System Dynamic Modeling of Engineered Landfill Covers

ABSTRACT

Engineered landfill covers are designed to prevent surface water from infiltrating and contacting waste and waste containers stored in the subsurface and thus reduce the risk to human exposure as well as environmental contamination. Waste cap designs are proving to be inadequate to the guarantee the protection that they were designed for. One EPA study has shown that a significant number of engineered waste caps have failed (146 out of 163) and others are almost certainly to follow suit[1]. Despite our current attempts to contain these wastes, there is a great deal of uncertainty in the long-term performance of such engineered systems, raising questions about how to better design, manage and monitor engineered environmental barriers. The Idaho National Engineering and Environmental Laboratory is developing a better understanding of the performance of caps through the development of a system dynamic model that explores the linkages between the various environmental and physical elements that make up a cap system.

Keywords: System Dynamics, Engineered Barriers, Landfills, Environmental Modeling.

I. INTRODUCTION

The Department of Energy (DOE) has been the leading agency in nuclear power and weapons research for the past 50 years. This research has left many contaminated sites that require some form of management or cleanup. Removal and subsequent treatment of wastes at many DOE sites is technically difficult, expensive, and hazardous, exposing workers and the environment to chemical and radiological contamination. Alternative approaches that leave the waste in place but incorporate robust containment and stabilization technologies will be a key factor in the success of DOE's strategy to manage legacy waste sites. DOE's management commitment for these waste sites will potentially extend for many thousands of years.[2]

The National Research Council (NRC) conducted a review of barrier technologies for interim and long-term containment of contaminants in 1997 and concluded "barriers such as surface caps and subsurface vertical and horizontal barriers will be needed as important components of remediation strategies."[3] Identified issues included the following:

* Existing barrier performance data are inadequate; we should learn more from how existing barriers are performing.
* Knowledge to predict lifetimes of selected barrier materials and resultant barrier systems is inadequate.
* The full range of ecological and engineering factors needs to be considered to predict and enhance long-term performance.

The NRC further reviewed the long-term institutional management of DOE legacy waste sites in 2000 and cited the need for a much broader-based, more systematic approach for contaminant reduction, isolation, and stewardship.[4] The report stated that "the objective is to achieve a barrier system that is as robust as reasonably achievable," given the current limitations. However, they went on to state that "the most important consideration in the use of engineered barriers and waste stabilization approaches in waste management is the fact that there is limited experience with most, if not all, of the systems being considered." They concluded that improvements are needed to enhance scientific and engineering understanding of barrier materials and designs.

A study done by EPA has shown that a significant number of engineered waste caps have failed (146 of 163) and others are certain to follow. Reasons for failure include insufficient depth of soil, inadequate maintenance and improper design and installation. Another problem being sited for barrier failure is that many of these caps were designed with a 30 to 50 year life cycles and now many of those barriers are reaching those life time limits. These are serious limitations in barrier design especially since most of the original landlords are no longer around or liable for the waste.

The Idaho National Engineering and Environmental Laboratory (INEEL), a multi-purpose national laboratory under management of DOE, is working to improve understanding in the linkages between how classical engineering can be merged with scientific principles from areas such as ecology, chemistry, materials, sensors, and hydrology (Figure 1). This focus will help us improve how barriers can be designed and managed, using an ecological engineering approach[5] to better understand and evaluate possible long-term changes in barrier performance. This work will focus on tasks to improve understanding of barrier performance, failure mechanisms as well as recovery capabilities through experimental and modeling approaches. This project tasks include selected exploratory studies (bench top and field scale), coupled effects testing, accelerated aging testing, and dynamic modeling.

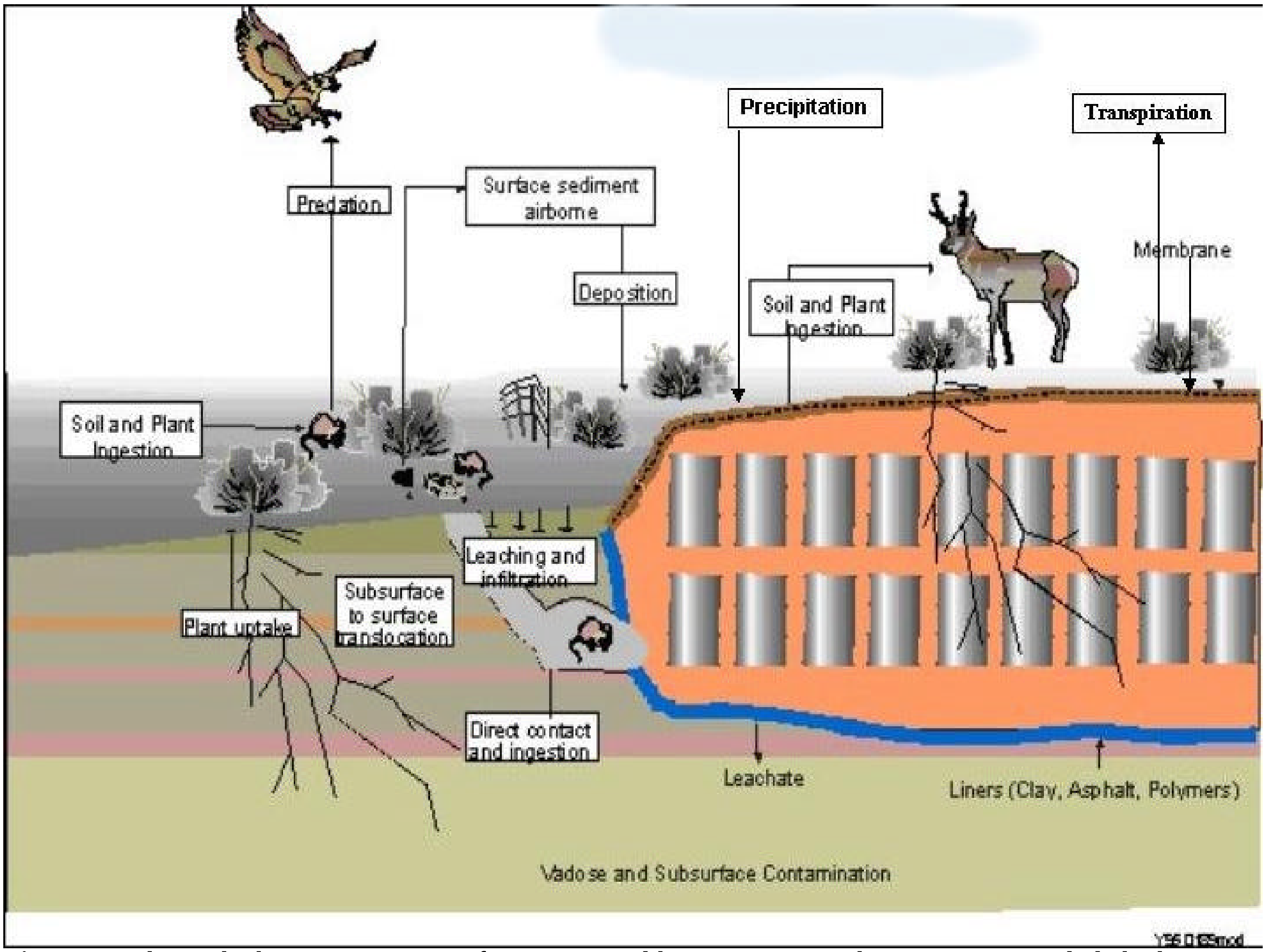


Figure 1: Shows the basic components of an engineered barrier system. The components include both ecological/environmental components as well as engineered components. It is the interactions of these components over time that determines the performance of the cap.

