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September 9, 2013

Mr. Geoffrey Leking
NM Oil Conservation Division
1625 N. French Drive
Hobbs, NM 88240

HOBBS OCD

SEP 11 2013

RECEIVED

RE: Presidente BPD State Com #1H
30-025-39660
Section 32, T25S-R32E
Lea County, New Mexico

Mr. Leking,

Yates Petroleum Corporation would like to submit the attached document from Dr. Kenneth C Carroll of NMSU regarding the release that occurred at the above mentioned facility on June 5, 2012 (1RP-6-12-2822).

On August 7, 2013 Robert Asher and I came to your office and we asked if you would accept us using a capillary barrier in order to get the release closed. You had asked for further information explaining the process. We asked Dr. Carroll to give us an explanation so that we submit it to you; the document is attached to this letter. Dr. Carroll has asked that this document remain confidential and not be put on any kind of internet site.

Should you have any questions of concerns, I can be reached at (575) 748-4111 or by email at acannon@yatespetroleum.com.

Thank You,

Amber Cannon

Amber Cannon
Environmental Regulatory Agent
Yates Petroleum Corporation

Enclosure: 1

commented

Geoffrey Leking
Environmental Specialist
NMOCD-DIST 1
9/12/13

Brief Overview of Capillary Barriers for Mitigation of Infiltration, Immobilization of Contaminants, and Reclamation of Contaminated Sites

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Prepared for and Submitted to:

Yates Petroleum

16 August 2013

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Executive Summary

Capillary barriers occur when infiltrating water reaches a coarser, higher-permeability material underlying a finer-grained, lower-permeability material. The coarser-grained material has a much lower unsaturated hydraulic conductivity than the finer-grained material, because of the low water content in the coarse sediment. The contrast in unsaturated hydraulic conductivity between the materials, and the low conductivity value for the coarse material inhibits water downward water flow, which mitigates migration of contaminants. They may be natural or man-made, and they function as covers to waste material by inhibiting downward water flow and contaminant flux. This barrier to water and contaminant flow occurs in the coarse material, because even with a higher permeability than the overlying fine material the unsaturated hydraulic conductivity of the coarse material is much lower than that of the fine material. Evaporation and drainage can be used to remove infiltrating water from the overlying fine-grained layer, which is likely to be highly effective in arid regions. These physical, unsaturated flow processes act to slow or immobilize contaminants, and may attenuate or even mitigate the downward vertical flux of contaminants, which supports the protection of groundwater from potential contamination. The attenuation of water flow and contaminant migration should be quantified to support design of barriers, and monitoring should be used to confirm effectiveness.

Introduction

This document provides a brief review of unsaturated (vadose) zone infiltration and water movement with relevance to the concepts behind capillary barriers and their application for reclamation of contaminated soils and mitigation of contamination migration (e.g., landfills, mine waste, waste water releases). The premise for this discussion is that a capillary barrier approach to mitigating contaminant migration in the vadose zone is useful because, in many cases, remediation decisions for the vadose zone will need to be made all or in part based on projected impacts to groundwater. Another guiding premise is recognition that significant natural attenuation of waste fluids added to the vadose zone can occur and decrease the impact to groundwater, because contaminant concentrations and the temporal profile of contaminant flux to groundwater are decreased by multiple processes in the vadose zone. Thus, remediation in the vadose zone to protect groundwater is functionally a combination of natural attenuation (EPA, 1999) use of other remediation techniques (e.g., surface barrier), as needed, to further mitigate contaminant flux to groundwater.

Prior to the discussion of capillary barrier application, a brief description of vadose zone flow and transport processes is used to highlight differences between processes controlling transport in the vadose zone compared to groundwater systems. These differences in transport processes impact contaminant attenuation behavior and need to be considered/evaluated during the remedy evaluation process. In particular for the unsaturated vadose zone, physical transport processes including advection, dispersion, and diffusion are critical to understanding contaminant transport in the vadose zone, primarily because 1) there is a non-linear relationship between water content and hydraulic conductivity that complicates water and contaminant flux and 2) subsurface interfaces can dramatically impact vertical moisture and contaminant movement.

