WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Macropore Flow: A Means for Enhancing Groundwater Recharge or a Potential Source of Groundwater Contamination

Focus Categories: GW, WQL

Keywords: Groundwater, Models, Runoff, Urbanization

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Statement of Critical Regional or State Water Problems:

As urban areas expand, groundwater levels and heads decrease as a result of the combined effects of groundwater pumping and loss of groundwater recharge. In some cases these decreases constrain the use of groundwater. More commonly, they result in reduced flows to springs, streams, lakes and wetlands. Diffuse infiltration of stormwater has been proposed as a potential management strategy for mitigating groundwater depletion due to urban expansion. The idea is to carefully manage storm runoff from impervious surfaces so that as much runoff as possible sheetflows over adjacent pervious surfaces that are managed to maximize infiltration capacity. Innovative consulting firms such as Conservation Design Forum in Naperville, IL are beginning to apply such an approach to development projects in the upper Midwest, including the expansion of the University Research Park in Madison, WI.

Successful implementation of diffuse stormwater infiltration requires identification of sites with high permeabilities. The matrix permeability of soils in the upper Midwest are generally low to moderate; however, if macropores are present, the effective permeabilities can be much higher. Hence, macropores may be critical to the effectiveness of diffuse infiltration. Exploiting macropore flow has a potential drawback

— urban stormwater can be highly contaminated and macropore plow could become a source of groundwater contamination.

Statement of Results or Benefits:

This proposed research will provide useful information about the potential benefits and risks associated with diffuse infiltration of stormwater runoff from impervious surfaces. Diffuse infiltration may offer an efficient and effective way to mitigate the reduction in groundwater levels and heads associated with urban development. At the same time, infiltration of contaminated stormwater could cause groundwater contamination. Macropore flow, which has been shown to be an important process in agricultural settings, would greatly enhance the potential of diffuse infilltration, but would also increase the risk of groundwater contamination. This research will provide useful information about the significance of macropore flow in urban greenspaces in Dane County, Wisconsin. The resulting information would be transferable to much of the upper Midwest.

Nature, Scope and Objectives of the Research:

The proposed research has two principal components -- infiltration testing of soils in urban/suburban greenspaces in Dane County, and modeling of diffuse infiltration of stormwater runoff. The objective of the infiltration testing is to investigate the importance of macropore flow in urban greenspaces as both a mechanism for increasing groundwater recharge as well as a source of groundwater contamination. The objective of the modeling component is to quantify the potential groundwater recharge rates achievable by coupling an impervious surface to a pervious one.

Two field methods will be used to investigate macropore flow in urban greenspaces in Dane County. We will use a large-diameter double-ring infiltrometer to determine whether macropore flow is occurring in a given location. Steady-state infiltration rates that greatly exceed those normally associated with the given soil type will be considered as an indicator of macropore flow. At these sites we will use a disc permeameter/tension infiltrometer to study infiltration in more detail and to quantify infiltration parameters for subsequent use in modeling. We will focus our field investigations on large greenspaces that are near to, and down-slope from, large impervious services, such as roofs, parking lots, and paved outdoor work areas. The former present potential opportunities for diffuse infiltration; the latter are potential sources of groundwater contamination.

The objective of the modeling is to quantify the potential groundwater recharge rates achievable by diffuse infiltration of stormwater runoff from impervious surfaces. We will model both hypothetical conditions as well as cases selected from our field studies. Modeling will be based on a public domain version of CASDC2D (Julien et al., 1995), a two-dimensional, physically-based rainfall-runoff model that simulates infiltration of runoff from adjacent upslope areas.

Methods, Procedures and Facilities:

The proposed research has two principal components: infiltration testing of soils in urban/suburban greenspaces in Dane County, and modeling of infiltration of runoff from pervious surfaces. The objective of the infiltration testing is to investigate the present and potential importance of macropore flow in urban greenspaces as both a mechanism for increasing groundwater recharge as well as a source of groundwater contamination. The objective of the modeling component is to quantify the potential groundwater recharge rates achievable by coupling an impervious surface to a pervious one. The infiltration testing will be completed in the first 16 months of the project. Although the modeling effort will begin during the first year, it will primarily be conducted in year two.

Infiltration Testing

Two methods will be used to investigate macropore flow in urban greenspaces in Dane County. The first method will employ a large-diameter double-ring infiltrometer to determine whether macropore flow is occurring in a given location. The infiltrometer will be constructed to allow for varying inner and outer ring diameters, depending on the site conditions. Steady-state infiltration rates that greatly exceed those normally associated with the given soil type will be considered as an indicator of macropore flow.

Sites of likely macropore flow will be investigated further using a disc permeameter/tension infiltrometer. These devices have recently been developed to rapidly determine saturated and unsaturated permeability, sorptivity, and various other unsaturated hydraulic parameters. They can be set to infiltrate water under positive-head, saturated conditions, as well as negative-head, unsaturated conditions. This ability allows disc permeameters/tension infiltrometers to be used to assess the contribution of macropores to the overall soil permeability. Disc permeameters and tension infiltrometers are essentially identical in design, and both draw on the theoretical underpinning of the Wooding equation (Wooding, 1968), but differ slightly in their application and data analysis. Disc permeameters are best suited for relatively dry soils, whereas tension infiltrometers can be used in moist to wet soils.