In order to address these issues, several important questions need to be answered:

1) What are the important elements to consider when designing a waste cap barrier?
2) What are the conditions where the cap will perform adequately and what conditions will cause the cap to fail?
3) How will the barriers perform over the long term (100-1000 years) and what are the management issues?
4) Can we incorporate natural ecological systems into the design to make the caps more resilient to changes over time?

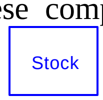
A new INEEL project is exploring barrier performance/degradation dynamics.[6] One task is the design and evaluation of relatively simple but very flexible system dynamic models to explore the dynamics of barrier performance. This research provides a means to map out the underlying feedback loop structure of the system and explore the relationships between the various components.

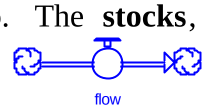
II. SYSTEM DYNAMICS

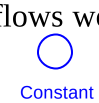
System Dynamics[7] is an analytical approach that examines complex non-linear feedback loop systems through the study of the underlying system structure. A thorough understanding of the structure of these complex systems can lead to an explanation of their performance over time and in response to both internal and external perturbations. By understanding a system's underlying structure, predictions can be made relative to how the system will react to change.

A System Dynamics model is a visual representation of a system. This visualization of the components and connections is one of the assets of this modeling technique. The visual model defines, through a graphical interface, a series of finite difference equations that define the behavior of the system over time. For this effort, we have used commercial software packages, STELLA© and VENSIM©. STELLA is somewhat easier and more flexible to use; VENSIM is more numerically powerful. The calculations are performed using numerical integration. Although the interface makes the modeling look superficial and almost trivial, there is a very sophisticated mathematical engine that generates a series of time dependent calculations of system parameters. Using this modeling technique it is possible to model very complicated systems.

System Dynamics models are descriptive in nature. All the elements in the model must correspond to actual entities in the real world. The decision rules in the model must conform to actual practice and real world phenomenon. Thereby, adjusting an element in the model corresponds to a physical change in the real system. The purpose of the model is threefold: 1) A visual diagram of the system from which to engage discussions on the various elements of the model and elicit input from interested parties; 2) To gain insights into the dynamics of the movement of moisture in the soil and to identify core structure of the system; and 3) To develop a tool for the analysis of long-term performance.

System Dynamic models are based on four basic components, stocks, flows, constants/auxiliaries and connectors. Figure 2 shows these components overlaying an illustrative graphic of an evapo-transpiration cap. The **stocks**, 

, accumulate quantities of material, in this case, moisture. The **flows**, 

, physically change the quantities of the stocks. The direction of the arrow defines whether it is an inflow into the stock or an outflow from the stock. Inflows would include precipitation, irrigation and run-on. Outflows would include runoff, deep drainage, evaporation and transpiration. **Auxiliaries/Constants**, 

, contain information that feeds into the stocks or flows. The **Connectors**, ✍, symbolize a relationship between two elements in the model and the direction of the arrow indicates the direction of the influence.

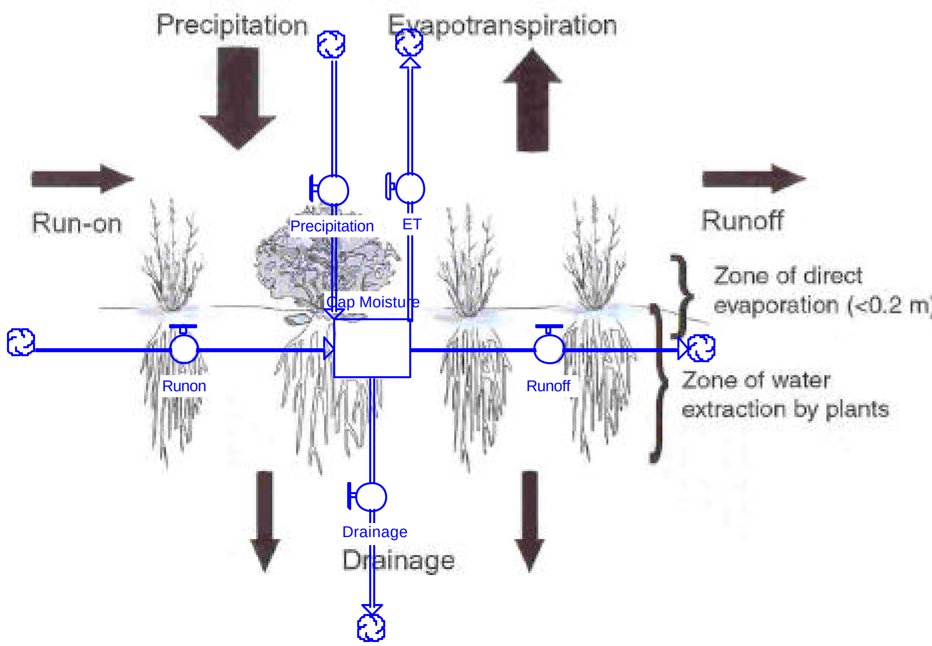


Figure 2. Simplified system dynamic model overlaying illustrative graphic of evapo-transpiration processes.

III. MODEL

Our first illustrative barrier model is a simple soil cap with a vegetative cover and underlying capillary break. The model tracks the soil moisture content in the cap as well as deep drainage into the waste level. The change in moisture in the cap layer is dependent on the inflow of moisture from precipitation, run-on and irrigation, field capacity of the soil, current moisture level of the soil, and extraction via evapo-transpiration and deep drainage.