The physical processes controlling fluid flow in the vadose zone are quite different from those within the groundwater system. In addition, the transport attenuation processes are generally more significant in the vadose zone compared to the groundwater system. The non-linear relationship between water content and hydraulic conductivity must be considered in evaluating flow and transport through the vadose zone. Ultimately, a primary driving force for long-term transport is often the net recharge at ground surface, a function of precipitation, infiltration, and transpiration processes. Subsurface interfaces that separate zones of different particle size distributions and properties (i.e., layering) are also important due to the impact on unsaturated flow processes.

Moisture Retention, Capillary Trapping, and Gravity Drainage

The most obvious difference between the vadose zone and groundwater is that the vadose zone is unsaturated with respect to water. The groundwater system pore space is completely filled with water and there is generally no gas present as a separate phase. Above the capillary fringe in the vadose zone, there is always some gas (i.e. air) present, and the pore space is not filled with water.

Capillary forces act on pore water in the vadose zone and impact fluid flow and water content distributions. Capillary pressure causes porous media to wick in the wetting fluid and displace the nonwetting fluid (Hillel 1998; Cohen and Mercer 1990). Water is generally wetting and air is generally nonwetting. The capillary pressure is also commonly referred to as suction or tension, and converted to matric potential (in terms of head).

This relationship of capillary pressure, or matric potential, versus water content is termed the moisture retention curve (Figure 1). The capillary pressure generally increases nonlinearly with decreasing water content. Alternatively, capillarity generally increases with decreasing pore radius (or decreasing grain size). Thus, the largest pores drain first and water contents are generally higher for finer-grained materials. The last water to drain comes from the smallest pore throats. Capillary pressure holds water more tightly in small pores compared to large pores, and causes water to wick (or flow by capillary pressure forces) into the smaller pore spaces.

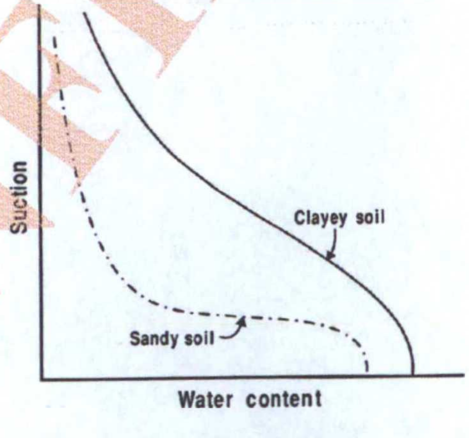

Figure 1. Soil characteristic curve for a fine (clayey) soil and a coarse (sandy) soil (Hillel 1998).

The dependence of the water content on the capillary pressure is a characteristic property of a soil (Figures 1). General properties of the characteristic relationship can be determined based on soil type alone. A clay-rich soil will have higher complete saturation, and the saturation and water content will decrease gradually with increasing capillary pressure. A sandy, or larger grain-size, soil will decrease in saturation very rapidly from very high saturation to very low saturation. Generally, the smoothness of the curve is related to the distribution of pore sizes; a narrow range of pore diameters leads to a step change in saturation.

This moisture retention relationship also varies depending on the direction and history (hysteresis) of change in water content, which will increase (wetting) during increased recharge/infiltration or decrease (drainage) after increased recharge/infiltration or during increased evaporation or drought (Figure 2). Hysteresis is known to occur in multiphase immiscible systems in intermediate saturation ranges, which complicates the prediction of constitutive relationships (Kechavarzi et al. 2005). Hysteresis is created by a combination of pore processes including saturation of variable pore sizes, saturation dependent residual saturations, and non-wetting fluid entrapment (Lenhard 1992; Lenhard et al. 2004).

