On the Physics of Low Impact Development – Pervious Pavement

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Abstract

Conventional wisdom in the low impact development (LID) community focuses on the fact that porous pavement structures function by allowing stormwater runoff to infiltrate vertically downward, or flow horizontally into the soil matrix, as primary mechanisms of stormwater disposal. Discussions of rain gardens qualitatively consider the role that evapotranspiration plays in stormwater disposal.

Soil scientists look in much more detail at water movement through soil structures, both vegetated and not. However, the current popular LID literature surrounding porous pavement only seems to consider infiltration capacity of the underlying soils. Often times the potential benefits of porous pavement structures are discounted because of low permeability soils that are postulated to inhibit infiltration and, consequently, porous pavement feasibility.

In reality, the mechanism of the removal of water from a porous pavement structure is much more complex involving such concepts as capillary action, diffusion, vapor pressure gradients, and heat/mass transfer. The magnitude of evaporation from porous pavement structures is potentially much greater than that predicted by pan evaporation data due to the increased surface area available for mass transfer when compared to the pavement "top" surface area. This paper presents a discussion of the broader considerations in explaining the workings of a porous pavement structure.

A review of some of the current thinking related to the evaporation process is presented. Estimates of available surface area in a porous pavement structure available for evaporation are considered and an approach to estimating the magnitude of evaporation as a result of that consideration is discussed.

Introduction

Low Impact Development (LID) professionals are well versed on the macro scale processes of precipitation, evaporation, infiltration, interflow, flow to groundwater, and runoff. The general proportions of each of these water balance components in the hydrologic cycle of a basin are generally understood. However, thinking confined to strictly this macro scale view of LID can hinder the ability to creatively apply LID techniques when one of the components is not "ideal". The argument against the use of LID often times comes up when the intercepting soil types are said to be not favorable or feasible for LID because of generalized site concerns relating to soils rated "not conducive to infiltration". The civil engineering LID community, which includes civil engineers, hydrologists, landscape architects and geotechnical engineers, often time discount the applicability of LID under less than ideal macro scale considerations of soil conditions.

For LID to achieve its true potential the processes at work need at to be considered at increasingly finer levels of detail than just those of the macro scale. For example, soil scientists examine the movement of water through soils considering the micro and atomic scales. Soil physics is a consideration that needs to be better understood by the civil engineering based LID community. The application of physics is presented here to serve as a framework for the analysis of a porous pavement structure.

Physics

The most widely accepted role of physics by the LID community is the part gravity plays in the infiltration process. Gravity causes water to flow downhill, but as explained below, more is at work in the movement of water through a porous pavement structure.

A consideration of the physics of LID begins with a basic understanding of the water molecule and the bonding of hydrogen atoms to the oxygen atom and the propensity of water molecules to adhere to other substances. Davis (2001) provides a concise description of the physics of water as related to the field of permafrost science and engineering. The basic physics described there is also applicable to LID.

With an understanding of the basic attractive forces at work in the water molecule one gains an insight into the phenomenon of capillarity. LID professionals generally recognize that capillary action is the force that draws water upward into vegetation whether it is short grasses or tall trees. Capillary action is also prevalent in moving water through and upwardly in fine grained soils ranging from clays to sands. This property has been commercially capitalized on in, for example, individual "mound type sanitary sewage septic treatment systems, including proprietary installations.

Physics is also at work in the soil matrix through the phenomenon of diffusion. Diffusion is the process that drives the flow of molecules from an area of higher concentration to one of lower concentration due to internal molecular energy. Fick's First and Second Laws of Diffusion provide the model for describing this process.

Evaporation, a significant component of LID, is a diffusion process. Water vapor molecules flow from a high concentration and energy level to a lower level. Under certain conditions water vapor may condense as droplets as in the case of fog or clouds, or on ground surfaces as dew. In a soil matrix liquid water may vaporize and then condense higher in the soil layer based upon available energy, only to re-vaporize and continue its upward movement as energy and concentration conditions allow. Work reported by Cahill and Parlange (1998) describes heat and mass transfer in field soils illustrating the physics of soil water movement by the diffusion process.

