Long-term monitoring of unsaturated-zone properties to estimate recharge at the Bemidji crude-oil spill site

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ABSTRACT

Ground-water recharge is an important factor affecting the Bemidji, Minnesota crude-oil spill site. About 400,000 liters of crude oil remained in the ground after remediation was completed following the 1979 pipeline break. An automated data logging system was used to measure unsaturated zone properties relevant to estimating recharge and to evaluate their effects on dissolution of the oil. Laboratory and field testing of several soil-moisture probes indicated that the CS615 probe was better suited to estimating recharge in the glacial outwash at the Bemidji crude-oil spill site than the CS605 probes. Both probes are manufactured by Campbell Scientific Inc. The CS615 probe provided dependable and accurate data over long time periods, using a limited power supply, under the extreme weather conditions typical of northern Minnesota. Based on results of the testing, arrays of the CS615 probes, zero-maintenance tensiometers, and thermocouples were installed in the unsaturated zone at the north oil pool in the fall of 1998. Computer simulations indicated that the rate of dissolution from the oil body is linearly related to the recharge rate. Additional multiphase flow model analyses are being conducted to quantify this increased dissolution. Additional model analyses are also being conducted to evaluate how dissolution is affected by recharge that varies in relation to the presence of crude oil in the unsaturated and saturated zones, discontinuous lenses of lacustrine silt and clay, and topography. The VS2DT code is also being used to estimate recharge rates and to evaluate the movement of water through the oil.

INTRODUCTION

Ground-water recharge is an important factor affecting the Bemidji, Minnesota crude-oil spill site. Although most recharge occurs as a result of spring snowmelt, its spatial and temporal variability at the site is complex and poorly understood. Recharge varies spatially in relation to the presence of crude oil in the unsaturated and saturated zones, discontinuous lenses of lacustrine silt and clay, and topography. Little is known of how ground-water recharge (in relation to these factors) affects the dissolution, transport, and degradation of oil at the site. Preliminary model analyses have indicated that ground-water recharge is a critical factor affecting the transport and dissolution rates of oil at the site.

This paper presents preliminary results of an investigation to better understand the effects of recharge on the dissolution and movement of oil through the unsaturated and saturated zones at the Bemidji, Minnesota crude-oil spill site. Included are selected results of measurements being used to monitor water movement through the unsaturated zone and to quantify ground-water recharge. Recharge estimates based on unsaturated-zone measurements are compared to estimates based on hydrograph analysis.

Site Description

On August 20, 1979, approximately 16 kilometers northwest of Bemidji, Minnesota, the land surface and shallow subsurface were contaminated when a crude-oil pipeline burst, spilling about 1,700,000 L (liters) (about 10,700 barrels) of crude oil onto a glacial outwash deposit. Crude oil also sprayed to the southwest covering an approximately 7,500 m^2 (square meter) area of land. After cleanup efforts were completed about 400,000 L (about 2,500 barrels) of crude oil remained at the site. Some crude oil percolated through the unsaturated zone to the water table near the rupture site (north oil pool, fig. 1). Some of the sprayed oil flowed over the land surface toward a small wetland forming a second area of oil infiltration (south oil pool).

Ground water affected by the oil spill discharges to a small lake 400-m east of the pipeline. The land surface is a glacial outwash plain underlain by stratified glacial outwash deposits. Sediments at the test site consist of poorly sorted glacial outwash sand of fine to very coarse grain size, with some fine gravel and cobbles. One- to 10-mm (millimeter) thick iron-cemented laminations occur between depths of 0.3 and 1.0 m. At a depth of about 25 m, a regionally persistent and uniform layer of low permeability sediment (till) restricts vertical ground-water movement. Crude oil (about 0.4-0.5- m thick) floats on the water table, which is about 2.7 m below land surface at the south oil pool. The water table is about 6 m below the land surface at the north oil pool.