The model precision depends on the exactness of the data and equations used to simulate the physical phenomena as well as the ? t, delta t, value used in the time step calculations. It should be noted that the movement of water through soil is highly non-linear and highly variable. There is a significant amount of on going research that is attempting to better model saturated and non-saturated moisture movement in soil. This model will use the results from those models to extract the relationships to estimate moisture movement. The basic model provides a focal point to begin to discuss the physical components (inflows, outflows, evapo-transpiration, etc.) and how they are connected. Our initial model has the following characteristics:

* Time-dependent precipitation (rain, snow) based on historical data from southeastern Idaho.
* Runoff based on slope and amount of precipitation.
* Evapo-transpiration is estimated using the FAO Penman-Monteith equations.[8] Transpiration is governed by root density. The higher the root density, the more transpiration occurs up to the point where the soil moisture reaches the lower limit of extraction; whereby transpiration from that zone ceases to occur. The root density will increase if there is sufficient moisture in the soil to sustain the current amount of plant life. If the moisture levels drop below the necessary amount to sustain the current amount of plants, then there is a decrease of plant root density and thus a

lower capacity to remove moisture from the soil. The FAO Penman-Monteith equations estimate the potential evapo-transpiration that could occur based on available sunlight, temperature, elevation, humidity, longitude and crop type. The potential evapo-transpiration is used with plant available water and soil type to estimate actual evapo-transpiration.

* The storage level is split into 10 layers/nodes for tracking the water down and up through the storage layer. The layers or nodes can have the same soil properties or can be varied if the cap has non-uniform layers.
* Downward movement of moisture through the soil is governed using the Green-Ampt equation.[9] The Green-Ampt equation governs unsaturated flow of water through a porous material. The Green-Ampt equation is derived from Darcy's Equation on flow in porous material.
* Capillary rise or wicking moves moisture from the wetter lower layers back up towards the surface as the surfaces areas dry through evaporation and transpiration. The capillary effect is affected by soil type, moisture content and height to surface. The model will use the unsaturated Darcy flow where total potential is capillary less gravity. The Darcy's Law is the law of water flow through a porous material. It governs how fast water will flow based on slope and hydraulic conductivity.
* Hypothesized capillary break interface degradation due to freeze/thaw, wet/dry, etc.

The following two sub-sections go into more detail on the evapo-transpiration and capillary break portions of the full model.

IV. EVAPO-TRANSPIRATION SUB-MODEL

An Evapotranspiration, ET, cap offers the potential to promote beneficial feedback dynamics and discourage detrimental feedback dynamics if we can identify and promote the important dynamic processes. Most of these are ecological – discourage plants (and animals) from doing detrimental things (intrusion); encourage evapo-transpiration from plants, and encourage stability of plant cover against perturbations (fire, drought, excessive precipitation, climate change, etc.)

It is possible that such a cap could have extremely long term functionality by providing sufficient robustness against the short-term perturbations from stressors. Some of those stressors may in fact be long-term such as climate change. Some stressors that are being considered are:

* Fires are a natural part of most ecosystems; how fast does vegetation re-establish? Does the same vegetation mix re-establish in the absence of active maintenance or is intervention required? As the post-fire ecosystem evolves, does the barrier provide adequate storage and protection each year?
* Droughts are natural. During the drought, there is less stress on the barrier, but as the climate returns to "normal", does vegetation re-establish soon enough so that the storage capacity of the barrier is not exceeded? As the post-drought ecosystem evolves, does the barrier provide adequate storage and protection?
* Abnormally high precipitation (relative to average) is natural. The natural ecosystem will respond to increased precipitation. The details of the response depend on whether the

increased rainfall is for a month, an entire season, multiple years, etc. Basically, the ecosystem will take advantage of the increased precipitation.

* If climate slowly changes will barrier's response to the net effect of precipitation, temperature, ecosystem changes continue to provide protection? These perturbations are similar to wet/dry year, except they continue for longer periods with more time for ecosystem responses.

The timing of the processes is critical to cap performance and subsequent failure. At semi-arid cold sites like the INEEL, precipitation typically exceeds evaporation for most of the year (Figure 3). Thus, ET caps must be able to remove sufficient moisture during the few hot months via evapo-transpiration to balance precipitation; the caps must have enough storage capacity (soil depth) to avoid water breakthrough into the waste at the transition between early precipitation and hot months (spring after snow melt). The yearly dynamic is further complicated by the fact that infiltration into the soil is relatively rapid during the spring thaw prior to the plants being active. Spring thaw events can result in a significantly greater amount of infiltrating water than individual precipitation events during the warm periods. Evaporation and transpiration during and immediately following periods of thaw are likely to be low, thus putting greater stress on the barrier system than during summer or fall.[12]

