Development of Screening Parameter for the Design of Monolithic Alternative Landfill Covers in Arid and Semi-Arid Climates

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Abstract: After landfills reach their storage limit, they need to have a final cover to reduce the amount of water that percolates from rainfall to diminish leachate production and the risk of additional contamination. Many States require that final covers provide the hydraulic impedance that limits flow into underlying contaminated materials. Water balance covers that rely on the capacity of fine-textured soils to store infiltration during rainier periods have been accepted to be used in arid and semiarid climatic zones of the US.

The objective of the study was to develop a screening parameter that will make alternative landfill cover design simpler. This study assessed how effective are previous design schemes and developed a new design index for water balance covers in Arid and Semi-Arid climates. Eighteen locations were selected across the Arid and Semi-Arid climate of the U.S. Ten typical soils were selected as representative of soils found in these regions. HYDRUS-1D was used as the model to simulate the water balance of several covers, each one for a different soil and thickness.

The results of the simulation were compared to that expected using previous design schemes. Surprisingly, Ten out of eighteen modeled locations resulted in percolation, which contradicts existing design methodologies. A new design parameter, $Sr_{NEW,}$ was developed by modifying the original Sr_{ACAP} to be specific to alternative covers in Arid and Semi-Arid climates.

Keywords: Aridity, water balance, landfill, evapotranspiration, alternative covers.

1. INTRODUCTION

Once a landfill has reached its design storage, needs to be covered with a specifically designed final cover. Final covers are used to reduce the quantity of water that percolates into polluted soils or into waste deposits at solid waste facilities. Reducing the volume of percolating water, reduces the amount of leachate that is generated and the risk of additional groundwater and surface waters contamination as well. Furthermore the cover is needed to avoid the intrusion of external elements, humans and animals that may be exposed directly to the health hazards, common to the waste, and then will extend these diseases to the community. At many states, the applicable rules and regulations require that the covers employ resistive principles, i.e., layers having low saturated hydraulic conductivity such as compacted clay barriers, geosynthetic clay liners with or without a geomembrane. These principles are used to provide the hydraulic impedance that limits flow into underlying contaminated materials or waste. This design philosophy is often referred to as “raincoat”, barrier, or “umbrella” approach. Barrier type covers, such as compacted clay covers, have been shown to lose their impermeable qualities over time in semiarid zones because of the influence of climate variations on the integrity of the soil layer [1].

Water balance covers are earthen final covers used as waste containment facilities covers, that depend on the capacity of fine-textured soils to store infiltration during some period of the year and then on evapotranspiration to remove the stored water during the rest of the year [2]. If the storage capacity of the cover is exceeded, percolation occurs at its base [3]. Percolation is minimized by selecting an adequate soil cover profile which provides acceptable storage capacity and possibly vegetation with appropriate transpiration potential to remove the stored water. Evapo -transpiration (ET) is defined as the combination of evaporation from soil and plant surfaces, and transpiration from plant leaves. That’s why, these types of covers are referred to as evapotranspiration (ET) covers or water balance covers. These covers are not designed to a level of impermeability that can be measured in the field, they are designed based on capacity to meet percolation minimums. This design relies heavily on computer modeling to simulate the soil cover properties, climate, and plants. As a result, although the lifecycle cost of such covers is much lower than a conventional cover, the design cost may be higher, making it difficult for many small landfills to afford the design of such covers. There are several areas with similar soil types, climate, and vegetation as well. Designs in one area ought to be applicable to other similar areas, resulting in a standard design method that only needs to be adjusted to the climatic conditions and soil. The US EPA final cover regulations require a provision for the use of alternative final

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covers. These regulations state that the alternative cover must provide: 1) an infiltration layer that provides equivalent reduction in infiltration to that of the prescribed cover and 2) an erosion layer that provides equivalent protection from wind and water erosion as the one of the prescribed cover. However, these regulations do not specify allowable percolation rates through any type of covers.

2. RECENT DESIGN METHODOLOGY

Albright *et al*. (2010) [17] introduced another methodology to estimate the required storage based on the ACAP field data, the amount of water that may accumulate in the cover is dictated by the climatic conditions. Apiwantragoon (2007) [18] used the results of regression analysis of percolation data from the U.S. EPA's Alternative Cover Assessment Program (ACAP) to define thresholds in the P/PET ratio that can be used to determine if water is expected to accumulate in the cover (Table **1**). Only the months where the threshold of P/PET is exceeded are summed up in the calculation of S_r, as water is not expected to accumulate in the other months (Albright *et al*., 2010) [17].

Table 1: Thresholds for Sr. ACAP

THRESHOLD For Sr. ACAP		
Climate Type	**Season**	**Threshold**
No Snow and Frozen Ground	Fall Winter	P/PET > 0.34
	Spring Summer	P/PET > 0.97
Snow and Frozen Ground	Fall Winter	P/PET > 0.51
	Spring Summer	P/PET > 0.32
Fall-Winter = September-February. Spring-Summer = March- August.		

The required storage (S_r), is an estimate of the amount of water that needs to be stored in the water balance cover based on local climate characteristics, and is a good index to guide the design of these covers (Albright *et al*., 2010; Apiwantragoon, 2007) [17, 18]. This parameter can be calculated as follows:

$$\mathrm{SrACAP} = \underset{\text{Fall - Winter Months}}{\sum_{m=1}^{6}\left\{\left(P_m - \beta_{FW}PET_m\right) - \Lambda_{FW}\right\}} + \underset{\text{Spring - Summer Months}}{\sum_{m=1}^{6}\left\{\left(\mathbf{P_m} - \boldsymbol{\beta}_{\mathbf{FW}}\mathbf{PET_m}\right) - \Lambda_{SS}\right\}}$$

Where:

P_m = monthly precipitation,

PET_m = monthly PET,

β_{FW} = ET/PET in fall-winter,

β_{SS} = ET/PET in spring-summer,

Λ_{FW} = Runoff and other losses in fall-winter,

Λ_{SS} = Runoff and other losses in spring-summer.