Infiltration testing will follow the procedures proposed by the developers of the devices, Ankeny (1988) and Perroux and White (1988). At each site, ponded and non-ponded tests will be conducted at the soil surface, and at least one other depth within the upper three feet of the soil profile. This will allow determination of the permeability and the relative importance of macropores at the soil surface where infiltration takes place, as well as within the soil profile where percolation, redistribution, and storage of the infiltrated water occurs. Great care will be taken during preparation of each test site to prevent disturbance of the soil and to retain the original soil structure. Where appropriate and necessary, soil samples will be collected for initial and final moisture content and particle-size analysis.

A critical step in the infiltration testing will be the selection of sites. We will focus on large greenspaces that are near to and down-slope from large impervious services, such as roofs, parking lots, and paved outdoor work areas. We will use recent aerial photographs to identify potential sites, which will then be visited to determine suitability. We will be interested in greenspaces that either currently receive, or have the potential to receive, large amounts of runoff from impervious surfaces. The former present potential opportunities for diffuse infiltration; the latter are potential sources of groundwater contamination.

Modeling

The objective of the modeling is to quantify the potential groundwater recharge rates achievable by diffuse infiltration of stormwater runoff from impervious surfaces. We will conduct two kinds of modeling experiments. The first will be a set of model runs for a hypothetical impervious surface connected to a pervious one. It will be assumed that both surfaces are of unit width, flat and uniformly sloping in the same direction, and that sheetflow occurs over the surfaces. Various combinations of vegetation type, infiltration properties, length, slope, and roughness will be explored. It is expected that the dimensionality of the problem can be reduced by using appropriate dimensionless parameters, such as the ratio of the surface lengths.

We will also model several of the sites at which we have conducted infiltration tests. Infiltration parameters will be based on the disc permeameter/tension infiltrometer measurements. To enable some degree of model verification, during storm events we will make field observations of runoff patterns and will estimate runoff amounts at the modeled sites.

Modeling will be based on a public-domain version of CASDC2D (Julien et al., 1995), a two-dimensional, physically based rainfall-runoff model. CASDC2D is a raster-based model which uses the Green and Ampt infiltration method and the diffusive wave formulation for overland and channel flow routing. Unlike most rainfall-runoff models, CASDC2D simulates infiltration of runoff from upgradient cells. Although CASDC2D does not explicitly model macropore flow, we believe it will give realistic representations of infiltration of surface runoff, provided we use reasonable estimates of saturated hydraulic conductivity.

We will use CASDC2D to evaluate annual groundwater recharge for our hypothetical and actual cases. Because of the difficulties associated with snow and frost, we will not model recharge due to snowmelt. Although snowmelt contributes significantly to groundwater recharge in undeveloped areas in southern Wisconsin, it is expected to be less of a factor when runoff is a major component of groundwater recharge. This is because snow only accounts for about 10% of annual precipitation.

For the hypothetical cases, model results will be presented as plots of average annual groundwater recharge as a function of the various properties of the pervious and impervious surfaces. Of greatest interest is the ratio of the length of pervious to impervious surface. (If the results do not scale approximately with length ratio, a more complex presentation will be required.) It is expected that average annual recharge will increase at a decreasing rate with this ratio, eventually reaching a constant maximum. Also of interest is the role of vegetation type. Deep-rooted vegetation, such as prairie plants, will have high infiltration rates and high rates of evapotranspiration. These will have the effect of reducing mean recharge rates.

Related Research:

As urban areas expand, groundwater depletion results from the combined effects of groundwater pumping and loss of groundwater recharge. In Dane County (WI) it has been estimated that groundwater withdrawals associated with the development of an acre of land reduce groundwater amounts by 500 to 1000 gallons per day (RPC, 1997). This is equivalent to an annual unit area loss of 7 to 14 inches, or about one to two times the pre-development recharge rate. An additional annual loss of 3 to 5 inches results from the introduction of impervious surfaces. In heavily urbanized areas these losses can constrain the use of groundwater. For example, as a result of groundwater depletion in the Chicago metropolitan area, Lake Michigan has become the water source for virtually all municipal users. In Dane County, groundwater depletion is not an immediate threat to the water supply. However, it is widely recognized that groundwater depletion has reduced baseflows to county streams and lakes, as well as caused the dessication of springs and wetlands. The flow reduction is greatest in the Yahara River/lakes system, due to the fact that most of the county's wastewater is treated at the Nine Springs Treatment Plant and the treated effluent is diverted out of the Yahara watershed. RPC (1997) estimates that the mean annual flow in the Yahara River near McFarland has been reduced by one-third as a result of pumping and wastewater diversion. As the population of the county increases, the problem will worsen.