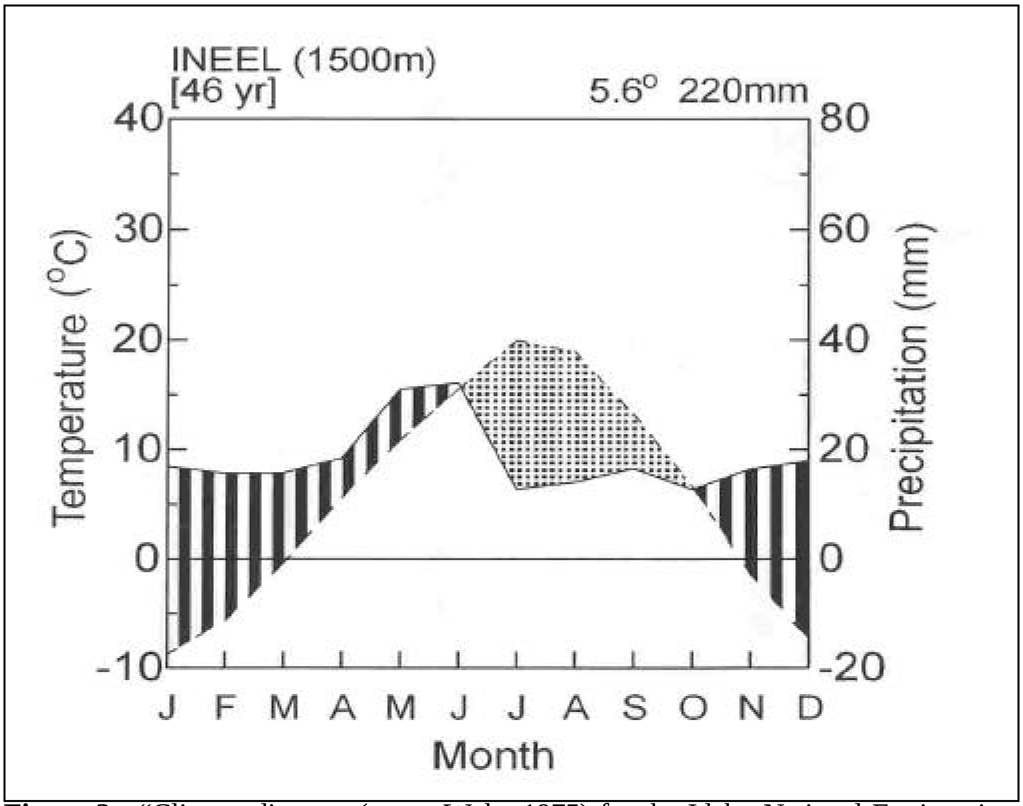


Figure 3. "Climate diagram (*sensu* Walter1975) for the Idaho National Engineering and Environmental Laboratory (INEEL) based on data for 46 years from the Central Facilities Area (U.S. National Oceanic and Atmospheric Administration, Idaho Falls, Idaho, unpublished data). Solid curve depicts mean monthly precipitation; dashed curve shows mean monthly temperatures. Vertical hatching indicates periods when precipitation generally exceeds potential evapotranspiration. Strippled area indicates periods when potential evapotranspiration generally exceed Precipitation."

The depth of the topsoil layer is essentially a buffer against perturbations. "In semiarid or arid regions, the mostly likely cause of such failures is simply an inadequate depth of soil."[10] At the INEEL, about 1.8-2.0 meter of soil is needed to store precipitation during "exceptionally wet years" and have "sufficient moisture storage capacity to sustain a healthy stand of perennial plants."[9] For long-term performance prediction, one must know not just whether precipitation increases or decreases (yearly fluctuations, climate change) but *when* during the year.

Consider the increased precipitation case further. One brute force design approach is for regulators to stipulate that a barrier has to withstand say 3x normal rainfall for a given number of years. The usual response from designers is to add depth to the cap to support the added moisture. This increases the cost of the cap but does it actually increase the efficiency of the cap? Also, the regulators don't specify how the added precipitation will be done. Is it a relative increase for the entire year or would it come in several increased individual events. These are important questions.

A more dynamic approach is to consider how the ET cap would respond over months and years - with more moisture available there would be more vegetation to take advantage of the increased moisture. The more vegetation responds to the increased moisture, the higher the uptake of moisture from the cap and the less additional storage capacity has to be added to the design.

For example, at Hanford, it has been hypothesized and studied that in a wetter climate, trees and other deeper-rooted plants could invade to take advantage of the increased moisture. They should have the beneficial impact of increasing ET, but a possible negative impact of deeper roots stressing the capillary barrier.[11]

The INEEL Protective Cap/Biobarrier Experiment (PCBE) provides 8 years of data on how ET caps behave in a relatively cold, semi-arid environment.[13] It's objectives "are to examine the effects of placing an intrusion barrier in a soil cap on water infiltration, water storage capacity, and plant rooting depths and to determine which species of plants, if any, will grow roots through an intrusion barrier and extract water from the soil below it (which would be necessary if the intrusion barrier were placed at a shallow soil depth)."[9] This experiment was started in 1993 and a major report has recently been released. We are using these data to develop and calibrate the model.

Figure 4 below illustrates key features of our evapo-transpiration sub-model. Starting on the left of the diagram, we note that inflows to the cap include:

* Surface run-on
* Precipitation
* Irrigation

Similarly, on the right of the diagram, we note a primary outflow, surface run-off. The model has a runoff component based on the slope and amount of precipitation. The current model has a slope component that can be adjusted, but for current analysis the slope is set at zero.

At the top of the diagram is evapo-transpiration, which is governed by the root density component of the model. The higher the root density and plant biomass, the more transpiration occurs up to the point where the soil moisture reaches the lower limit of extraction, whereas transpiration from that zone ceases to occur. The root density will increase if there is sufficient moisture in the soil to sustain the current amount of plant life. If the moisture levels drop below the necessary amount to sustain the current amount of plants, then there is a decrease of plant root density and thus a lower ability to remove moisture from the soil.

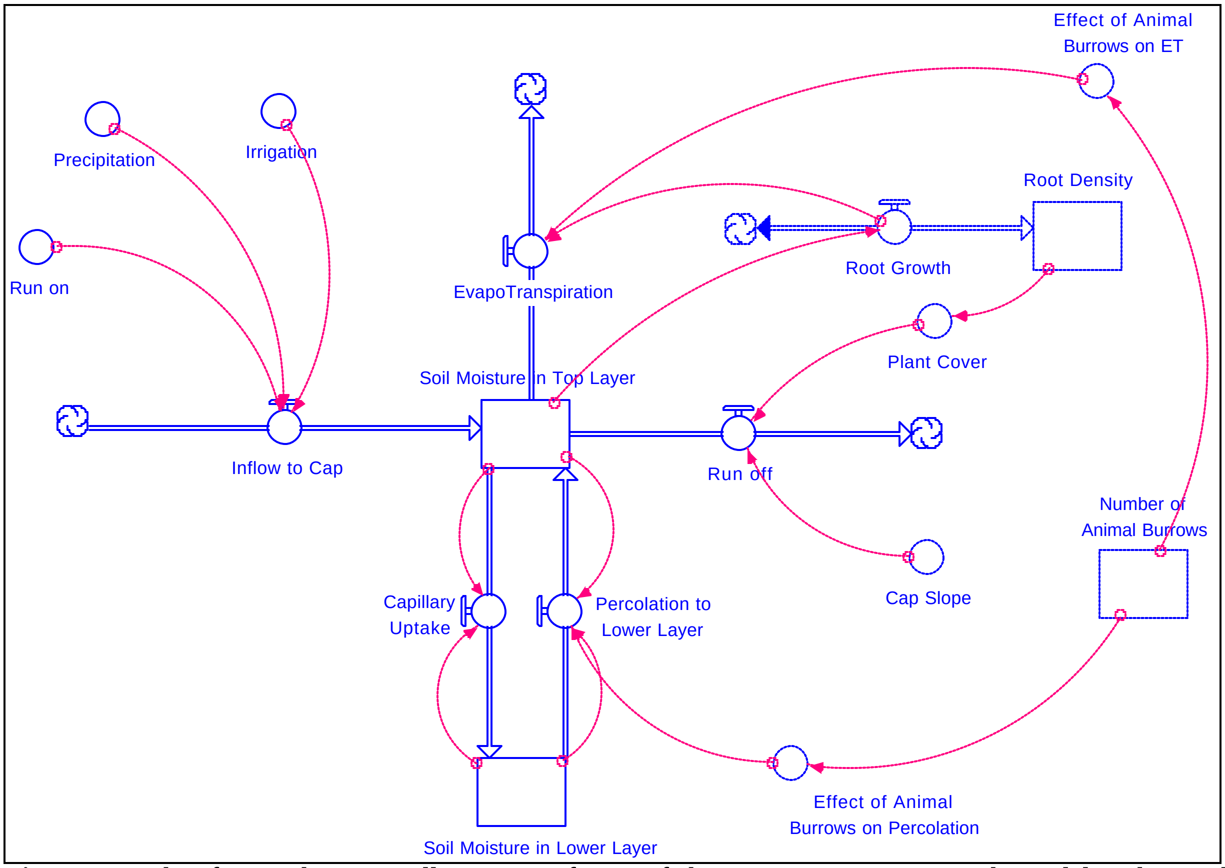


Figure 4. This figure shows an illustration of part of the evapo-transpiration sub-model. The model shows two stocks with multiple flows both in and out of the stocks. This diagram is a simplified version used to outline some of the important elements in the system.