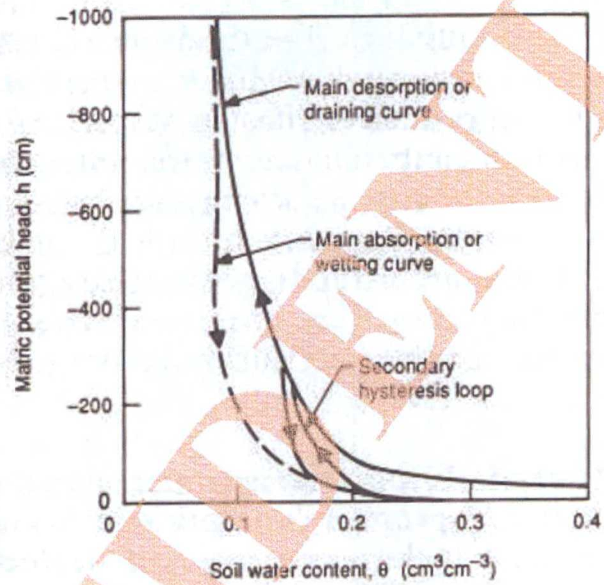

Figure 2. Impact of hysteresis on water retention curves ((Maidment 1993) Figure 5.1.4)

Another force controlling unsaturated water content is gravity. Gravity works to induce vertical migration of water, but the rate of movement is a function of both gravity and capillary forces. For instance, accompanying a significant pulse of water infiltration (waste discharge), water content can be elevated near the surface such that there is water in larger pores where capillary forces are weaker and vertical movement (drainage) due to gravity can be rapid. However, as the pulse of water moves through into the vadose zone, retention of water along the flow path reduces the amount of water that can fill larger pores and capillary forces begin to become significant with respect to control of water movement. With further vertical and lateral movement, water content will continue to decrease, and will tend toward conditions in the vadose zone where movement is controlled by the recharge rate (e.g., steady-state conditions).

Darcy's Law, Hydraulic Conductivity, and Relative Permeability

Groundwater systems are water saturated (contain no gas phase), and thus only liquid water is available for fluid flow. For groundwater systems, the Darcy flux [L/T] is a function of the hydraulic conductivity [L/T] and the hydraulic gradient [L/L] (Darcy, 1856). Water movement in the vadose zone can also be described with a version of Darcy's Law that was modified by Buckingham (Buckingham 1907). The driving force for infiltration flux is the hydraulic head gradient, which can be separated into the matric potential head gradient and the gravity unit gradient. However, the primary difference for Darcy's Law in the vadose zone is that the hydraulic conductivity is not a constant for a given porous media. The unsaturated hydraulic conductivity is highly variable as a function of the water content, which varies depending on the distance from the water table or with changes in grain size and permeability. Figure 3 illustrates the nonlinear changes in hydraulic conductivity as a function of water content for a lower (clayey soil) and a higher (sandy loam soil) permeability material. Generally, as water content decreases, the volume of water and the cross sectional area within pores available for flow decreases, which restricts water permeability and water flow similar to decreasing the pore size from a coarse to a more-fine grained material.

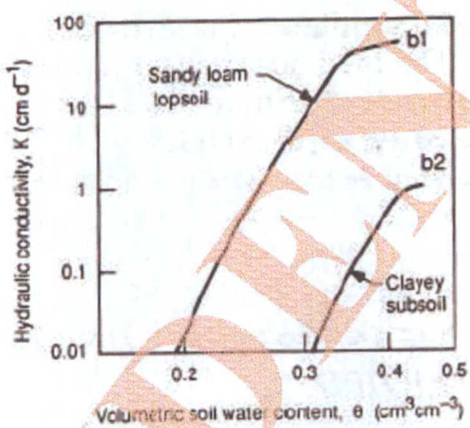

Figure 3. Hydraulic conductivity versus water content for lower (clayey soil) and higher (sandy loam soil) permeability materials ((Maidment 1993). Figure 5.1.3)

The relative permeability of a given soil can change over many orders of magnitude with changes in saturation. For practical application purposes, unsaturated hydraulic conductivities may become essentially negligible under the dry conditions that are typical for the arid Southwest U.S. These processes control fluid and contaminant flux in the vadose zone and can act as attenuation processes for infiltrating water and contaminant mass.