Table **2** shows two sets of β and Λ parameter values for fall-winter and spring-summer for a given climate type which were also calibrated from the ACAP dataset (Apiwantragoon, 2007, cited in Albright *et al*., 2010) [17, 18]. Unlike conventional final covers, water balance cover designs do not have well-defined regulation-based requirements for materials and layer thicknesses (Albright *et al*., 2010) [17]. Instead, water balance cover designs are based on required performance, often defined as meeting a predetermined acceptable maximum annual percolation rate (Albright *et al*., 2010) [17]. Acceptable percolation rates, however, have not been formally established in many locations. In areas where

Table 2: Parameters for Water Accumulation Equation

PARAMETERS FOR WATER ACCUMULATION EQUATION				
Climate Type	**Season**	**Threshold**	***β*** **(-)**	**Λ mm**
No Snow and	Fall	P/PET > 0.34	0.30	27.1
	Winter			
Frozen Ground	Spring	P/PET >0.97	1.00	167.8
	Summer			
Snow and	Fall	P/PET > 0.51	0.37	-8.9
	Winter			
Frozen Ground	Spring	P/PET > 0.32	1.00	167.8
	Summer			

acceptable percolation rates are defined, one modeling approach is to simulate iteratively for selected soil types, changing the thickness with every model run until the predefined percolation rate is achieved. The combinations of thickness and soil type that achieve the desired percolation rate may then be used in the design guidance. If an acceptable rate has not been defined, an alternative approach is to model a range of thicknesses for selected soil types and use the resulting percolation rates to determine a threshold for an acceptable cover thickness. This second approach provides percolation values for a range of cover thicknesses and soil types. In addition, the variation in percolation rates over a range of thicknesses may provide insights into the sensitivity of percolation rates to soil type and other parameters. The movement of water through the soil profile should be simulated in a rigorous manner and should include water lost to uptake by roots. To achieve this, the model ought to be based on a solution to Richards' equation for unsaturated water flow (Richards, 1931) [19]. The surface boundary conditions should simulate the interactions at the soil-atmosphere interface (i.e. precipitation, infiltration, evaporation, and runoff) and should be driven by user-provided climatic inputs.

The thickness, then, is calculated by dividing this Sr_{ACAP} by the Unit Soil Storage Capacity θ_a to obtain the penetration that will store the water in the soil. As said before, this thickness needs to be corroborated by modeling or simulation to conform that the percolation is going to be the minimum.

3. STUDY MOTIVATION AND OBJECTIVES

The early design methods of water balance covers relied on calculating the amount of water that needed to be stored by the soil layer, Sr., to be equal to the amount of precipitation outside the growing season as follow:

$Sr = P(t)-Pgs$

Where P(t) is the total precipitation in the location, Pgs is the precipitation during the growing season. This design assumes that the soil is supposed to provide enough storage for the precipitation outside the growing season and the vegetation during the Growing Period, is assumed to be able to remove all of the stored water. The thickness is achieved by dividing this Sr. obtained under the previous assumption, by the unit storage capacity of the soil as follow:

$L = Sr/\theta a$

Where L is the cover thickness and Sr is the precipitation outside the growing season or the required storage of the soil [4]. The final step is to use this thickness and perform numerical simulations using a daily climatic data to estimate percolation for a given design year.

The objective of this study is to assess how effective is the scheme proposed by the above methodology to estimate Sr_{ACAP} and to develop a new design index for water balance covers in Arid and Semi-Arid climates. This purpose is met by modeling the water balance of simulated monolithic non-vegetated covers across a wide range of soils and micro-climates of the Arid and Semi-Arid regions of the U.S. This conservative approach focuses generally on modeling cover performance under conditions that favor percolation. It is assumed that if the modeled cover is predicted to perform well under non-vegetated conditions, then performance during typical years is also likely to provide the needed environmental protection

4. WATER BALANCE COVERS IN ARID AND SEMI-ARID CLIMATES

At the Integrated Test Plot (ITP) in Idaho Falls, ID from 1984 to 1987, were evaluated some monolithic and capillary barriers [5]. The average annual precipitation in the location is 469mm/yr. The monolithic cover consisted of 0.2-m sandy loam placed on top of 1.08-m crushed tuff; the capillary barrier consisted of 0.71-m sandy loam, 0.46-m gravel, 0.94-m cobble, and 0.38-m crushed tuff. The resultant percolation that occurred in the monolithic barrier, measured with Lysimeters, fluctuated from 0 to 6.1% of the total precipitation. Evapotranspiration (ET) from the capillary barrier was higher than ET from the monolithic cover; and percolation from the capillary barrier was 5.4% of precipitation which is lower than the one from the monolithic cover.

From 1990 to 1993 at Hill Air Force Base in Ogden, UT; one monolithic cover and two capillary barriers were evaluated [6, 7, 8]. The investigated average precipitation was 520mm/yr. for this locality. The monolithic cover comprised 0.9m of sandy loam and the capillary barrier was made of 1.5m of sandy loam resting over 0.3m of gravel. The capillary barriers included 10-mm-thick gravel covering on the surface. One capillary was vegetated with grasses and the other with grasses and shrubs. Monolithic cover transferred more percolation, 6.5 to 80.1% of precipitation, than the capillary barriers 0.31 to 49.7% of precipitation. The capillary barrier with grass and shrubs transmitted more percolation, ranging between 2.7 and 49.7% of precipitation, than the capillary barrier with grasses only, 0.3-35.9% of precipitation. The differences in percolation between all three covers were not statistically substantial. More than 90% of the percolation occurred during early spring as a result of snowmelt, spring rain, and low ET.

On 1997 three sets of un-vegetated capillary barriers were evaluated at Los Alamos, NM from 1991 to 1995 [9]. One set of test sections was continued through 1998 [10]. Each set had test sections with slopes of 5, 10, 15, and 25%. The first set consisted of 0.15-m of loam overlying 0.76-m crushed tuff, and 0.3-m gravel; this set was evaluated through 1998. The other two sets had 0.61m of loam or clay loam, overlying 0.76-m fine sand and 0.3-m gravel. Runoff increased as the slope increased from 5 to 25%, but it was a small portion of precipitation less than 4% for all investigated sections. Percolation decreased with increasing slope, but the difference in percolation rate between experimental sections with different slope was less than 1% of precipitation. Percolation rates were higher for the capillary barrier with 0.15 m of loam, but average annual percolation rates were less than 7.5mm/yr.

At the Rocky Mountains Arsenal near Denver, CO, between 1998 and 2001, were evaluated four monolithic covers [11]. Three of the monolithic covers were constructed with silty clay having thicknesses of 1.07, 1.22, and 1.52 m. The fourth monolithic cover was constructed with clayey sand and was 1.07 m thick. Combined precipitation and irrigation ranged in the 546-568mm/yr. Precipitation interval during the first and third years of the monitoring period. Percolation was less than 0.1mm/yr., measured for all covers.