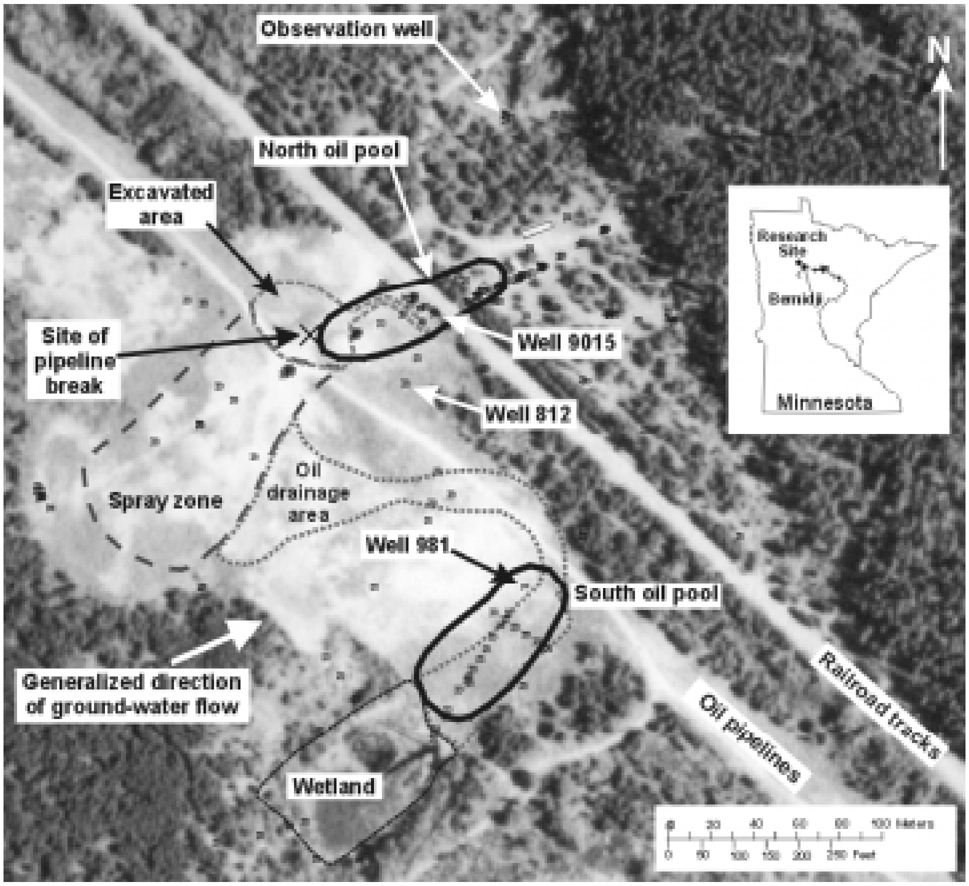

Figure 1. Features of the Bemidji crude-oil spill research site superimposed on a 1991 aerial photograph.

Methods

An automated data logging system was installed near Well 981 (south oil pool) in late 1996 primarily to compare the performance of several different soil-moisture probes manufactured by Campbell Scientific Inc.[1] Three different soil-moisture probes were compared to determine which was the most appropriate for evaluating recharge at the north oil pool, which is the primary area of research interest. Other data collected at the site included soil temperature (at ½ -meter depth intervals), ground-water level, and precipitation. The soil moisture and other data were collected 6 times per day from late 1996 to present. Solar-charged batteries initially powered the CR10X data logger and time-domain reflectometry (TDR) system. The batteries were replaced in the fall of 1997 with 110-volt AC power.

Three types of Campbell Scientific soil-moisture probes were compared at the Well 981 site (fig. 2). The CS615 probes were 30-cm (centimeter) long and had 2 prongs. The CS615 is a self-contained “reflectometer” that does not require a TDR cable tester to determine water content. This probe was compared to two CS605 three-prong TDR probes (30-cm long and 50-cm long) that require a cable tester. An array of 4 probes of each type was installed horizontally at ½ -meter depth intervals in the wall of a 2-

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[1] The use of brand names herein is for identification purposes only and does not constitute endorsement by the U.S. Government.

meter-deep pit. A fourth array of vertically oriented CS605 30-cm long probes was also installed at ½-m depth intervals in small-diameter boreholes to evaluate how probe orientation affected soil-moisture measurements.