Other non civil engineering disciplines, including chemical engineers and the chemical process industry, have recognized the power of the diffusion process and exploited this process in such applications as material drying operations, medical technology, and electronics manufacturing to name just a few. Gu, Ho, Plumb and Webb (1998) present just one example of a description of the evaporation and condensation process in porous media.

The implication of these two principles of physics, capillary action and diffusion, for LID relate to the current paradigm that soil infiltration rates and pan evaporation rates, as currently viewed, are limiting factors for determining LID feasibility in a given setting. While at the macro scale this may be true, the physics of the molecular scale suggest that there may be more potential than infiltration test and pan evaporation data portray. The currently accepted limitation of infiltration rates, partially controlled by gravitational forces, evaporation rates, and solar incidence, may be overcome if energy in the soil/porous pavement structure matrix and the water stored in it are given thorough consideration.

A key to the potential of LID is the energy available to the water molecule to exploit or overcome the various forces of physics. In the current world of LID professionals, solar radiation and wind have been viewed as primary sources of energy to drive the evaporation process. Xu and Singh (1998) report accuracies in predicting evaporation by such commonly accepted models as the Penman and the Thornwaite equations. Their work shows inconsistence in predictive accuracies over varying time scales using common meteorological parameters.

The concept of the earth as a heat source/sink has not yet been found in the literature to be extolled as an energy source to assist LID processes.

Mankind and the animal kingdom have utilized the earth for its stable heat(energy) source to stay warm in the winter and cool in the summer. Recently, sustainability considerations are once again driving us to look at harnessing the heat stored in the earth to moderate the temperature of our shelters. The temperature stability and heat availability just a few feet below the ground surface provides significant energy potential for LID.

Soil profile temperature information is important to understanding the physics and potential of LID. In moderate climates the relatively stable soil temperatures near the ground surface provide an energy source to drive temperature gradient based diffusion (evaporation) processes when compared to cooler air temperatures during winter months. Virginia Tech University (2009) presents a concise summary of near earth surface temperature gradients to help understand this potential.

Evaporation, Surface Area and Porous Pavement

Current thinking regarding LID and evaporation is centered on the use of pan evaporation data and soil infiltration rates as the primary indicators of the efficacy of LID to reduce surface runoff. It has been demonstrated through reported research that the process is much more complicated involving the basic principals of physics. It is postulated, then, that the potential for LID to reduce stormwater runoff may be more than predicted through the sole use of the macro scale parameters of soil infiltration rate and pan evaporation rates.

Pan evaporation data is the current benchmark used by hydrologists and civil engineers for determining evaporation potential. If one considers this device from the physics standpoint it is evident that this approach is inadequate in its ability to describe the LID evaporation/transpiration processes at or near the ground surface/atmosphere interface. The porous pavement structure is presented here as a basis for analysis of this inadequacy.

In the United States the National Weather Service has standardized its evaporation measurements on the Class A evaporation pan. This device is a cylinder with a diameter of 47.5 inches (120.7 cm) that has a depth of 10 inches (25 cm). The pan rests on a carefully leveled, wood base. Evaporation is measured daily as the depth of water (in inches) that evaporates from the pan. The measurement day begins with the pan filled to exactly two inches (5 cm) from the pan top. At the end of 24 hours, the amount of water to refill the pan to exactly two inches from its top is measured.

While this device may be representative of the surface of open water bodies such as lakes, ponds and marine water bodies, it is hardly representative of the atmosphere/soil/water interface of the ground surface and surrounding zone of LID device influence.

The process of evaporation is related to available surface area for heat and mass transfer to take place. Pan evaporation only presents the free water surface of the device as the area available for evaporation. A porous pavement structure, due to its internal surface area, porosity and connectivity of voids that are open to the atmosphere, presents a potential available evaporation surface area many times to hundreds and possibly thousands of times greater than the top surface area for the evaporation process. This property of porous pavement and LID devices in general, deserves quantification and consideration.

