ETP if deficit previous day	4	85(6.4)	336	5690	4834
45%w, 90%s of daily ETP if deficit previous day	4	85(7.8)	287	4596	3855
25%w, 95%s of daily ETP if deficit previous day	4	87(7.9)	220	3523	2504

Inter-annual Variability in Efficiency

There was **a high (up to 25%) inter-annual variation within the various irrigation schemes** (Figure 5). An analysis of the inter-annual variability in efficiency (averaged for all irrigation algorithms) for the last 25 years of simulation indicates a **high dependency on annual rainfall** (Figure 6). As expected, efficiency decreases as annual rainfall increases. The scatter around this general trend is not surprising given that differences in the size and persistence of rainfall events, as well as total rainfall, would be expected to effect system efficiency.

Figure 5. Inter-annual variation in efficiency for three irrigation algorithms: 45%w, 90%s no deficit (red); 45%w, 90%s deficit (blue); 45%w, 45%s, no deficit (green).

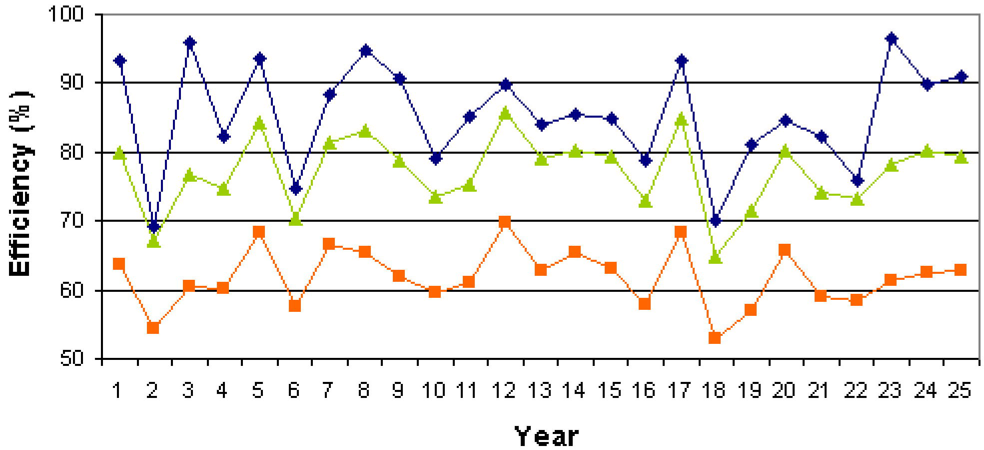
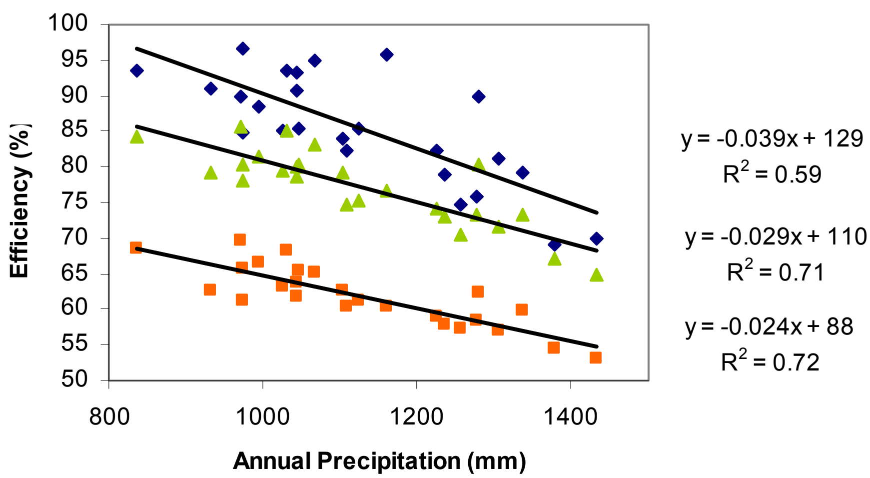


Figure 6. Dependence of efficiency on annual rainfall.



Intra-annual Variability in Efficiency

We evaluated several irrigation strategies in which the irrigation rate varied with season (e.g. higher in summer and lower in winter). In Figure 7, daily average irrigation water applied over the course of a year is contrasted for three irrigation algorithms. As expected, the seasonal pattern of water application varies considerably, depending on the irrigation algorithm. The impact on daily average tritium transpired (Figure 8) shows the expected seasonal trend (Figure 2) for the two algorithms that were solely dependent on ETP. The irrigation algorithm that requires a soil water deficit on the previous day in order to irrigate (which increased in summer relative to winter), while highly efficient, resulted in reduced summertime application and transpiration compared to the other irrigation algorithms (Figure 8). Although high tritium phytoremediation rates were maintained with the algorithm that required no deficit, the scenario that included high summer applications rates also resulted in some relatively high late summer and fall rates of tritium leaching (Figure 9).