At the bottom of the diagram are upward and downward flows deeper into the cap. The capillarity effect (wicking) would move moisture from the wetter lower layers back up towards the surface as the surface areas are dried by evaporation and transpiration. The capillary effect is affected by soil type, moisture content and height to draw soil back up.

The model keeps track of current moisture content in each of the different layers as well as total drainage from the bottom of the cap into the waste zone. Graphs are used to display the moisture levels throughout the simulation period. The user can track the inflow of moisture and see the effects on the moisture content in the various layers and see the effect of the drying cycle through the evapo-transpiration process.

The system operates on a system of feedback loops. For example, figure 4, illustrates both beneficial and harmful effects from animal burrows. In the upper right we include the beneficial effect that animal burrows have been shown to have to increase evaporation. "During the summer months, more water is lost from plots with animal burrows than from plots where no animal burrows are present. During the winter months, both the animal burrows plots and the control plots gain water. In addition, water does not infiltrate below ~1 m, even though burrow depths always exceed ~1.2 m. The lack of significant water infiltration at depth and the overall water loss in the lysimeter plots is occurring despite the following worst-case conditions: 1) No vegetative cover (no water loss through transpiration), 2) no water runoff (all incipient precipitation is contained), 3) The burrow densities in the lysimeters are greater than the burrow densities found in "natural" settings, 4) Extreme rainfall events are applied frequently (three 100-year storm events in 3 months), and 5) Animals burrow deeper in the lysimeters than in "natural" settings. … "The overall water loss from soils with small-small burrows appears to be enhanced by a combination of soil turnover and subsequent drying, ventilation effects from open burrows, and high ambient temperatures"[15]. Thus, in this case, animal intrusion had a net positive effect. Indeed, earlier Hanford work shows that soils were dryer beneath burrows than elsewhere.[11, 14] Link reports that the increased moisture in burrows facilitated vegetation response that increased plant transpiration as plants took advantage of the moisture, sent roots to use it, leading to dry zones under the burrows. "Ecologically, it is expected that a local abundance of a limiting resource, in this case soil moisture, would be rapidly used and therefore depleted."[10]

Another feedback in the model (not shown in the figure to preserve readability) relates to excess soil moisture above transpiration capacity. Excess moisture in the soil causes an increase in plant growth thus plant root density which in turn increases transpiration which reduces the excess moisture in the soil until the two elements (transpiration, moisture) are in equilibrium. The amount of moisture the soil will be able to hold will depend on the type of soil and the depth of the cap. Both of these parameters will be adjustable to test the performance levels of different soils as well as cap depth. In addition, different plant species have different transpiration rates and capacities and will affect the performance of the cap. The model will allow for the user to select the variety of plants on the cap. In addition, some plants will send roots down very deep where others will keep their roots relatively close to the surface. This difference would change the performance of the ET component in terms of transpiration performance as well as rooting into waste zone.

Another set of feedbacks that are only partially in the model relate to vegetation response against various perturbations. ET caps require a stable mix of plants that uses as much water as possible (at least as much as assumed in the design). "Stability" has to be judged against various perturbations. If plant mix evolves toward plants that use less water, the cap may not function adequately.

* Soil depth must be sufficient to provide for stable and health vegetative cover and adequate storage for "wet" years
* Plants have to re-establish after drought.
* Plants have to re-establish after fire. The **fire** concern is highest late in the growing season when soil moisture is low, above ground vegetation is maximum and become

dormant (Figure 5). "If vegetation on an ET cap includes a diverse mix of species and life forms, including healthy populations of perennial grasses, cover on the cap can be expected to recover to pre-fire levels within two growing seasons (S. Buckwalter and J. Anderson, unpublished data). It is likely that there would be sufficient cover in the first post-fire season to use most of the precipitation received, but additional research is recommended to confirm this."[11]

Accordingly, we are currently formulating models for soil erosion, plant growth after a fire, plant and animal intrusion, geosynthetic clay liner (GCL) degradation, etc. Rate parameters and submodels will be adjusted as additional experimental data becomes available.

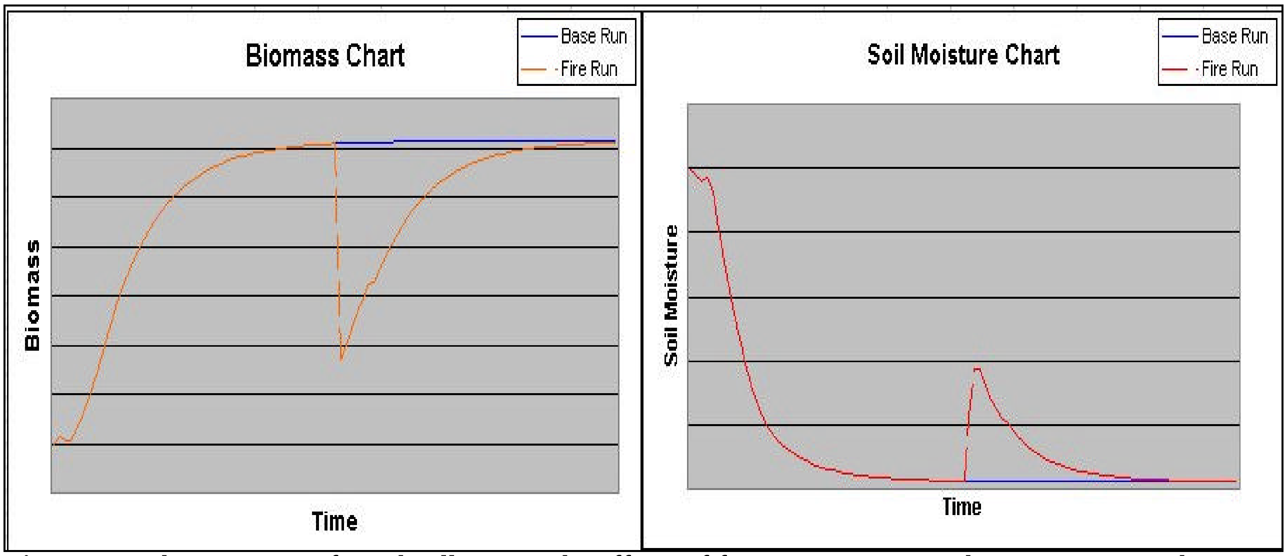


Figure 5. The sequence of graphs illustrates the effects of fire on an ET cap. The vegetation on the ET cap increases until it reaches equilibrium. Equilibrium is established when the amount of transpiration from the vegetation (moisture removal) matches the amount of moisture being supplied to the cap through precipitation, run-on and irrigation. The effect of a fire is to decrease the amount of vegetation thereby decreasing the amount of transpiration, which then increases the amount of moisture in the cap. The cap recovers but it takes time. The time scales and magnitudes of moisture and biomass depend on the ecological and environmental conditions of the local area.