A number of field evaluations of conventional and water balance covers have been conducted. These studies have shown that percolation rates for conventional covers and water balance covers can vary by more than two orders of magnitude depending on factors such as climate, cover design, soil properties, and type of vegetation. However, most studies have been conducted at a single location and only a few have considered side-by-side comparisons of conventional and water balance covers. Consequently, reliable generalizations regarding cover performance or equivalency criteria cannot be made. USEPA's Alternative Cover Assessment Program (ACAP) was conducted to provide the information needed to make such generalizations.

ACAP consisted of a network of field sites across the United States in climates ranging from arid to humid, hot to cold, and seasonal to temperate, where fifteen water balance covers and twelve conventional covers were evaluated for 2 to 6 yr. In this study, data from ACAP and past studies were used to evaluate equivalency criteria, evaluate and refine design methods, and to identify percolation rates likely to be achieved by water balances throughout the United States.

ACAP consisted of 15 covers distributed as follows: Nine are monolithic covers, and six are capillary barriers. All of the capillary barriers employ a simple two-layer fine-over-coarse design. The capillary barrier located at Monticello also includes a gravel admixture at the surface (upper 200mm) and a biota barrier layer (cobbles embedded in the final soil) at a depth of 1.1 m. The cover thickness ranges from 0.76 m to 2.45 m. The sites evaluated in ACAP are located in 12 different cities located in 8 different states, representing a broad range of climates, precipitation amount and type, as well as types of soil and vegetation.

Climate characteristics for each location and Climatic designation for each site are based on the ratio of precipitation to potential evapotranspiration (P/PET), according to the definitions given by United Nations Educational, Scientific and Cultural Organization (UNESCO) (UNEP, 1992) [12]. Based on these definitions, one site has an arid climate, seven sites have semi-arid climates, two sites have sub-humid climates, and two sites have humid climates. The long-term average annual precipitation ranges from 119mm/yr. to 1263mm/yr., and P/PET ranges from 0.06 to 1.10. Precipitation occurs principally as rain at five of the ACAP sites, and as rain and snow at the remaining sites. Annual snowfall as water equivalent ranged from 1.6% to 41.9% as a percentage of annual precipitation.

Three of the ACAP sites have cool growing season between fall to summer, seven have warm growing season between spring and early fall, and two have annual growing season. The covers were constructed using soils obtained on-site or from a nearby borrow area. All of the covers were vegetated with a mixture of annual and perennial grasses. Shrubs were also incorporated at four locations; poplar trees were integrated at two locations. Construction of the test sections was accomplished by 2000, except one, where construction was concluded in 2002.

Soil samples were collected during construction from four quadrants in each lift of the test sections. As a general conclusion, Environmental Protection Agency (US EPA) introduced the Alternative Cover Assessment Project (ACAP) in 1998 to provide a more general understanding of the hydrologic behavior of conventional and alternative landfill final covers [13], where the concept of Sr_{ACAP} (amount of water that needs to be stored) was introduced.

5. MATERIALS AND METHODS

Eighteen locations were selected across the Arid and Semi-Arid climate of the U.S. (Figure **1**). Monthly, daily, and yearly climatic data were collected from each location as described below. The collected data was used to estimate Sr_{ACAP} as proposed by Albright *et al*.

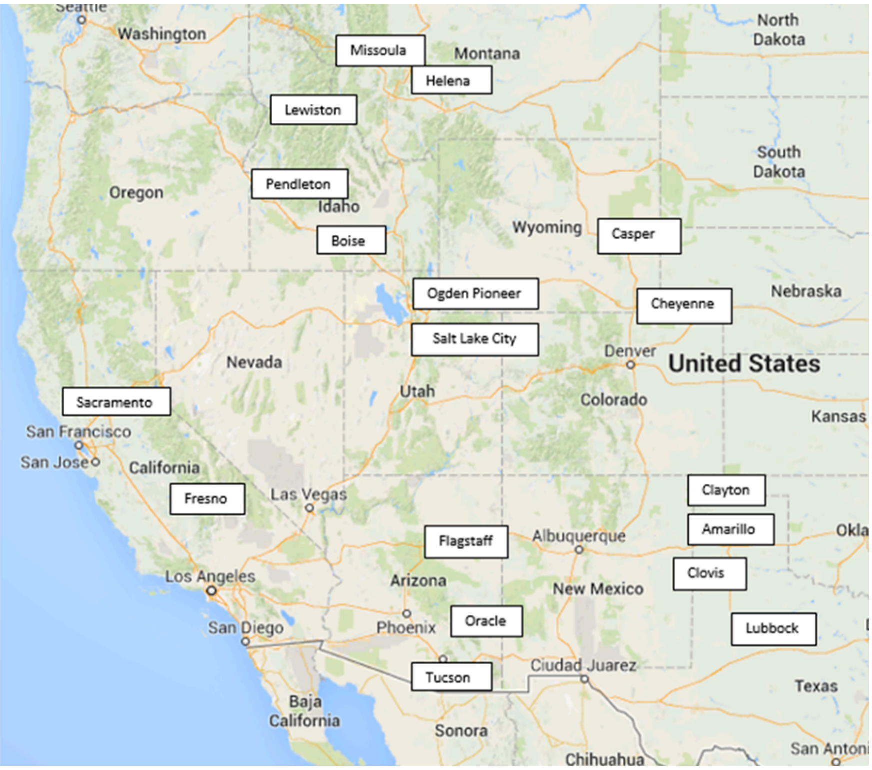


Figure 1: Locations selected in present study.

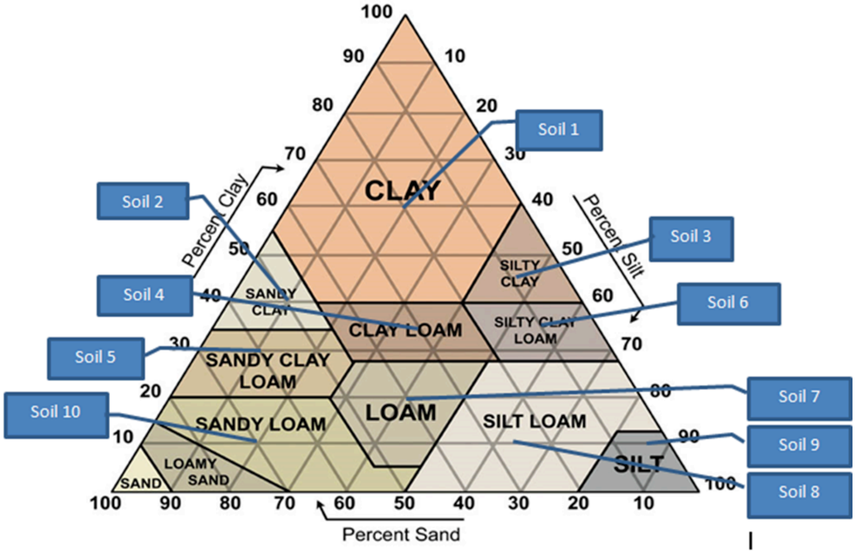


Figure 2: Soils classification in study.