Figure 7. 25- year simulation of the average daily irrigation water applied (mm/day). 45%ETPw, 90%ETPs (red); 45%ETPw, 90%ETPs when deficit (blue), 45%ETPw, 45%ETPs (green).

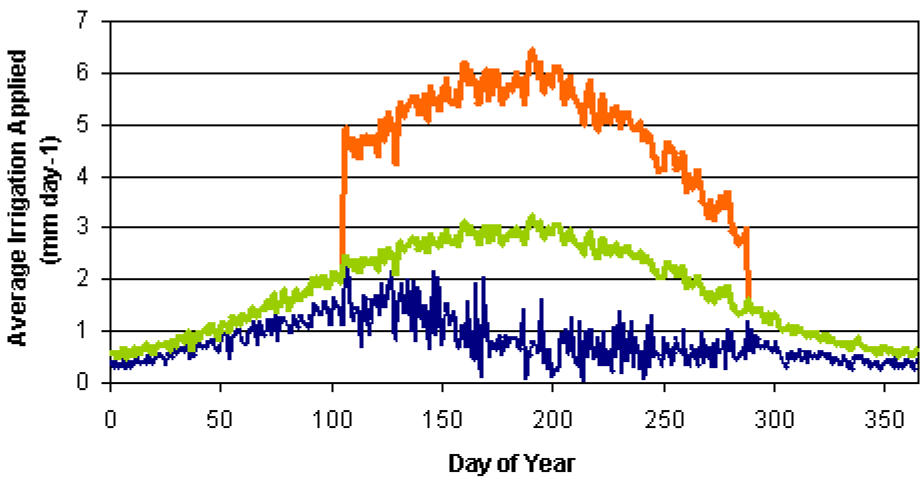


Figure 8. 25- year simulation of the average daily daily tritium transpired (μCu m^{-2} day^{-1}). 45%ETPw, 90%ETPs (red); 45%ETPw, 90%ETPs when deficit (blue), 45%ETPw, 45%ETPs (green).

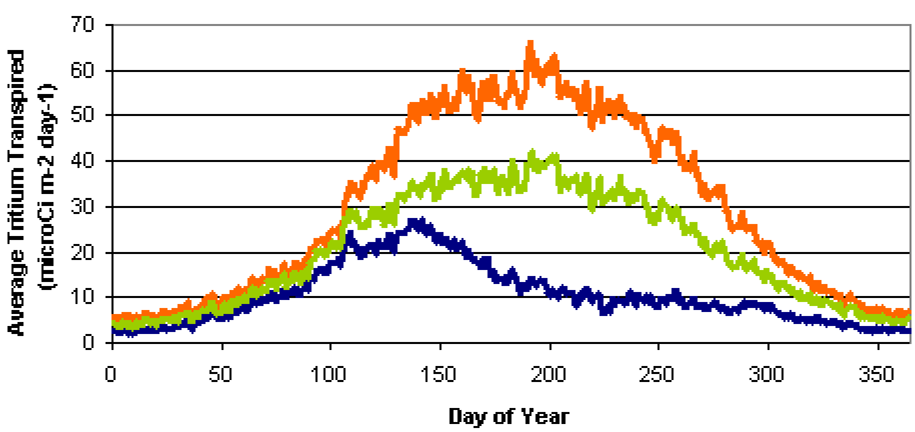
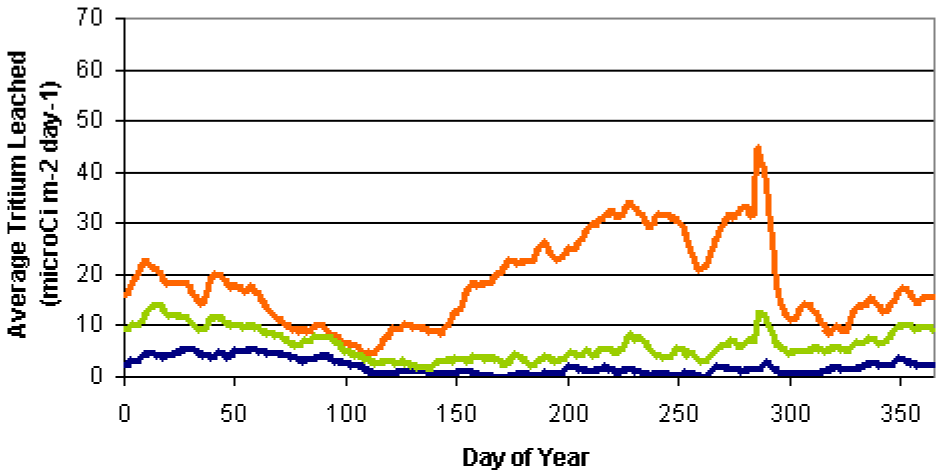