Diffuse infiltration of stormwater has been proposed as a potential management strategy for mitigating groundwater depletion due to urban expansion. The idea is to carefully manage storm runoff from impervious surfaces so that as much runoff as possible sheetflows over adjacent pervious surfaces which are managed to maximize infiltration capacity. Innovative consulting firms such as Conservation Design Forum in Naperville (IL) are beginning to apply such an approach to development projects in the Upper Midwest, including the expansion of the University Research Park in Madison, WI.

The idea behind this approach is simple. For most rainfall events in southern Wisconsin, infiltration rates for pervious surfaces are supply limited. If direct rainfall (or snowmelt) is the only source of water, total annual groundwater recharge will be bounded by the difference between annual rainfall and annual evapotranspiration. For heavily vegetated southern Wisconsin, about 20 of the 30 inches of annual rainfall evaporates, leaving a maximum of 0 inches for groundwater recharge. Actual recharge is typically a few inches lower as a result of occasional runoff events. But if additional water is provided by surface runoff from an adjacent impervious surface, annual recharge could significantly exceed 10 inches, mainly because evaporation losses from impervious surfaces are negligible.

Consider, for example, an impervious surface draining on to a highly pervious vegetated surface of equal area. As long as all of the runoff can infiltrate the pervious surface and evapotranspiration from the pervious surface does not increase, the total groundwater recharge there would be 40 inches--30 inches of rainfall, plus 30 inches of runoff from the impervious surface, minus 20 inches of evapotranspiration. Over the combined pervious and impervious surfaces, the total groundwater recharge would be 20 inches, twice the amount that would occur on an isolated pervious surface. Any additional runoff or evapotranspiration would, of course, decrease this amount.

Successful implementation of diffuse stormwater infiltration requires identification of sites with high permeabilities. In practice, soil permeabilities are generally taken from the county soil surveys prepared by the U. S. Department of Agriculture Soil Conservation Service (now known as the National Resource Conservation Service). Recent infiltration tests conducted by Havlena (1997) on several soils in Dane County indicate that the actual soil permeabilities can be much higher than the values reported in the Dane County Soil Survey (USDA, 1978). Havlena (1997) conducted a series of 19 air-entry permeameter tests at 12 agricultural sites within the Nine Spring watershed in Fitchburg to determine the in-situ permeability of surface and near surface soils. All of these tests were conducted in silt loam soils with listed permeabilities of 0.63 to 2.0 inches per hours. For 10 of the 12 test sites, the permeability of the surface soils determined by the air-entry permeameter testing was found to be considerably greater than the soil survey values. The average permeability for these 10 cases was about 13 inches per hour, with the highest value of 33 inches per hour. In virtually all of these cases Havlena noted strong evidence of macropore flow, which he attributed primarily to the observed presence of earthworm burrows. These wormholes were observed to be up to 0.3 inches across, and vertically continuous to depths of at least 3 feet. The presence and degree of development of the wormholes appeared to be correlated to the prevailing landuse and vegetation at each test location, with the highest values for permeability at depth consistently occurring at grass-covered and restored prairie sites.

Legg at al. (1995) found evidence of the importance of macropores to infiltration in residential lawns. Based on sprinkler tests on 20 lawns in Madison (WI), Legg et al. (1995) found that saturated hydraulic conductivities varied significantly from lawn to lawn, but did not vary within individual lawns. Lawns established within three years produced higher runoff volumes than older lawns, possibly reflecting the time required for continuous, surface-vented macropores to develop. Hydraulic conductivities estimated for soils of varying texture indicated that texture was not an important explanatory variable, further supporting the dominant role of macropores.

It has been known for many years that the presence of macropores can greatly increase the rate of water and solute transport in soils (eg., Bouche, 1971; Ehlers, 1975; Douglas et al., 1980; Bouma, 1981; Tyler and Thomas, 1981; Germann et al., 1984; Smettem and Collis-George, 1985; Smith et al., 1985; Everts et al., 1989; Andrein and Steenhuis, 1990; Jury and Fluhler, 1992). Most of the research conducted on macropore flow has focused on its role in facilitating contaminant transport to the groundwater. The general assumption has been that macropore flow can be a primary contributor to contaminant transport, but is unlikely to constitute a significant component of groundwater recharge under normal conditions. However, under ponded conditions, macropore flow can become the dominant recharge mechanism. For example, Wood et al. (1997) estimate that macropore flow constitutes between 60% and 80% of annual groundwater recharge in the floors of topographically closed basins in the Southern High Plains region of Texas and New Mexico.

Hence it appears that if macropores are present, diffuse infiltration of stormwater offers a promising way to partially mitigate the reduction of groundwater levels and heads accompanying urbanization. But there is a potential downside to such an approach. Numerous contaminants are present in urban stormwater (Pitt et al., 1994). Preferential flow of these contaminants to the groundwater poses a potential threat (NRC, 1994), particularly when groundwater is the major source of drinking water source. However, if macropore flow is known to be occurring, the threat to groundwater can be reduced by limiting diffuse infiltration to clean water, such as roof drainage, or by pretreating the stormwater with a retention pond or other management practice.

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