Unsaturated Infiltration and Recharge

Recharge is when infiltrating water is released from the vadose zone and mixes with the groundwater system. All precipitation may not infiltrate (e.g., surface run off) and all infiltrated water may not recharge the groundwater system (e.g., due mainly to evapotranspiration and vadose zone storage). The infiltration rate depends on water application rate at the surface, capillary pressure distribution in the subsurface, and water-relative permeability. In some cases, water ponding at the surface may occur.

The infiltration through soils with ponding at the land surface was characterized by Bodman and Coleman (Bodman and Colman 1944). Figure 4 illustrates the water content versus depth profile at a point in time during infiltration for a relatively deep vadose zone (compared to the time and amount of water released). At the lower portion of the vertical profile, the water content is still at pre-infiltration, initial-moisture level, because the infiltrating water has not reached that depth in the profile. Above that point, the wetting front is a sharp increase in water content, because its migration is limited by the low unsaturated hydraulic conductivity of the underlying dry soil, leading to a small wetting zone region immediately overlying the wetting front. The wetting zone is supplied by water moving downward through the transmission zone, which after the initial transient period is under gravity drainage with relatively uniform water content. The region near the point of infiltration in which the water contents change sharply with distance is known as the transition zone. The water content at land surface, or the water release location, may reach saturation if water is released at a large enough rate, and causes ponding.

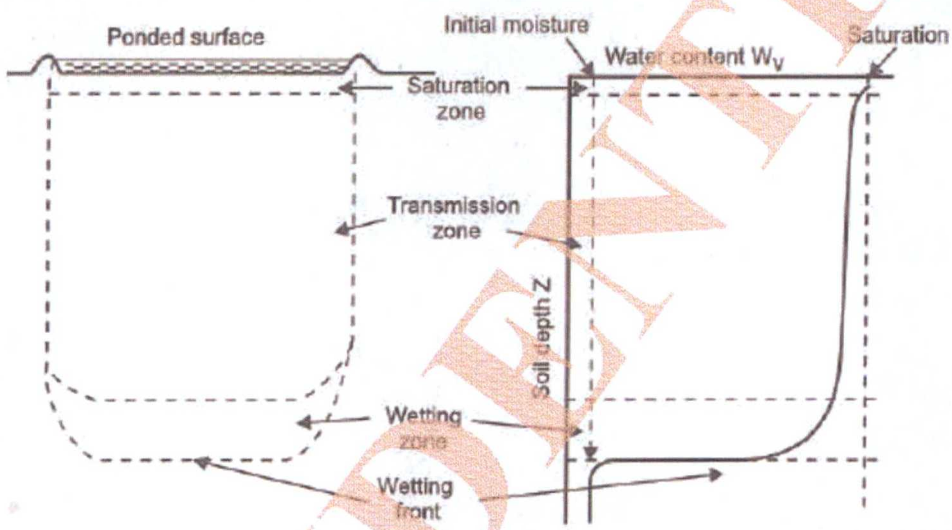

Figure 4. Diagram of moisture content versus depth during infiltration with ponding ((Hillel 1998), pg. 390; after (Bodman and Colman 1944)). The diagram at left indicates the extent of each zone, and the water content profile is shown at right.

As the wetting front advances, it becomes more dispersed, and the infiltrating water becomes partially wicked in the drier zones both laterally and vertically. This is a significant attenuation process for water flux in the vadose zone.

When water application rates are lower than the maximum infiltration rate allowable by the sediment properties, ponding of water at the land surface will not occur. In this case, the porous medium will continue to allow infiltration, capillary pressure gradients will decline, and the medium will remain at a water saturation level for which the unsaturated conductivity is equal to the infiltration rate. The resultant water saturation level increases and decreases over time with increases and decreases in the infiltration rate, which suggests that water saturation may be used to indicate relative magnitudes and natural attenuation of water and contaminant flux rates in the vadose zone.

Most increases in infiltration and contaminant transport are associated with a temporary leak or release, which is terminated at some point. As mentioned above, the water saturation increases during the additional infiltration period, but then drainage occurs decreasing the water content and infiltration rates. After the termination of water release, the elevated saturation dissipates rapidly during drainage where the added water is wicked laterally and vertically as a function of gravitational and capillary forces (Figure 5).