V. CAPILLARY BREAK SUB-MODEL

Figure 6 below illustrates part of the capillary interface sub-model. A capillary barrier is a layer of coarse material placed below a layer of fine soil. This change in coarseness creates a barrier that allows the upper layer to store more water before breakthrough. A capillary barrier (or the capillary portion of a multi-layer barrier such as an ET-capillary cap) uses the change in hydraulic conductivity between an upper layer of fine material and a lower layer of coarse material to increase water storage capacity and inhibit downward water movement. The performance of such a barrier depends on maintaining a sharp gradient at the interface. Some capillary barriers also include slopping of the barrier to promote lateral flow in the fine layer to further inhibit downward water movement

The capillary break sub-model contains two stocks. One is the soil moisture in the layer just above the capillary interface; the other is a simplified attribute, "capillary interface effectiveness." The figure shows several of the factors that could degrade the effectiveness of the barrier; note that "effectiveness" only flows outward. That is, the model has no provision for processes that could *improve* the interface effectiveness. (Were such processes to be observed or hypothesized, they could be easily added to the model.)

There are limited data regarding interface degradation processes acting individually and no known data regarding any coupling or synergistic interactions. For example, consider a class of scenarios that start with one or more of the following effects that increase the amount of moisture getting into the coarse layer: excessive rainfall/snowmelt, animal/plant intrusion, mechanical effects, and microbial effects on capillaries. Normally, plants have no incentive to send roots into the coarse layer because it is dry; similarly, there should be little moisture to foster microbe communities. (This stimulates the question of how much moisture for how long a time?) If roots impact the capillary layers, the barrier could be subject to a cascading or propagating failure. Similarly, water breaking through the capillary interface can carry fines into the coarse zone, weakening the interface. The processes and the coupling of these processes must be understood to have confidence in the long-term robustness of capillary barriers. The model provides a way to conceptualize relationships; data from the rest of the project will clarify the relationships and underlying processes.

At the top is the effect of freeze-thaw cycles. We hypothesize that freeze-thaw cycles and associated expansion/contraction can promote migration of fines into coarse, degrading the interface. Similarly, when GCLs are used at the interface, freeze-thaw cycles over decades may slowly degrade performance.

Throughout a previous two-year experiment[15], vegetation was prohibited to maximize the effect of increased (simulated) precipitation. Thus, the water loss from the surface was only via evaporation, not transpiration. Replicates of both a capillary barrier and a thick soil cover were irrigated in 1997 to induce breakthrough of water to the bottom of the cells. The objective was to study the dynamics of recovery. The dominant water infiltration both years was snowmelt in March. The thick soil design also showed additional infiltration during short-term rain periods in 1998 (May, 11 days, 43.7-mm water) and FY1999 (June, 10 days, 49.5-mm water). The capillary barrier recovered faster, partially in year-1 and almost completely in year-2. The capillary barrier stored more water in the upper portion of the cap. "Within two years of intentionally induced breakthrough, evaporation alone (without transpiration) restored the capability of the capillary barrier covers to function as intended, although water storage in these covers remained at elevated levels."[15] Thus, the capillary barrier can recover from abnormally wet conditions leading to breakthrough. However, the study showed that there could be significant delay in stopping water breakthrough (1-2 years in this case) and a residual effect of increased water content in the "fine" layer of the barrier, which would presumably return to "normal" in another year or two. These response times would be expected to be faster with vegetated capillary caps because of the increased water removal via transpiration.

