Report for 2001NE2461B: Evaluation of Conductive Properties of the Surficial Aquifer in the Nebraska Sand Hills

There are no reported publications resulting from this project.

Report Follows:

Statement of the Problem

Hydraulic properties of the aquifer underlying the Nebraska Sand Hills control water availability and quality in an area of 50,000 km^2 (Figure 1). The Sand Hills is one of the largest grass-stabilized dune fields in the world (Ahlbrandt et al., 1980, Loope and Swinehart, 2000). Deposited by eolian processes, this dune field serves as a water buffer that preserves precipitation and conveys a part of it to the underlying alluvial sand, gravel, and silt, and further to the High Plains aquifer (Ogallala formation). In absence of this buffer, water would be consumed by the evapotranspiration in the area where potential evapotranspiration exceeds the average annual precipitation by at least 70 cm (Winter, 1986). Hydraulic conductivity is the major property of this buffer that controls groundwater recharge.

However, surprisingly little is known about the hydraulic conductivity of this area (Keen, 1992, Gosselin et al., 1999) in spite of the importance for water resources of Nebraska, the High Plains aquifer, and wetlands protection. Therefore, it is important to develop methodology and to initiate studies of hydraulic conductivity in the Sand Hills that will provide the field data needed for evaluation of water resources and water quality of the region. The developed methodology will also have broader scientific ramifications by providing a tool for field investigations of conductive properties in unconsolidated aquifers in unsaturated conditions.

Related research

Analysis of permeability for assessment of hydraulic conductivity was used for older consolidated sediments of eolian origin (Goggin et al., 1988a) or alluvial sands (Dreyer et al., 1990). We propose to take advantage of this approach for unconsolidated sand of the modern sand dunes and surficial aquifers in the Nebraska Sand Hills.

Hunter's (1977) work on coastal dunes has shown that wind-blown sand can be deposited by three distinct processes: 1) grainflow (sand avalanches down the lee face); 2) grainfall (sand is shot over the dune crest and lands on upper lee face), and 3) wind ripple migration (traction deposits mainly found on the stoss slope and the apron or plinth at the base of the slip face. Sand deposited by migrating wind ripples should have the lowest porosity (and *k*) and grainflows should have the highest. These processes develop a structured (layered) heterogeneity in *k.*

In the Sand Hills another anticipated source of heterogeneity relates to post-depositional processes. Fine-grained material, chiefly silt and clay can move downward through the sand with infiltrating water, thereby creating soil lamellae. These features are well developed at many Sand Hills localities and probably increase the moisture retention of soil (Sweeney, 1999, Sweeney and Loope, 2001).

Another critical related development in studies of permeability of porous materials is use of air injection that eliminates difficulties of operating with large volumes of water in difficult terrain conditions. This new approach requires development of several components: instruments, field methodology, and data interpretation. Use of air received significant attention recently in laboratory (Sharp et al., 1994, Tidwell and Wilson, 1997) and field investigations (Davis et al., 1994). However, new instruments were designed for use in outcrops of the aquifers with different degrees of consolidation or with laboratory rock slabs only that limited spatial analysis of *k* heterogeneity.

These methods of permeability estimating by air injection avoided the drilling or use of subsurface probes at depths from the surface. In contrast, recent developments in remediation methodology address the subsurface testing (when measurements are performed at depth from the surface), but the methodology requires installation of permanent wells (Baer and Hult, 1991). The direct push method for delivery of the screen to different depths became common in aquifer hydraulic testing (Butler et al., 2001), however its applications for air testing has not been reported yet.

Nature and scope of the project

The project combined theoretical, laboratory, and field studies for development of methodology and *in situ* assessment of permeability of eolian sediments forming the surficial aquifer in typical dune areas of the Nebraska Sand Hills.

Measurements of hydraulic conductivity K in unconsolidated sediments for aquifer characterization are based commonly on a range of methods (Zlotnik et al., 2000). The most common group of methods - hydraulic testing – involves water injection into or withdrawal from the aquifers below the water table. Difficulty of this approach in the dune environment of the Nebraska Sand Hills lies in several factors: large depth to the water table, high variability of this depth due to the dune relief, significant quantities of water required for injection in a relatively highly permeable formation, and inaccessibility of the area for standard drilling and testing equipment.

To overcome these difficulties, we took advantage of an important sedimentary feature of eolian dunes, i.e. relative vertical consistency of the dune lithology. The grain size characteristics of dune sediments vary only slightly over large thickness (Schlee et al., 1964). After investigation of the hydraulic properties of sand dunes one can extrapolate data collected in the unsaturated zone (above the water table) to the larger depth (including saturated conditions). In this approach, one measures permeability k of formation, which is in a relatively simple relationship to the hydraulic conductivity K.

The scope of this work is three-fold:

1. Development of new methodology for estimation of permeability by air injection (equipment, procedures, and data interpretation)
2. Evaluation of hydraulic conductivity in characteristic dune areas and analysis of spatial patterns of eolian sediments (shallow aquifer) of the Nebraska Sand Hills
3. Validation of the methodology by comparing data with previously collected data in the area.