The Class A evaporation pan is situated where all surfaces are exposed to generally the same air temperature. This condition negates any significant temperature gradients to drive heat and mass transfer from within the water mass in the pan, other than that created by solar radiation. Solar radiation heats the water mass in the pan, imparting energy to the water and creating a temperature gradient between the water in the pan and the atmospheric temperature surrounding the pan. The intensity of the sun's energy, as the primary energy source driving the temperature gradient, is continuously changing throughout the day and night.

In addition to the sun's direct influence on the energy flow in the porous pavement structure, the porous pavement structure energy balance is aided by the fact that it is surrounded by the relatively stable heat source/sink of the surrounding soil and the earth itself. Hourly, daily, seasonal, and annual temperature variations are mitigated in the ground when compared to the overlying atmosphere. This fact provides porous pavement with a relatively stable energy source needed to drive temperature gradients, between the pavement and the atmosphere, for evaporation through heat and mass transfer physics.

In review, it is accepted that evaporation calculations are based upon available wetted surface area. In the case of the evaporation pan it is simply the area of the free water surface. Modeling of porous pavement and other LID facilities is typically based upon the surface area of the facility at ground level. No correction is made for all the potential available surface area within the porous pavement structure or LID device itself.

Shahidzadeh-Bonn, Azuni, and Coussot (2007) discuss the wetting of porous media surfaces and its implications with respect to drying of those surfaces. The implications of this understanding for application to LID and porous pavement are obvious.

Porous Pavement as a Reactor

A porous pavement structure can be thought of as heat and mass transfer reactor and analyzed using principals of physics and approaches typically used by soil scientists, chemical engineers, environmental engineers, and others. The components of the reactor include the different layers of media of the pavement structure, including the underlying native soil and constant heat source, the reservoir course, the choker course, the pavement course, and the atmosphere. Each layer has its own density, heat capacity, porosity, surface area, moisture content, etc. Current popular hydrologic simulation programs only allow for layer thickness definition and associated porosity.

Researchers have formulated similar diffusion problems for theoretical situations using idealized glass beads, sand, or silt loam. Webb and Ho (1998) present a review of modeling results. Similarly, researchers have simulated heat and water vapor transfer through a matrix of field soil conditions.

The basic physics principles such as Fick's Laws and the Navier-Stokes equation have been used for the analysis of a wide range of applications ranging from medicine to the food industry. The differential equations with complex boundary conditions have been solved for a myriad of situations equal to or more complex than the porous pavement model. As just one example, Halder and Data discuss the use of COSMOL Multiphysics software in modeling multiphase, porous media transport of thermal processes and evaporation. This tool and others are available for application to address the LID reactor.

Conclusion

To this point in time the state of the science of LID that has been reported on has centered on the macro scale. Gross level of detail simulations of the hydrology of a water basin have been developed using hydrologic simulation models with the macro scale parameters of pan evaporation data and soil infiltration rates. Estimates of the performance of LID devices such as pervious pavement and rain gardens have relied on this same input and approach to modeling.

While LID is gaining broader acceptance, its potential has been and will continually be constrained in less than ideal situations unless there is a broader understanding of the basic mechanisms involved in LID. Disciplines outside of the traditional civil engineering community have been studying, for some time, issues similar to those found in LID. Work reported by soil scientists, chemical engineers, physicists and others is complementary to solving LID problems related to infiltration and evaporation constraints. Their work needs to be more widely explored.

The basic principals of physics are at work in LID and can provide insight into more aggressively applying LID on difficult sites. The COMSOL Multiphysics software presents a simulation modeling platform to aid in the analysis of the full potential of the porous pavement stormwater best management practice.

Kaku (2008) in his book *The Physics of the Impossible* makes the statement ". . . that the impossible is often a relative term". He goes on to say that as the basic laws of physics and science were better understood, advances, once considered to be impossible, were realized. Over time, this phenomenon of understanding will make a difference in the success of LID as a tool for more effectively dealing with stormwater.

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