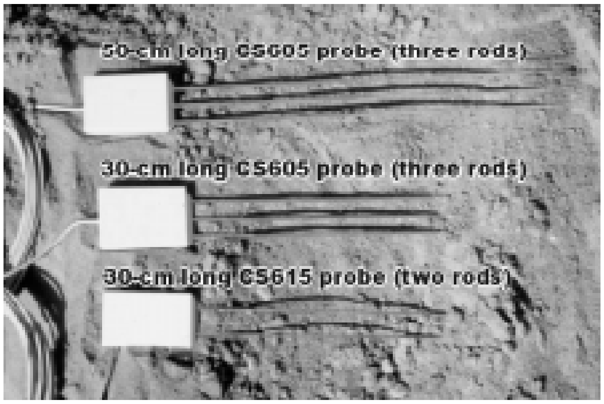

Figure 2. Campbell Scientific soil moisture probes used at the Bemidji crude-oil spill site.

Using the methods described in Herkelrath and others (1991), the three types of soil-moisture probes were calibrated in the laboratory using repacked columns of sandy sediments obtained from the field site. The columns were saturated from the bottom through a tube. Relative permittivity of the sediments was determined for the saturated sample using each soil-moisture probe. The column mass was determined by weighing. Water was removed incrementally through the bottom of the column by suction with permittivity and mass being measured for each increment. Total water content corresponding to each measurement was calculated from the difference between the measured column mass and the oven-dry mass. Volumetric water contents were determined by the ratio of total water content to soil volume.

Ground-water recharge estimated using the soil-moisture data near Well 981 was based on a rudimentary water balance. The primary assumption is that water in the soil above a certain depth (boundary) in the unsaturated zone moves upward in response to evapotranspiration and water below that boundary drains to the water table. Seasonal movement of the evapotranspiration/drainage boundary is typically measured directly using soil-water tensiometers. Several tensiometers were installed at the site, but the instruments failed, and the measured data could not be reliably used. Therefore, the depth of the boundary was assumed to be 50 cm during the summer months based on previous research (unpublished data). These recharge estimates were compared to estimates based on the method of hydrograph analysis (Rasmussen and Andreason, 1959). The hydrograph analysis method is based on relating changes in water-table elevation measured in a well with changes in the amount of water stored in the aquifer. The change in storage is attributed to ground-water recharge. Recharge is equivalent to the water table rise over a given time period multiplied by the aquifer specific yield of 0.3.

RESULTS AND DISCUSSION

Results of laboratory tests indicated that the moisture content calculated using the factory-supplied calibration for the CS615 probe was accurate to within about +/- 0.02 cc/cc (cubic centimeters per cubic centimeter) of the actual value over the whole moisture content range (fig. 3). This error was deemed acceptable and the field data were not adjusted. The moisture content values calculated using the factory-supplied calibration for the CS605 probes were generally higher than the actual moisture content. Therefore, the field data were shifted downward 0.07 and 0.02 cc/cc, respectively, for the 30-cm-long and 50-cm-long CS605 probes.

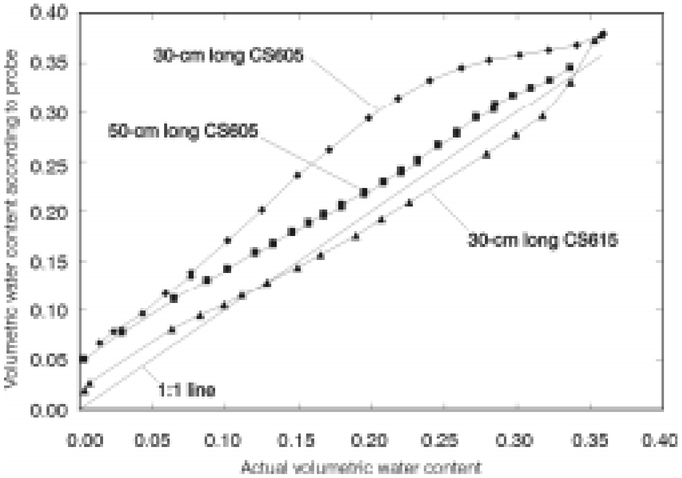

Figure 3. Calibration results for the Campbell Scientific soil moisture probes used at the Bemidji crude-oil spill site.