Methods and procedures

The laboratory studies lead to a development of the air permeameter that could be applied at depths ranging from few cm to 1.5 m. All previously proposed air permeameters are based on developing a steady-state air mass flow rates and pressure head. Use of previously published design (Davis et al., 1994, Sharp et al., 1994) was not robust enough in field conditions due to a significant size needed to store and supply the steady air flow and necessity of relatively prolonged injection. To provide sufficient air supply and accurate interpretation of relationship between the air mass flux relationship, a new design was proposed. Schematic diagram of the air permeameter is shown in Figure 2. This permeameter includes the subsurface and the ground components. The subsurface component consists of a steel pipe of 2.8 cm diameter fitted with a short screen (8.8 cm long). This pipe can be driven to the tested depth. The ground component involves the air mass flowmeter for measurements of the mass flow rate *Q,* pressure transducer for measurements of the injected air pressure *P*, and thermometer. Together with the screen depth, these characteristics can be used for estimation of permeability of the formation zone that is adjacent to the screen.

Theoretical studies will include derivation of the formula for permeability estimates. In steady-state regime, the permeability *k* can be estimated from a simple equation

$$k=f\,Q/\,P,$$

where f is a shape factor for the particular configuration of the device (Goss and Zlotnik, 2000). Shape factor for this instrument was derived by generalization of previous studies of the air permeameter (Tartakovsky et al., 2000, Goggin et al., 1988 b, Zlotnik, 1994). Analysis of the quasi-linear airflow in the system was reduced to a solution of the boundary value problem for the Laplace equation in uniform media. Hydraulic conductivity K is related to the formation permeability by relationship $K = k\rho g / \mu$, where ρ is water density, μ is dynamic viscosity, and g=9.81 m/s^2 (Freeze and Cherry, 1979). The parameter μ is temperature dependent; and this was taken into account in the process of field data collection (see Ronan et al., 1998). This was included in the calculation of the factor f above. The viscosity of water in the conversion of k to K was taken to have the value characteristic of the mean annual temperature (20 °C) of the ground at the latitude of the site. The pressure sensor was calibrated in the laboratory by direct comparison with water manometer.

At the stage of field studies, the characteristic site locations for air permeameter applications were identified. Considering limited resources, these studies emphasized the collection of permeability data at morphologically different locations at one representative dune (Figure 3).

Summary

Devices – air permeameters - were designed and constructed to supply air at known pressure and mass flow rate to a subsurface probe. Subsurface probes were designed and constructed for use in the near subsurface (at depths up to 1.5 m from ground surface) for use in with poorly consolidated sediment.

After selecting the optimal system, the guidelines for instrument operation and data interpretation for evaluation of the permeability in the vicinity of the probe were developed. Geometric effects were incorporated by calculation of a shape factor f.

The permeability *k* was estimated by measuring the flow rate *Q* and the applied pressure *P* for a given geometric configuration. In each test, this pressure was measured using linear relationship *V'* between voltage across a pressure sensor and *P* for a given geometric configuration. The correlation coefficient *r* for each site and depth location had a range r=0.915-1.00, with the most values greater than 0.99.

Systematic measurements were made upon a selected dune location (Gudmundsen Sandhills Lab, approximately N42°4.9'and W101°28.3')with a history of episodic vegetative covering in characteristic locations. Measurements of the permeability were performed at five depths between 0.1 m and 1.3 m at 34 distinct locations.

The depth-averaged permeability values of *k* and hydraulic conductivity *K* may be sorted into distinct ranges according to the dune features at different site locations. The five highest values of k= (61.9-72.4)10^{-12} m^2 or K=(60.3-70.6) 10^{-5} m/s, were associated with a step in the dune profile; the 22 lowest values of k= (3.3-11.9)10^{-12} m^2 or K=(3.2-11.6) 10^{-5} m/s were

associated primarily with the stoss slope and the compacted steep face of the dune; most of the seven intermediate values of *k*= $(12.7\text{-}25.5)10^{-12}$ m^2 or *K*=$(12.4\text{-}24.9)\ 10^{-5}$ m/s were associated with alluvial fans.

For modern unvegetated dunes, the permeability followed qualitative expectations of being greatest for grainflow and grainfall regions, and smaller for stoss slope ripple strata. For vegetated dunes, there were two sets of permeability found that differed by an order of magnitude; these were located at different identifiable locations and may be related to the form of the dune while it was investigated. The implication is that the lee slope grain flow deposits correspond to the high permeability cases, and the stoss slope ripples correspond to the lower permeability. Permeability and hydraulic conductivity values obtained were consistent with a few earlier hydraulic conductivity measurements by Sweeney (1999). The later were performed using steady-state water injection in unsaturated zone. More direct investigations of hydraulic conductivity were unavailable due to inaccessibility of wells.