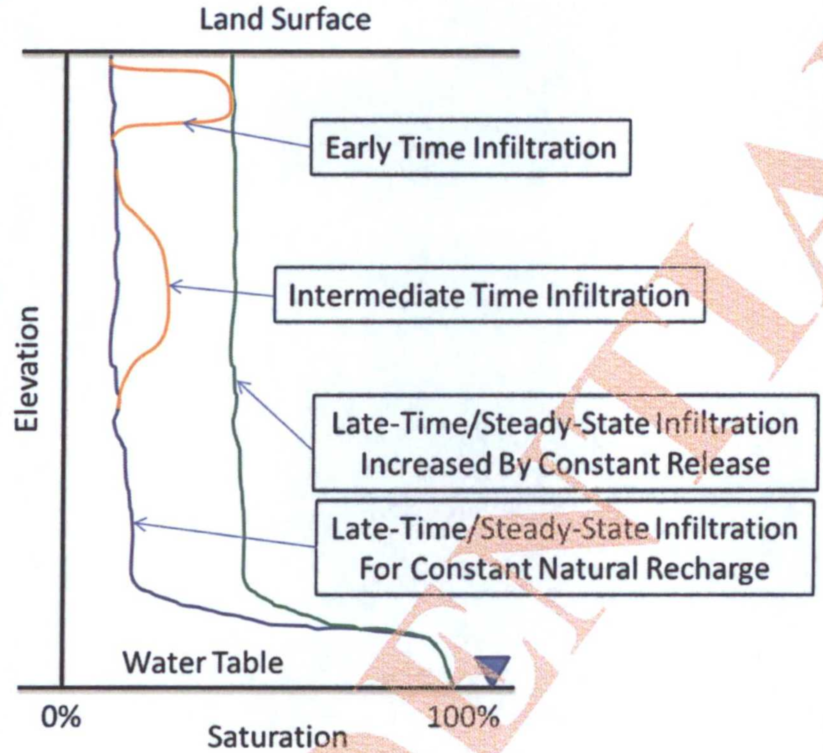

Figure 5. Illustrative plot of water saturation versus depth below land surface for both transient and steady-state infiltration cases. The blue and green lines indicate steady conditions for natural, constant recharge and anomalously increased, constant infiltration rates, respectively. The orange lines indicate the transient water content increase due to a temporary release of water and subsequent decline and dispersal during drainage.

Increased infiltration flux rates due to temporary releases are short-lived transient behaviors, and infiltration rates decay exponentially until they reach the long-term, natural recharge rate of infiltration. As water content decreases during this drainage process (Figure 5), the relative ratio of capillary to gravity force increases (Figure 1), which induces more lateral flow and increases retention and immobilization of water within vadose-zone pores. This restriction to vertical flow with decreasing water content during drainage is also enhanced by the nonlinear decreases in hydraulic conductivity (Figure 3). Transitions in material permeability (i.e., heterogeneity), especially horizontal layering (e.g., many sedimentary deposits), typically enhance these restrictions to vertical flow and induce increased lateral flow, which further reduces water content during drainage.

Infiltrated water released into the vadose zone will migrate through the vadose zone vertically and mix into the groundwater. However, if the storage capacity and size of the vadose zone are large compared to the amount of water released, the water will be wicked into storage and trapped by capillary forces as the water saturation profile decreases (Figure 5). The size of the vadose zone, its capacity for water storage, and its tendency to spread/disperse infiltrating flow rates (i.e. water flux) control the water and contaminant attenuation behavior and capacity.

If these processes are quantified, they can be compared to release quantities to determine how much attenuation of the waste release will occur in the vadose zone. This evaluation then supports consideration of monitored natural attenuation as a remedy and any subsequent evaluations of other or additional remedies that might be required (e.g., capillary or other surface barriers).