(2010) [17] and to model that water balance through several simulated covers at each location with different thicknesses, (77cm, 91cm, and 107cm.) for each location. Each one of these covers was simulated with 10 properties of alternative soil types (Figure **2**), to cover a range of possible cover designs. A total of 540 simulations were performed.

5.1. Data Collection

Previous research studies in arid and semi-arid climates recommend using data from the rainiest 10-year period on record for producing an ET cover design. Another alternative approach for preliminary design is to use consecutive years of the average yearly climatic data. In this study the selected alternative was the use of the average daily precipitation in records of 30 years beginning from 1971 and ending in 2000. Total precipitation data was collected from the Western Regional Climate Center of NOAA. Precipitation values in total include both snow and rain and are reported in equivalent length units of liquid water. The selected method to obtain daily PET data is through the use of the Penman-Monteith equation. Table **3** shows the basic climate charac-teristics for the locations studied in this investigation. The growing period was identified according to its definition which is: the time period enclosed between the last freezing average temperature in spring or winter up to the first freezing average temperature in Fall. For each location, 10 soils were considered (Table **4**). The USDA textural classifications for all the ten soils is shown in Figure **2**. The corresponding percent silt, clay and sand, from the soil classification chart (Figure **2**) were used to obtain the unsaturated characteristics of the soils using the Rosseta method inserted in the HYDRUS Model.

5.2. Water Balance Modeling

HYDRUS-1D, is the model used in this study to simulate unsaturated flow. It is important to note that the percolation and flux values resulting are predictions and not observations, and that the results of the analysis should be used only as a general guide. Local variations in climate, soil type, and vegetation may have an impact on actual percolation in the field.

Table 3: Climatic Summary for Modeled Locations in Semi-Arid Zone

CLIMATE SUMMARY FOR MODELED LOCATIONS IN SEMI ARID ZONE						
NAME	**LATITUDE DEGREES**	**ALTITUDE m.**	**PRECIPE mm/yr**	**PET CALC mm/yr**	**P/PET**	**GROW PER. Days**
TUCSON ARIZONA	32.22	753.77	327.66	2024.40	0.16	270
FRESNO CALIFORNIA	36.75	91.74	277.88	1289.10	0.22	300
BOISE IDAHO	43.64	824.18	298.70	1164.07	0.26	210
SALT LAKE CITY UTAH	40.76	1305.15	399.54	1535.10	0.26	240
PENDLETON OREGON	45.64	370.33	310.13	1159.17	0.27	240
LUBBOCK TEXAS	33.58	975.36	479.04	1726.80	0.28	300
CASPER WYOMING	42.87	1584.66	302.01	1701.30	0.28	210
CLAYTON NEW MEXICO	36.45	1542.90	393.45	1325.15	0.30	210
CLOVIS NEW MEXICO	34.4	1302.41	455.17	1528.35	0.30	270
LEWISTON IDAHO	46.4	317.60	322.33	969.65	0.33	240
HELENA MONTANA	46.56	1228.34	302.26	907.17	0.33	210
AMARILLO TEXAS	35.22	1103.00	498.35	1466.70	0.34	270
CHEYENNE WYOMING	41.25	1856.84	385.32	1093.80	0.35	210
OGDEN PIONEER UTAH	41.3	1333.20	527.56	1475.70	0.36	210
ORACLE ARIZONA	32.6	1383.79	429.76	1193.12	0.41	270
FLAGGSTAFF ARIZONA	35.2	2125.68	542.29	1070.70	0.51	180
MISSOULA MONTANA	46.86	970.79	432.56	763.24	0.57	210
Aridity index ranges from 0.16 to 0.57.						

Table 4: Soil Hydraulic Characteristics

SOIL HYDRAULIC CHARACTERISTICS												
SOIL No	**SILT %**	**CLAY %**	**SAND %**	**θr**	**θs**	**α**	**n cm^-1**	**Ks cm/day**	**Ks cm/sec**	**θfc**	**θw**	**θa**
1	20	60	20	0.0971	0.4852	0.0210	1.2058	17.7300	0.0002	0.3536	0.1711	0.1825
2	10	40	50	0.0817	0.4063	0.0281	1.2263	14.0900	0.0002	0.2755	0.1308	0.1447
3	45	45	10	0.0994	0.4950	0.0128	1.3387	15.0200	0.0002	0.3340	0.1300	0.2041
4	35	35	30	0.0841	0.4435	0.0129	1.3892	7.5800	0.0001	0.2816	0.1030	0.1786
5	10	30	60	0.0717	0.3855	0.0271	1.2741	12.5400	0.0001	0.2416	0.1039	0.1378
6	55	35	10	0.0921	0.4791	0.0091	1.4813	12.3100	0.0001	0.3072	0.1041	0.2031
7	40	20	40	0.0627	0.4063	0.0097	1.4966	9.9400	0.0001	0.2454	0.0719	0.1735
8	65	10	25	0.0513	0.4338	0.0043	1.7129	37.5900	0.0004	0.2997	0.0551	0.2446
9	85	10	5	0.0606	0.4870	0.0069	1.6471	26.5700	0.0003	0.2897	0.0654	0.2240
10	20	10	70	0.0426	0.3846	0.0349	1.4271	45.6700	0.0005	0.1619	0.0514	0.1105

θ a Soil Unit Storage Capacity.

HYDRUS-1D, developed by Simunek *et al*. (1998) [14], is one of the most widely used models for unsaturated flow and solute transport modeling (Simunek *et al*., 2009) [20]. It is a freely-available one-dimensional model that can be applied to analyze vertical flow. The remainder of this section describes the inputs, conditions, and results for HYDRUS-1D. Required model inputs for HYDRUS-1D include parameters related to soil properties and boundary conditions, including precipitation and evapo-transpiration. The input parameters were based on data from the scientific literature.

Boundary inputs for water flow were specified at the top and bottom of the cover's soil profile, and also at the bottom of the waste layer. For the upper boundary, atmospheric limits can be simulated by applying prescribed flux boundary conditions. For the lower boundary, a free drainage surface was used. The unit gradient approach assumes that flux equals hydraulic conductivity and is a more conservative approach. Another approach would be to model a two-layer system. A unit gradient lower boundary may be more appropriate than the two-layer model.