The permeability of the vegetated dunes is strongly influenced by the existence of vegetation and herbivores. For example, the intermediate to low permeability values on the steep face appear to be the result of compaction of soil in the process of formation of climbing cow trails (catwalks). Low spots on the dune surface are seasonally covered with lose sand ejected from ground squirrel burrows; this fluffy material seems to have a higher permeability than the surroundings.

Sand features due to erosion, transport, and deposition by running water showed systematic variations in permeability according to features. Clay bands (lamellae) decrease the permeability locally and cause it to be anisotropic and moisture dependent. This was verified by coring a sand location where the permeability was unreasonably low, and finding lamellae at the depth where the permeability was unmeasurable.

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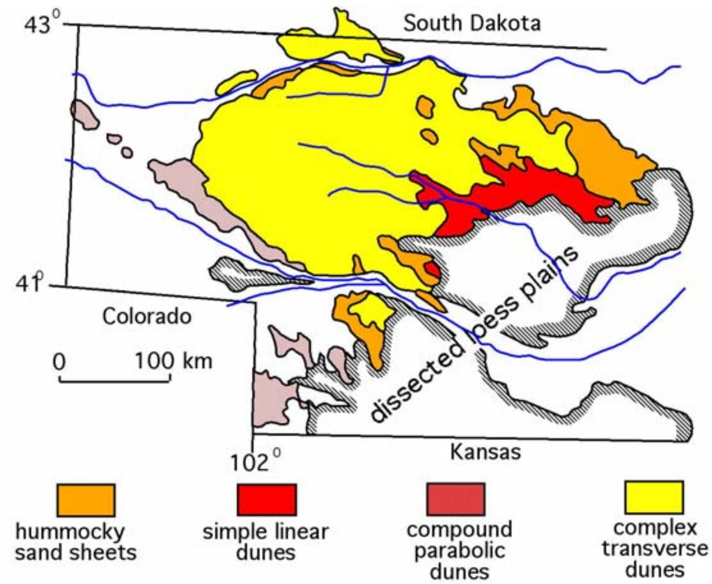
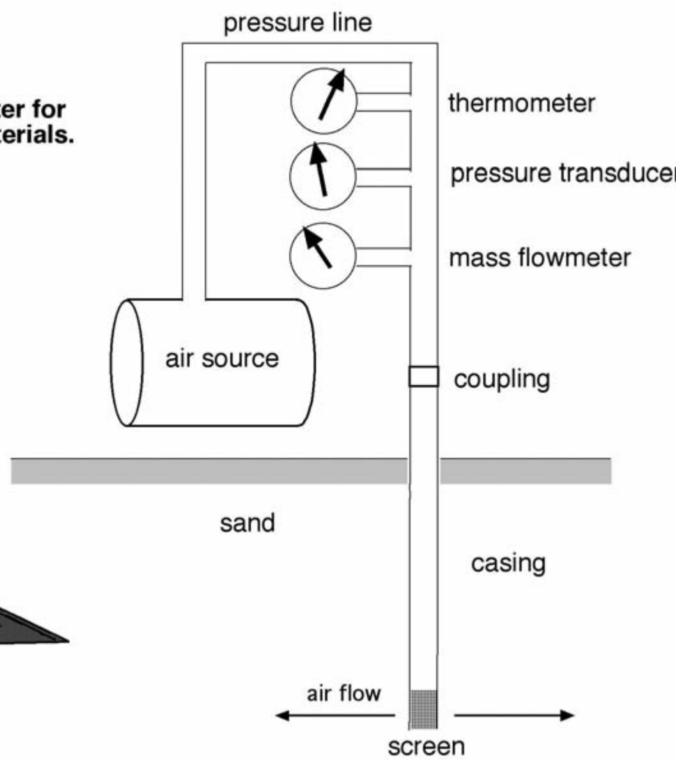


Figure 1. Distribution of wind-blown sediment and dune types in the Nebraska Sand Hills.

Figure 2. Air permeameter for use in sandyaquifer materials.



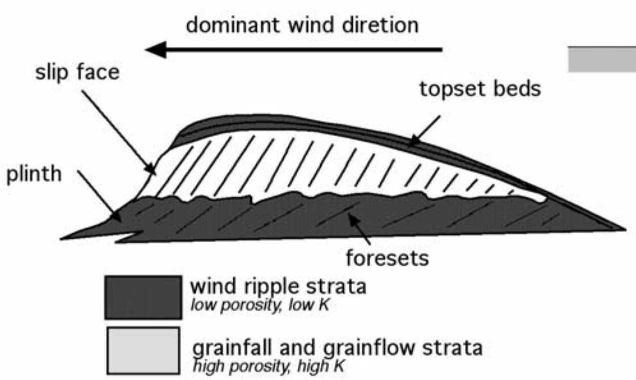


Figure 3. Cross-section of wind-blown sand dune showing distribution of different stratification types