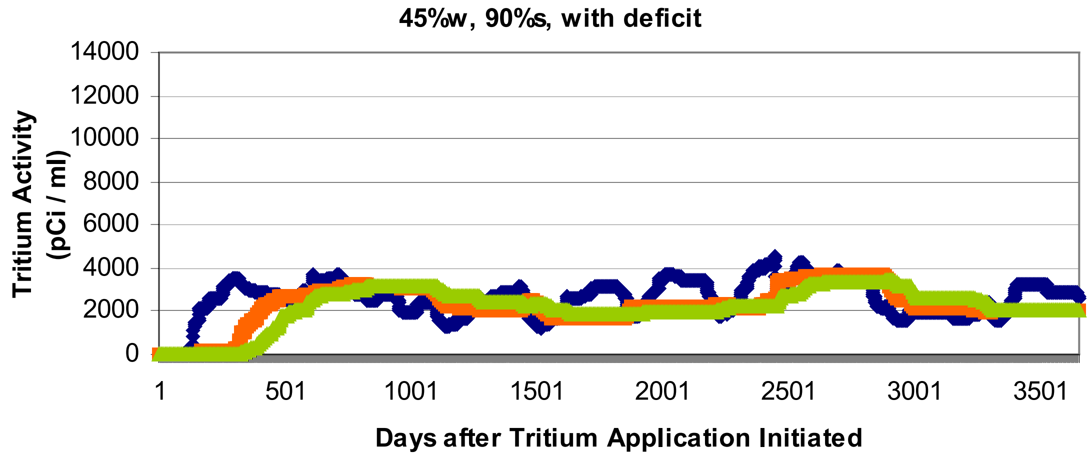
Figure 9. 25- year simulation of the average daily tritium leached (µCu m^{-2} day^{-1}). 45%ETPw, 90%ETPs (red); 45%ETPw, 90%ETPs when deficit (blue), 45%ETPw, 45%ETPs (green).