Heterogeneous Permeability Impacts on Infiltration

As noted above, there are significant implications for the vadose zone's spatially variable hydraulic conductivity that are relevant for the attenuation of the transport of water and contaminants. Generally, for groundwater systems we consider coarse-grained materials (higher permeability) to have much higher hydraulic conductivities compared to fine-grained materials (lower permeability) for groundwater systems. However, capillary pressure holds water more tightly in fine-grained materials. So, the largest pores drain first, which may be the majority of the pores within coarse-grained materials. Figure 6 shows that at the same capillary pressure, a fine-grained sediment may have a higher water content and a higher unsaturated hydraulic conductivity than a coarse-grained material.

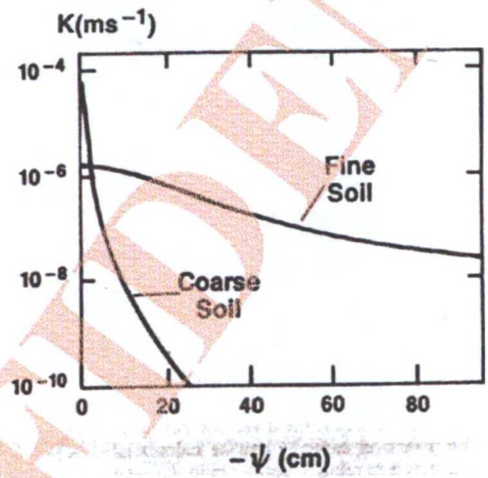

Figure 6. Hydraulic conductivity versus pressure head for a fine and coarse soil (Morris and Stormont 1997).

The presence of low-permeability zones, or layers, act to mitigate the magnitude of the infiltration rate, which is an attenuation process. The lower permeability layers, even relatively thin ones, will become a dominant control over the maximum infiltration rate, and they also serve to enhance lateral fluid flow in the unsaturated zone. This lateral flow is important as an attenuation process for several reasons. First, increases in lateral flow equate to decreases in vertical flow toward the water table. Additionally, lateral migration increases the volume of vadose zone impacted and the amount of water that can be stored and trapped by capillary forces. The additional volume of vadose zone increases the potential for geochemical retention processes (e.g., adsorption) to immobilize contaminants. Finally, lateral flow increases the mixing of contaminated water with noncontaminated water, which attenuates concentrations and mass flux through dilution, diffusion, and dispersion.

Capillary Barrier Application for Infiltration Mitigation and Protection of Groundwater

A capillary barrier involves the above discussed principles of unsaturated flow between soils of different textures and permeabilities (Rasmuson and Eriksson 1988; Morris and Stormont 1997). Capillary barriers occur when infiltrating water reaches a coarser, higher-permeability material underlying a finer-grained, lower-permeability material. At initially gravity drained conditions, the coarse material has a lower water content and lower unsaturated hydraulic conductivity than the overlying finer-grained material (Figure 6). The air is trapped in the coarse material and the water is wicked in the finer material due to capillarity, and this force must be exceeded to allow flow of water from the overlying fine-grained material into the underlying coarser material. This causes the vertical water and contaminant flux to decrease, or essentially stop, due to the lower hydraulic conductivity of the coarser-grained material until enough water collects in the overlying materials to exceed the air-entry pressure of the coarser-grained material. Some vertical movement of water and solutes may occur upward within a capillary barrier as water is wicked into the overlying finer-grained material.

Capillary barriers are caused by differences in physical properties of soil textures, and can occur naturally or are man-made. Capillary barriers have been considered instead of compacted soil covers for waste-disposal systems especially in arid climates (Morris and Stormont 1997) and as landfill covers (Melchior et al., 2010). Capillary barriers have been considered to reduce water infiltration into mine tailings (Rasmuson and Eriksson, 1988). These capillary barriers are used for various landfill or mine waste material covers to inhibit the infiltration of water vertically through a contamination zone, which could mobilize contaminants. Capillary barriers may contribute significantly to the attenuation of infiltrating water and contaminant mass flux vertically toward the groundwater. As water and pressure build up above the capillary barrier, lateral flow is induced. Both the vertical flux reduction and induced lateral flow are contaminant attenuation processes.