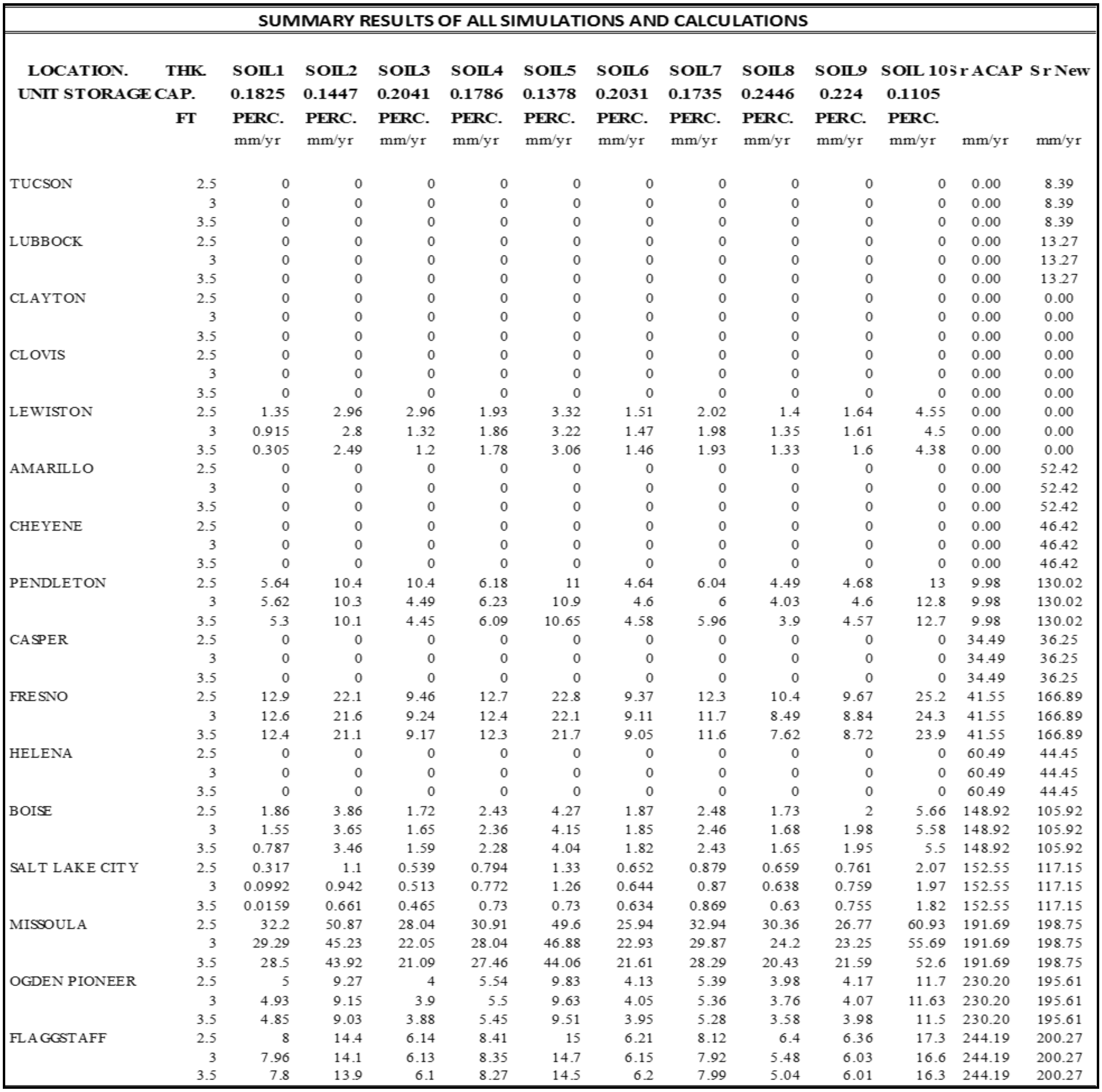
A variety of soils may be considered for a cover depending on the types of soils locally available. Modeling was performed for range of possible soil types. The following section describes the latter approach.

The USDA defines 12 soil texture classifications that are represented by the relative fractions of sand, silt, and clay on a soil texture triangle (Figure **2**). Finally, these textures were hydraulically characterized using the pedotransfer function in Rosetta and using published/measured data to determine the appropriate soil parameter values for the model. Required soil-related model input parameters for HYDRUS-1D include saturated hydraulic conductivity (K_s), residual water content (θ_r), saturated water content (θ_s) (equivalent to soil porosity), and a series of parameters used in the van Genuchten and Mualem functions that describe the functional relationship between soil moisture, matric potential, and unsaturated conductivity: α, *m, n* and *l*. Each of these is an empirical constant; α is inversely related to the air-entry pressure value, *m* and *n* are related to the pore-size distribution, and *l* is a pore interaction term that describes connectivity. In HYDRUS-1D, unsaturated hydraulic functions are based on a combination of the van Genuchten (1980)[15] function with the Mualem (1976) [21] pore-size distribution model.

6. RESULTS

A total of 540 simulations were performed during this study. Table **5** shows the results of all the simulations. The yearly vertical percolation values for the last year of simulation were considered to be the long term predictions of the water balance for the simulated covers. Seven locations of the Table **5** show that Sr_{ACAP} is zero. The zero value of Sr_{ACAP} means that there is no water that needs to be stored by the soil cover, in all seven but one location is required. That means that any cover with any available soil is