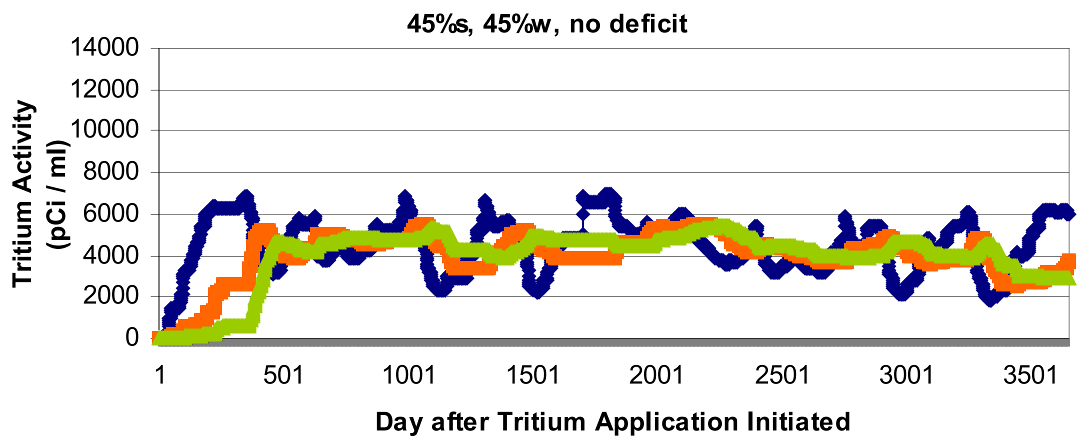


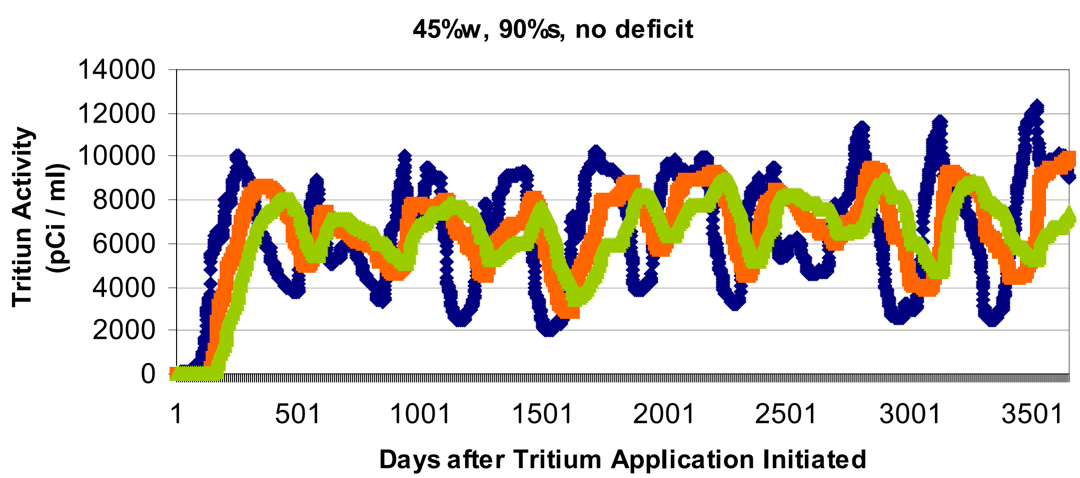
<u>Tritium Activity in the Soil Profile</u>

Tritium activity increased in the soil profile after irrigation was initiated, reaching a quasi steady state within two years (Figure 10). In these simulations, tritium activity in the irrigation water was assumed constant. If the tritium activity in the irrigation water varied over time, tritium activity in the soil profile would fluctuate to a greater degree than in these simulations. As expected, day-to-day variability in tritium activity decreased with depth. The quasi steady state values of tritium activity in the soil profile differed greatly among treatments. The algorithms with higher efficiencies (e.g. 45% ETP in winter, 90% ETP in summer when there was a soil deficit) had considerably lower tritium activity at depth in the soil profile than the less efficient algorithms (e.g. 45% ETP in winter, 90% ETP in summer) (Figure 10).

Figure 10. Tritium activity at 95 cm (blue), 205 cm (orange) and 295 (cm) in the soil profile during the first ten years after initiating tritium application


45%w, 90%s, with deficit
Tritium Activity (pCi / ml)
14000
12000
10000
8000
6000
4000
2000
0
1
501
1001
1501
2001
2501
3001
3501
Days after Tritium Application Initiated


45%s, 45%w, no deficit
Tritium Activity (pCi / ml)
14000
12000
10000
8000
6000
4000
2000
0
1
501
1001
1501
2001
2501
3001
3501
Day after Tritium Application Initiated


45%w, 90%s, no deficit
Tritiun Activity (pCi / ml)
14000
12000
10000
8000
6000
4000
2000
0
1
501
1001
1501
2001
2501
3001
3501
Days after Tritium Application Initiated

Conclusions

- The irrigation algorithms tested resulted in average applications of irrigation water ranging from 220 to 1370 mm of water and efficiencies (percent of tritium applied that is transpired) ranging 56 to 87%

- There is a strong ($r^2 = 0.99$) negative linear relationship ($y=-0.028x + 93$) between the amount of irrigation water (x in mm) applied and the long-term efficiency (y in percent) of the tritium phytoremediation project using the range of irrigation algorithms explored in this study. As more irrigation water is applied, more tritium is transpired (e.g. there is greater phytoremediation) but the system becomes less efficient (tritium transpired / tritium applied). This is because at higher application rates, more tritium is stored in and leached from the soil.

- Relatively lower efficiencies in the first one to two years of system operation can be expected due to the time it takes the system to reach a quasi steady state with respect to tritium storage in soil. The simulations indicated that higher values of tritium activity at depth in the soil would occur under the less efficient irrigation management algorithms.

- Quantification of the relationship of irrigation strategies to irrigation water applied and system efficiency will allow irrigation managers to choose irrigation strategies based on desired long-term system efficiency.

- There was considerable (up to 25%) inter-annual variation within the various irrigation schemes. An analysis of the inter-annual variability in efficiency for the last 25 years of simulation indicates a high dependency of efficiency on annual rainfall for the algorithms that are not using soil water deficits as a criterion for irrigation.

- An understanding of the dependency of inter-annual variability in efficiency on annual average rainfall will allow irrigation managers to evaluate irrigation strategies that maintain efficiencies within an expected range.