The design for a capillary barrier consists of a series of layers of differing material types including (in series downward from the top to the bottom of the barrier) capillary layer (a fine-grained, low-permeability material) and a capillary block (a uniform and coarse-grained, high-permeability material) as illustrated in Figure 7. If the barrier is designed to create a slope or a horizontal elevation gradient, then the capillary layer may be drained. This keeps the capillary layer from becoming saturated and allowing flow into the capillary block (e.g., Ross, 1990; Kampf and Montenegro, 1997).

Capillary barriers can divert the flow of infiltrating water based on different hydraulic conductivities for varying pressure potentials in unsaturated systems (Ross, 1990). As described above, in unsaturated systems hydraulic conductivity decreases by orders of magnitude with decreases in water content (Figures 3 and 6), and coarse-grained materials remain at low water content ranges for most of unsaturated zone capillary pressures or suctions (except for when capillary pressure or suction is minimized at near atmospheric pressures).

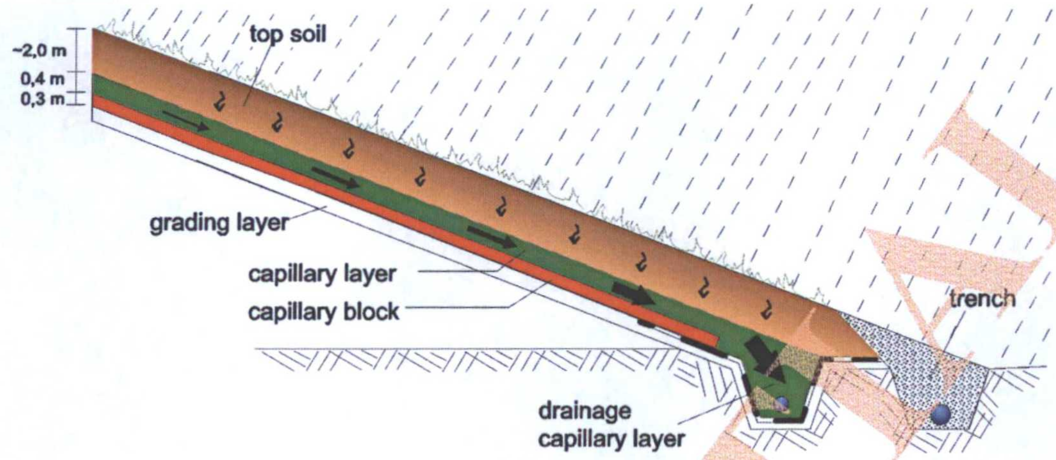

Figure 7. A typical constructed capillary barrier. Infiltration from rain transports through the topsoil and into the capillary layer where fluid flow is diverted by a capillary barrier created by the capillary block. Due to the hydrologic gradient, there is no infiltration below the capillary block (Kampf and Montenegro, 1997).

Soil capillary pressure versus saturation characteristic curves vary for different materials depending on their pore sizes, and these curves help explain the processes behind capillary barriers. For a coarse material, as the pressure becomes more negative (capillarity and suction increases) the water content and hydraulic conductivity decreases dramatically while for a fine material the water content and hydraulic conductivity decreases less rapidly (Figure 6). The point where the curves meet is called the asymptotic down-dip limit. This point represents the largest amount of fluid that the capillary barrier can transport laterally, divert, in a fine material before breakthrough into the coarse material, and it is also known as the diversion capacity of a capillary barrier (Ross, 1990). For a capillary barrier to be effective, the majority of infiltration water needs to be diverted or breakthrough will occur. There are generally two methods for removing moisture from the capillary layer, which include evapotranspiration and lateral transport. Some capillary barrier may be designed with higher permeability layers within the capillary layer to increase the drainage of water laterally to mitigate water content and pressure buildup in the capillary layer. To achieve this, a typical configuration of a capillary barrier containment might consist of layered soils alternating between fine and course at a specific grade allowing the fine layers to drain before saturating along flow into the coarse material (Melchior et al., 2010). Vegetation is also commonly used covering the top of the capillary barrier to control infiltrating water through evapotranspiration (Figure 7, (Kampf and Montenegro, 1997)).