Table 5: Summary Results of all Simulations and Calculations



SUMMARY RESULTS OF ALL SIMULATIONS AND CALCULATIONS

LOCATION.	THK.	SOIL1	SOIL2	SOIL3	SOIL4	SOIL5	SOIL6	SOIL7	SOIL8	SOIL9	SOIL 10	Sr ACAP	Sr New
UNIT STORAGE CAP.		0.1825	0.1447	0.2041	0.1786	0.1378	0.2031	0.1735	0.2446	0.224	0.1105		
	FT	PERC.	PERC.	PERC.	PERC.	PERC.	PERC.	PERC.	PERC.	PERC.	PERC.		
		mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr
TUCSON	2.5	0	0	0	0	0	0	0	0	0	0	0.00	8.39
	3	0	0	0	0	0	0	0	0	0	0	0.00	8.39
	3.5	0	0	0	0	0	0	0	0	0	0	0.00	8.39
LUBBOCK	2.5	0	0	0	0	0	0	0	0	0	0	0.00	13.27
	3	0	0	0	0	0	0	0	0	0	0	0.00	13.27
	3.5	0	0	0	0	0	0	0	0	0	0	0.00	13.27
CLAYTON	2.5	0	0	0	0	0	0	0	0	0	0	0.00	0.00
	3	0	0	0	0	0	0	0	0	0	0	0.00	0.00
	3.5	0	0	0	0	0	0	0	0	0	0	0.00	0.00
CLOVIS	2.5	0	0	0	0	0	0	0	0	0	0	0.00	0.00
	3	0	0	0	0	0	0	0	0	0	0	0.00	0.00
	3.5	0	0	0	0	0	0	0	0	0	0	0.00	0.00
LEWISTON	2.5	1.35	2.96	2.96	1.93	3.32	1.51	2.02	1.4	1.64	4.55	0.00	0.00
	3	0.915	2.8	1.32	1.86	3.22	1.47	1.98	1.35	1.61	4.5	0.00	0.00
	3.5	0.305	2.49	1.2	1.78	3.06	1.46	1.93	1.33	1.6	4.38	0.00	0.00
AMARILLO	2.5	0	0	0	0	0	0	0	0	0	0	0.00	52.42
	3	0	0	0	0	0	0	0	0	0	0	0.00	52.42
	3.5	0	0	0	0	0	0	0	0	0	0	0.00	52.42
CHEYENE	2.5	0	0	0	0	0	0	0	0	0	0	0.00	46.42
	3	0	0	0	0	0	0	0	0	0	0	0.00	46.42
	3.5	0	0	0	0	0	0	0	0	0	0	0.00	46.42
PENDLETON	2.5	5.64	10.4	10.4	6.18	11	4.64	6.04	4.49	4.68	13	9.98	130.02
	3	5.62	10.3	4.49	6.23	10.9	4.6	6	4.03	4.6	12.8	9.98	130.02
	3.5	5.3	10.1	4.45	6.09	10.65	4.58	5.96	3.9	4.57	12.7	9.98	130.02
CASPER	2.5	0	0	0	0	0	0	0	0	0	0	34.49	36.25
	3	0	0	0	0	0	0	0	0	0	0	34.49	36.25
	3.5	0	0	0	0	0	0	0	0	0	0	34.49	36.25
FRESNO	2.5	12.9	22.1	9.46	12.7	22.8	9.37	12.3	10.4	9.67	25.2	41.55	166.89
	3	12.6	21.6	9.24	12.4	22.1	9.11	11.7	8.49	8.84	24.3	41.55	166.89
	3.5	12.4	21.1	9.17	12.3	21.7	9.05	11.6	7.62	8.72	23.9	41.55	166.89
HELENA	2.5	0	0	0	0	0	0	0	0	0	0	60.49	44.45
	3	0	0	0	0	0	0	0	0	0	0	60.49	44.45
	3.5	0	0	0	0	0	0	0	0	0	0	60.49	44.45
BOISE	2.5	1.86	3.86	1.72	2.43	4.27	1.87	2.48	1.73	2	5.66	148.92	105.92
	3	1.55	3.65	1.65	2.36	4.15	1.85	2.46	1.68	1.98	5.58	148.92	105.92
	3.5	0.787	3.46	1.59	2.28	4.04	1.82	2.43	1.65	1.95	5.5	148.92	105.92
SALT LAKE CITY	2.5	0.317	1.1	0.539	0.794	1.33	0.652	0.879	0.659	0.761	2.07	152.55	117.15
	3	0.0992	0.942	0.513	0.772	1.26	0.644	0.87	0.638	0.759	1.97	152.55	117.15
	3.5	0.0159	0.661	0.465	0.73	0.73	0.634	0.869	0.63	0.755	1.82	152.55	117.15
MISSOULA	2.5	32.2	50.87	28.04	30.91	49.6	25.94	32.94	30.36	26.77	60.93	191.69	198.75
	3	29.29	45.23	22.05	28.04	46.88	22.93	29.87	24.2	23.25	55.69	191.69	198.75
	3.5	28.5	43.92	21.09	27.46	44.06	21.61	28.29	20.43	21.59	52.6	191.69	198.75
OGDEN PIONEER	2.5	5	9.27	4	5.54	9.83	4.13	5.39	3.98	4.17	11.7	230.20	195.61
	3	4.93	9.15	3.9	5.5	9.63	4.05	5.36	3.76	4.07	11.63	230.20	195.61
	3.5	4.85	9.03	3.88	5.45	9.51	3.95	5.28	3.58	3.98	11.5	230.20	195.61
FLAGGSTAFF	2.5	8	14.4	6.14	8.41	15	6.21	8.12	6.4	6.36	17.3	244.19	200.27
	3	7.96	14.1	6.13	8.35	14.7	6.15	7.92	5.48	6.03	16.6	244.19	200.27
	3.5	7.8	13.9	6.1	8.27	14.5	6.2	7.99	5.04	6.01	16.3	244.19	200.27

supposed to allow no percolation into the waste mass. It can be said that the Sr_{ACAP} methodology, did not work for one site with Sr_{ACAP} equal to Zero. Figures **3**, **4**, and **5** showcase how the Sr_{ACAP} failed to correlate to percolation from the simulated water balance covers in general and in areas with and without frozen ground. The highest R^2 for the correlation between yearly percolation and Sr_{ACAP} was obtained using a polynomial curve fit with an R^2 of 0.27. When the data is separated into locations with and without snow and frozen ground, the correlations are R^2 of 0.33 and 0.01.

To investigate the reasons why Sr_{ACAP} failed to predict the performance of the modeled water balance covers, monthly precipitation, potential evaporation, and percolations were calculated for all modeled locations. Table **6** and Table **7** show examples of such calculations in locations with and without snow and frozen ground. For both locations, modeled percolation occurred during the months that no percolation was supposed to happen according to the ACAP proposed method.