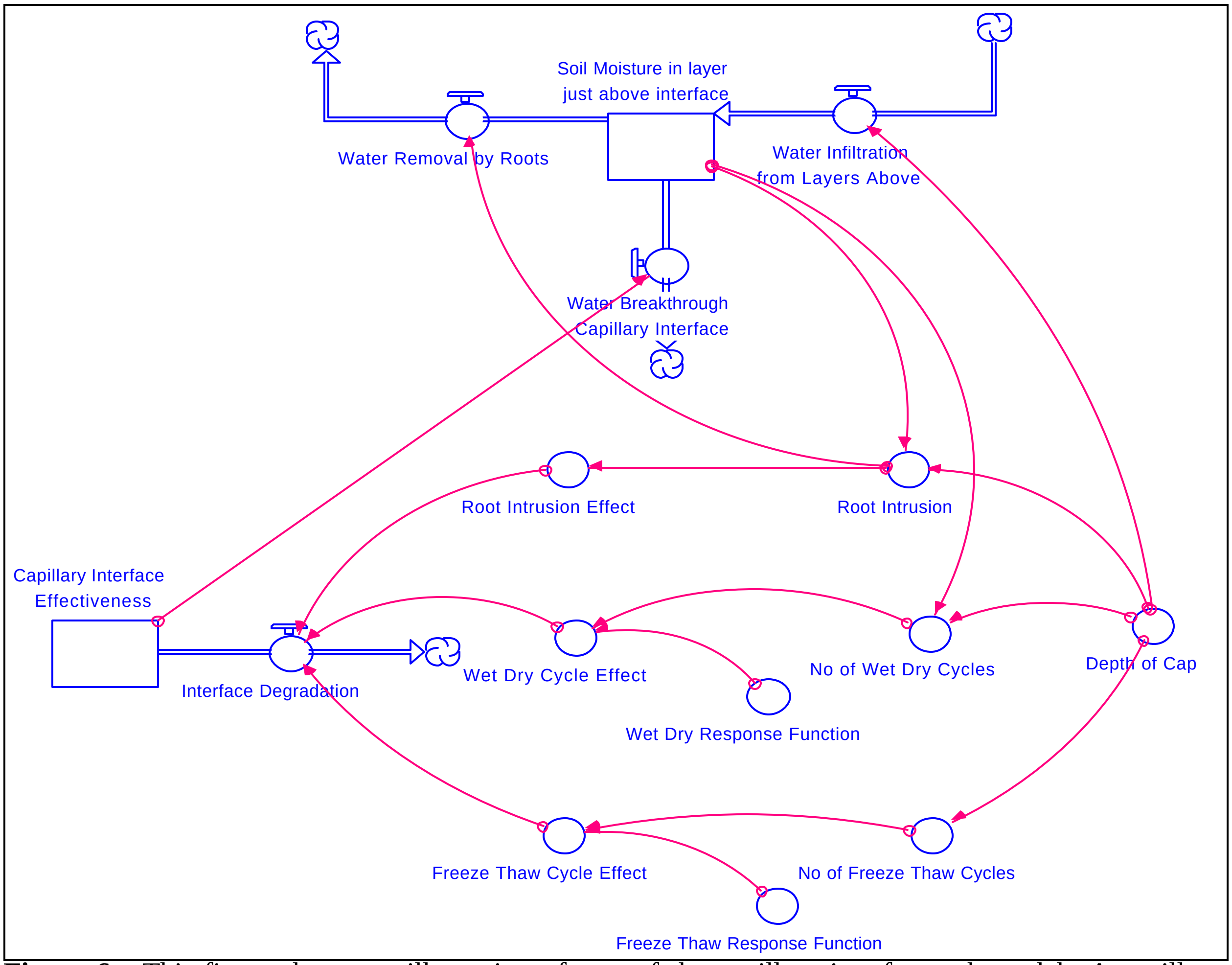


Figure 6. This figure shows an illustration of part of the capillary interface sub-model. A capillary interface is a coarse layer of soil installed below a fine layer of soil. The change in coarseness causes an increase in water storage capacity in the upper layer. A mixing of the fine soil with the coarse soil breaks down the interface effectiveness.

Below freeze-thaw is wet-dry. The recovery of capillary barriers following abnormally high precipitation has been (and is being) studied at the INEEL Engineered Barrier Test Facility (EBTF).[15] The facility has 10 cells, each with concrete walls and floor and measuring 3.05-m wide, by 3.05-m long by 3.05-m deep. The top is open to the atmosphere. An access trench runs between the cells and houses instrumentation and data acquisition systems.[15]

What about repeated cycles? Stormont conducted column experiments with silty sand (25% fines) and clay (85% fines). "The silty sand apparently has enough cohesion for it to bridge over the voids of the coarse layer and remain stable. The clay was initially stable, but eventually failed. The clay would crack during drying, and progressively erode during rewetting. Eventually, swelling of the clay was not sufficient to prevent a continuous crack to develop." "These results indicate that conventional criteria are not necessarily applicable to capillary barrier configurations. Further, the stability of the capillary barrier may be jeopardized if the cover is susceptible to large volume changes in response to wetting and drying."[17]

Root intrusion is another phenomenon that is modeled. The fear is, of course, that roots can create flow paths that defeat the interface. The classic approach to the problem is to guard against such an occurrence by inserting a bio-intrusion layer. However, what is the likelihood that this occurs, how bad would it be? If we have to guard against it, are there simpler, longer-lasting ways?

Plants will not grow in soils with water content below the "wilting" point. "Because coarse materials drain to low water contents, typically below the wilting point, they can serve as barriers to root penetration. To be effective as a root barrier, fines must be kept out of the coarse layer. This suggests the size of the coarse layer either has to be limited so that overlying fines do not penetration into it, or an intermediate layer has to be used to retain the overlying soil."[16]

Root channels, animal burrows, and cracking in the fine zone (significantly above the interface) should not compromise a capillary barrier because the storage layer is unsaturated and water is held in the soil matrix - just as a hole cut in a sponge will not cause the sponge to loose its water. Thus, such penetrations that do not approach the interface should not compromise the barrier because the water will eventually be drawn into the soil matrix.

As the penetrations approach the interface, the situation becomes more complex. A partially penetrating hole could provide a water path (e.g. rapid snowmelt, thunderstorm or other large infiltration event) that could cause locally saturated conditions at the interface, causing localized leakage.

If root channels or animal burrows penetrate to the coarse layer and a large infiltration event occurs, water could flow down the pathways (short circuiting the barrier interface) instead of being drawn into the soil matrix or running off the barrier.

Thus, plants and animals have little incentive or ability to get into the coarse zone as long as it stays dry. The coarse zone tends to stay dry as long as intrusion (or penetrations or beyond-design basis precipitation) does not occur. It remains to be shown how much moisture (breakthrough) into the coarse zone, for how long, for how many times creates enough of a perturbation that the system cannot recover and plant and animal intrusion becomes a problem. On the other hand, roots have observed to have a beneficial effect - remove water.[11] Thus, the model includes both harmful and beneficial effects of plant roots on the capillary interface. As we calibrate the model with data, we will have a tool to explore the interplay between harmful and beneficial effects.

VI. SIMULATION

The model has a flight simulator (Figure 7) front end that allows the user to experiment with different cap designs as well as environmental parameters and run the simulation to see the effects on cap performance. The user can change a variety of parameters form cap thickness, precipitation, initial soil moisture, elevation, latitude, average wind speed and average temperature. The cap depth is a user-defined value, which defaults to 3 meters. The user can select a cap as thin as 0.5 meters or as thick as 6 meters. We chose 0.5 m as the lower boundary because this is the minimum allowed under EPA's current requirements for RCRA Subtitle D landfill caps. The interface allows the user to adjust various options by adjusting slide bars, dial knobs and graphical inputs. When the user is ready to test a cap design they click on the run button. The results appear on the chart on the interface. It should be noted that the simulation capacity although touted at the start of the project as the main feature of the modeling effort is currently a lesser component of the research effort. The modeling exercise and the visual display of the system have proven to be a valuable piece of the research puzzle.

Figure 7 shows a trial run where there is initial spike inflow of 100 mm of precipitation into a cap that is 3.0-meters thick with a moderate permeability level. The results show the sharp increase in moisture content of the top layer (#1, blue line) and then a steady drop as the moisture percolates from the top layer down into the middle layer. The middle layer shows a gradual increase in moisture content until it creeps slightly above the storage capacity (#4, green line). At that point moisture begins to percolate from the middle layer into the third layer. The moisture content for the third layer rises slightly but doesn't reach the storage capacity. By the tenth day the system has reach equilibrium. The top and middle layers are at field capacity level but the third layer is still below the field capacity. In this case, the cap had sufficient capacity to store the influx of moisture to prevent any drainage into the waste layer. This shows the response of the cap to short term perturbations. Longer runs can be made to test other responses such as plant growth and erosion.