Capillary barriers have been found to be effective cover systems especially in arid regions, and they do not have to have the soil conditioned like compacted soils where a wet compacted fine soil can desiccate and crack. However, the ability of a capillary barrier to shed water laterally is an important consideration when determining whether to use capillary barrier. Some of the processes that affect capillary barrier effectiveness include their ability to divert and transfer infiltrating water (Ross, 1990), erosion and biota intrusion into the course layer leading to vertical breakthrough of moisture, structured layers within the fine layer, and heterogeneous properties within the coarse and fine layers. These processes should be considered when evaluating the barrier effectiveness. Quantification of water and contaminant flux mitigation should be quantified to support design of barriers, and monitoring should be used to confirm effectiveness.

Summary

Capillary barriers occur when infiltrating water reaches a coarser, higher-permeability material underlying a finer-grained, lower-permeability material. They function as covers to waste material, and inhibit downward water flow. This barrier to water and contaminant flow occurs in the coarse material, because even with a higher permeability than the overlying fine material the unsaturated hydraulic conductivity of the coarse material is much lower than that of the fine material. Evaporation and drainage can be used to remove infiltrating water from the overlying fine-grained layer. These physical, unsaturated flow processes act to slow or immobilize contaminants, and may attenuate or even mitigate the downward vertical flux of contaminants, which supports the protection of groundwater from potential contamination. The attenuation of water flow and contaminant migration should be quantified to support design of barriers, and monitoring should be used to confirm effectiveness.

References

Bodman, G. B. and E. A. Colman (1944). "Moisture and energy conditions during downward entry of water into soils." Soil Science Society of America Procedings 8: 116-122.

Buckingham, E. (1907). Studies on the movement of soil moisture. Bull. 38, USDA, Bureau of Soils, Washington D.C.

Cohen, R. M. and J. W. Mercer (1990). "Review of Immiscible Fluids in the Subsurface: Properties, Models, Characterization and Remediation." Journal of Contaminant Hydrology 6(2): 107-163.

Darcy, H. (1856). Les Fontaines Publiques de la Ville de Dijon. Dalmont, Paris. 647 p. & atlas.

EPA (1999). Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites. OSWER Directive 92000.4-17P, Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C.

Hillel, D. (1998). Environmental Soil Physics: Fundamentals, Applications, and Environmental Considerations, Academic Press.

Kechavarzi, C., et al. (2005). "Two-dimensional laboratory simulation of LNAPL infiltration and redistribution in the vadose zone." Journal of Contaminant Hydrology 76(3-4): 211-233.

Lenhard, R. J. (1992). "Measurement and Modeling of 3-Phase Saturation Pressure Hysteresis." Journal of Contaminant Hydrology 9(3): 243-269.

Lenhard, R. J., et al. (2004). "A constitutive model for air-NAPL-water flow in the vadose zone accounting for immobile, non-occluded (residual) NAPL in strongly water-wet porous media." Journal of Contaminant Hydrology 71(1-4): 261-282.

Maidment, D. R. (1993). Handbook of Hydrology. New York, McGraw-Hill.

Melchior, S. et al. (2010). "Results from 18 Years of In Situ Performance Testing of Landfill Cover Systems in Germany." Journal of Environmental Engineering, Vol. 136, No. 8, 815-823.

Morris, C. E. and J. C. Stormont (1997). "Capillary barriers and subtitle D covers: Estimating equivalency." Journal of Environmental Engineering-Asce 123(1): 3-10.

Rasmuson, A. and J. C. Eriksson (1988). "On the Physicochemical Basis for the Capillary Barrier Effect." Nordic Hydrology 19(5): 281-292.

Ross, B. (1990). "The diversion capacity of capillary barriers." Water Resour. Res., 26(10), 2625–2629, doi:10.1029/WR026i010p02625.

Melchior, S. et al. (2010). "Results from 18 Years of In Situ Performance Testing of Landfill Cover Systems in Germany." Journal of Environmental Engineering, Vol. 136, No. 8, 815-823.