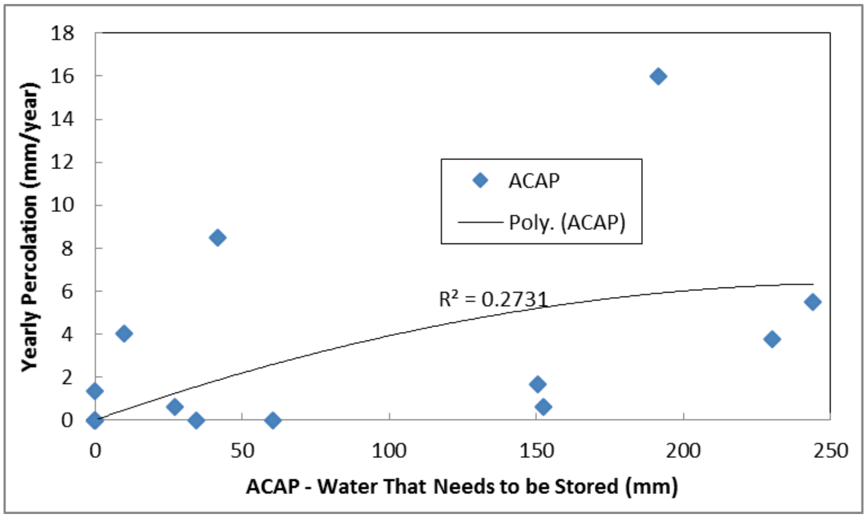


Figure 3: Modeled yearly percolation versus S_{rACAP}. for 90cm thick covers for Soil 8.

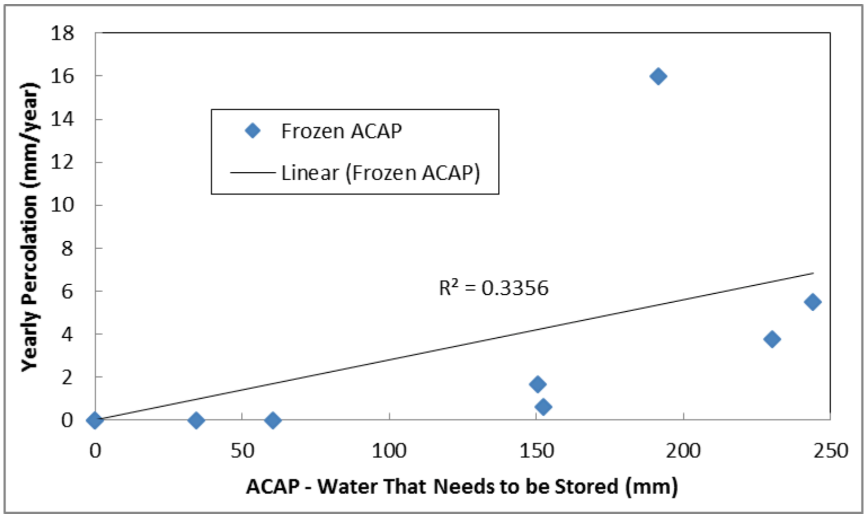


Figure 4: Modeled yearly percolation versus S_{rACAP} for 90cm thick covers for locations with frozen ground during winters for Soil 8.

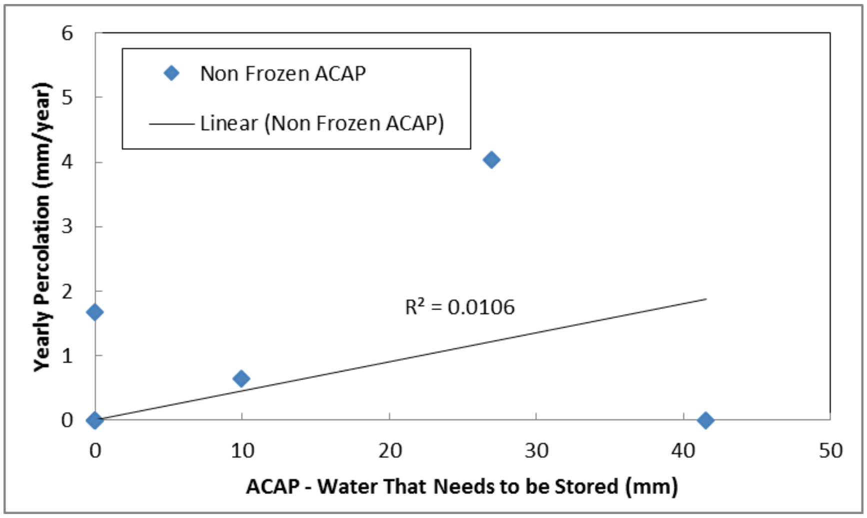


Figure 5: Modeled yearly percolation versus S_{rACAP} for 90cm thick covers for locations without frozen ground during winters for Soil 8.

Table 6: Monthly Precipitation, PET and Percolation for Missoula Mo (Snow and Frozen ground)

MONTHLY PRECIPITATION, PET AND PERCOLATION MISSOULA, (SNOW AND FROZEN GROUND)												
SOIL	1	2	3	4	5	6	7	8	9	10	PRECIP	PET
MONTH	PERC. mm	PERC. mm	PERC. mm	PERC. mm	PERC. mm	PERC. mm	PERC. mm	PERC. mm	PERC. mm	PERC. mm	mm	mSm
JANUARY	0	1	0	0	1	0	0	0	0	1.5	36.32	8.68
FEBRUARY	5	9	3	5	9	3	5	3	3	11	24.89	15.08
MARCH	7	13	5	7	13	5	7	5	5	14	31.5	33.48
APRIL	6	8	4	5.5	8.5	4	6	4	4	9.5	59.94	60.00
MAY	3	4	4	3	4	2.5	3	3	2.5	4.5	59.94	89.90
JUNE	2	2.5	2	2	2	1.5	2	2	1.5	3.5	59.18	111.00
JULY	3	3.5	1	3	4	3	3	2.5	3	4.5	30.99	150.97
AUGUST	0	0	0	0	0	0	0	0	0	0	28.96	141.67
SEPTEMBER	2	3	2	2	3.5	2.5	2	3	2.5	5.5	33.02	83.70
OCTOBER	0	0	0	0	0	0	0	0	0	0	28.45	40.61
NOVEMBER	1.3	1.5	1	1	1.5	1.5	1.5	1.4	1.5	1.5	28.45	11.10
DECEMBER	0	0	0	0	0	0	0	0	0	0	35.31	17.05
TOTAL	**29.30**	**45.50**	**22.00**	**28.50**	**46.50**	**23.00**	**29.50**	**23.90**	**23.00**	**55.50**	**432.82**	**763.24**