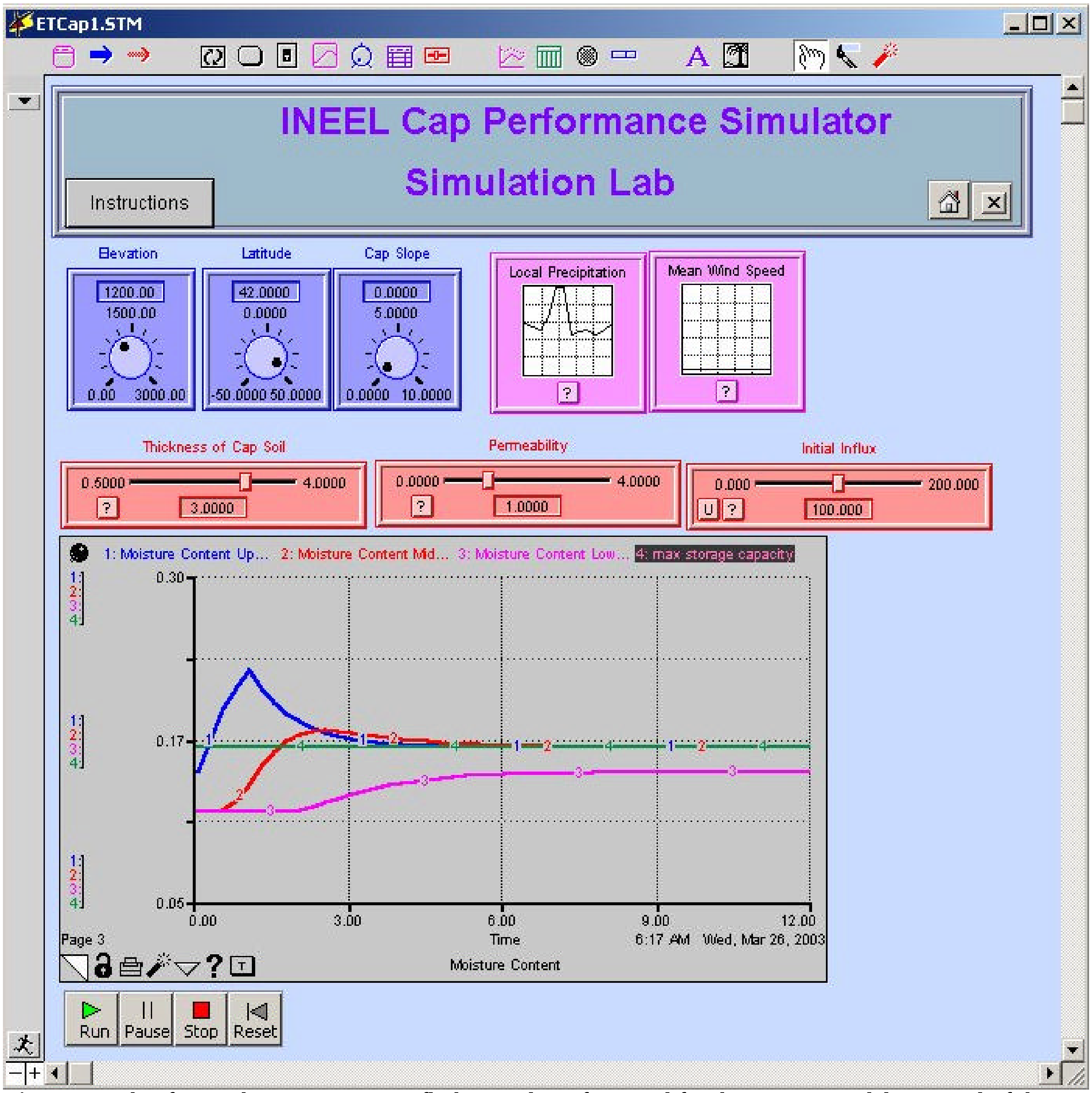


Figure 7: This figure shows a prototype flight simulator front end for the ET cap model. Several of the inputs include initial soil moisture, precipitation as well as average daily temperature and several ET parameters. This is only a subset to the total set of parameters that could be included on the simulator front end. We are experimenting with users on the most useful parameters to use for the simulator.

VII. MODEL STATUS

This is a simple preliminary model. It does not yet include all the components needed to evaluate the long-term structural integrity of a cap design. It is included here to trigger discussion about the different components already captured in the model as well as the components that are not in the model but should be included. Furthermore, the model, even in this simplistic stage, can test some simple cap designs and give insight as to the complex behavior of ET-capillary Caps.

We are calibrating the model with existing data and data generated from the rest of the larger project.

The model will eventually allow simulations such as the following:

* Time-dependent balance for animal intrusion burrows between harmful open porosity versus beneficial increased evaporation.
* Time-dependent balance for plant intrusion between harmful macropores versus beneficial increased wicking and evapo-transpiration.
* Time-dependent system response as the water storage layer thickness changes due to soil erosion.
* Response to fire - plants providing evapo-transpiration are destroyed, cap is initially less protective, time and water allows plants to reestablish
* System response to fluctuating precipitation (one or more abnormally wet or dry years will cause plant changes, thereby changing evapo-transpiration; long-term wet or dry periods will cause ecosystem changes)
* Hypothetical long-term capillary break degradation.
* Hypothetical long-term GCL degradation.

VIII. CONCLUSIONS

DOE-Environmental Management's accelerated cleanup strategy depends in large degree on leaving substantial contamination in the ground and capping it. Meanwhile, DOE regulations now require new caps to have 1000-year design lifetimes. Yet, the Nuclear Regulatory Commission staff has stated that longevity assumptions in current barrier performance assessments "*have no basis in the scientific and technical literature and experience*." [Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Radionuclide Transport in the Environment Research Program Plan, March 2002.]

Our project is the first systematic attempt at establishing the basis for long-term prediction and maintenance of ET caps. If we can begin to establish the "safety case" for long-term caps that user natural systems to help maintain cap integrity, it should be possible to modify the current cap designs. This should decrease the cost of engineered waste caps as well as improve long-term performance.

The system dynamic modeling is helping to direct research as well as give a systemic view of the cap performance over the long-term. The visual model has benefited both the researchers as well the regulators. Further research is on going and the results will help to calibrate and validate the model. This is a three-year research project but the prototype model has already been a fruitful endeavor.

CONFERENCE PRESENTATION

For the conference, it is planned to show the latest version of the model and discuss the results of this research. In addition, there will be a discussion about what was learned through the process with the researchers and managers involved in the project. The model is not included in the review process because of some discussions from management on proprietary property issues and it was easier to omit the model than fight the system. The model will be available at the conference.

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