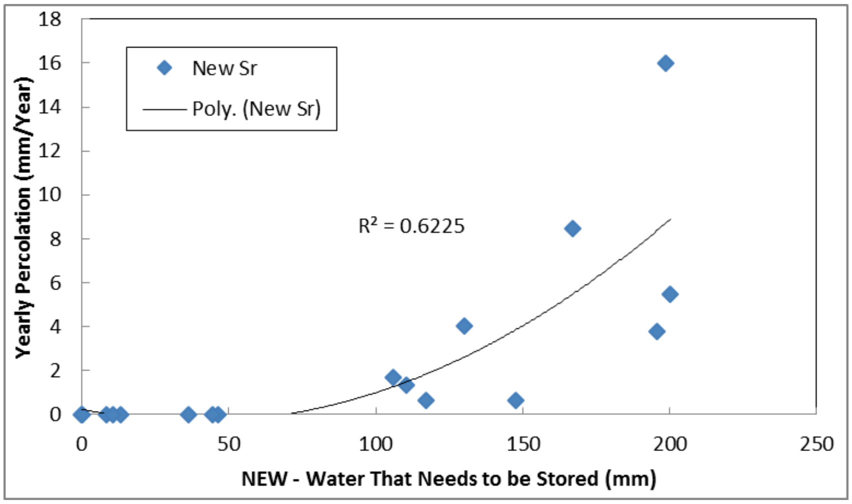


Figure 6: Correlation of yearly percolation with Sr_{NEW} for simulations of 90cm thick cover with Soil 8.

To develop a new approximation to the amount of water that needs to be stored, which is the most important parameter in the water balance cover design, changes were introduced to the ACAP method described in other publications, (Albright *et al*. 2003) [15]. The original formula is described as follows:

$$SR = \sum_{m=1}^{6}\left\{\left(P_m - \beta_{fw}PET_m\right) - \Lambda_{fw}\right\} + \sum_{m=1}^{6}\left\{\left(P_m - \beta_{SS}PET_m\right) - \Lambda_{SS}\right\}$$

The proposed modifications are as follow:

- For the location with snow and frozen ground, Fall-Winter period was extended 10 months and, Spring-Summer was shortened to 2 months.
- For locations without snow and frozen ground, Fall-Winter and Spring-Summer are both 6 months long.
- Eliminate the constants Λ_{fw} and Λ_{SS}. In all the calculations conducing to the final calculation of Sr_{NEW}. This is a very conservative determination because it leads to a non runoff situation.

Figure **6** showcases how the Sr_{NEW} correlates to percolation from the simulated water balance covers in general and in areas with and without frozen ground. The R^2 of this new correlation is 0.62, which is an indicator of how better index the new developed Sr_{NEW} is as compared to Sr_{ACAP}.

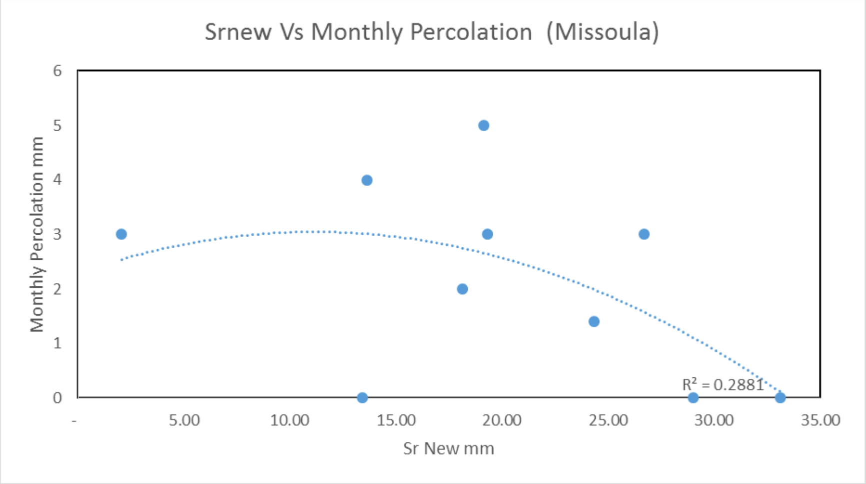


Figure 7: Correlation of monthly percolation with Sr_{NEW} for simulations of 90 cm thick cover with Soil 8. (Snow and Frozen Soil).

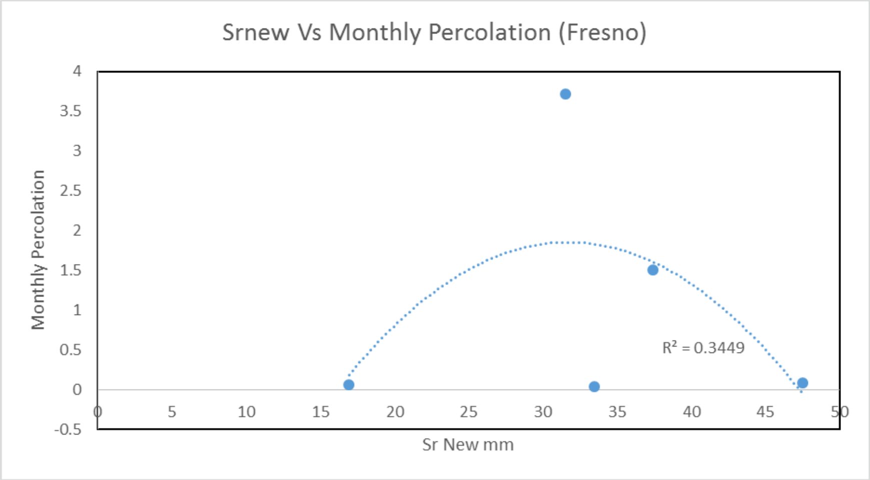


Figure 8: Correlation of monthly percolation with Sr_{NEW} for simulations of 90cm thick cover with soil 8. (No Snow and no Frozen Soil).

Figures **7** and **8** show the behavior of the Soil 8 in two locations, one having frozen soil and snow and other don't, comparing the monthly percolation against Sr_{NEW} where it can be seen that in the monthly behavior the Sr_{New} covers in a better way the prediction of the percolation than the one of Sr_{ACAP}. It can be seen that only in 4 months the prediction of the percolation fails against Sr_{New}. In the case of Missoula and in Fresno also 4 months fail to predict the percolation. The R^2 of this correlations is acceptable because the index is being used in long range of time.

CONCLUSIONS

The recommended equation to be used in the calculation of the amount of water that needs to be stored will be as follows:

For the locations with snow and frozen grounds:

$$\mathrm{SrNEW} = \sum_{m=1}^{10}\left(P_m - \beta_{fw}PET_m\right) + \sum_{m=1}^{2}\left(P_m - \beta_{SS}PET_m\right)$$

And for the locations without snow and frozen grounds:

$$\mathrm{SrNEW} = \sum_{m=1}^{6}\left(P_m - \beta_{fw}PET_m\right) + \sum_{m=1}^{6}\left(P_m - \beta_{SS}PET_m\right)$$

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