Temperature Measurements

Analysis of the temporal variation in soil temperature was both qualitatively and quantitatively useful in estimating the timing, depth, and duration of recharge events. The typical profile of soil temperature with depth is observed in figure 4 where the normal summer pattern of decreasing temperature with depth becomes inverted during October, followed by increasing temperatures with depth during the winter months. The thermocouples detected wetting front movement following precipitation events that exceeded about 2 cm, most noticeably the event during early July 1997 (fig. 4). Soil temperatures generally decreased following each of these precipitation events, with slightly smaller decreases at greater depths. The shifting low temperature with depth following the July precipitation (recharge) event is evidence of movement of the recharge water through the unsaturated zone. This shift in temperature with depth and time is not noticeable for precipitation events that did not result in ground-water recharge, such as the one on August 19th. In addition to the late summer and fall time period represented in figure 4, the temperature data also proved very useful in determining the timing of recharge from spring snowmelt.

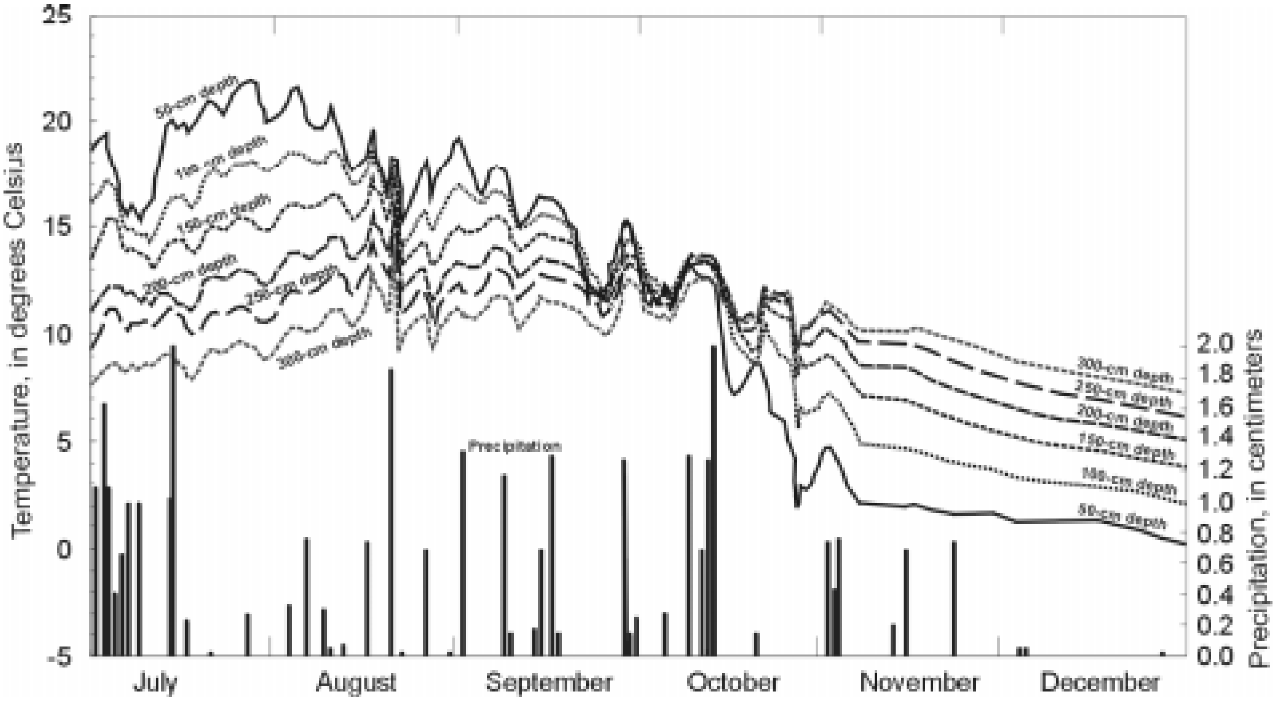

Figure 4. Soil temperature and precipitation near Well 981, July – December 1997.

Comparison Of Soil-Moisture Probes

Each type of soil-moisture probe simultaneously detected wetting front movement at the 150-cm depth following precipitation events (fig. 5). The greatest difference in measured soil moisture between the probes occurred during precipitation events when the magnitude of the soil-moisture changes for the vertically oriented CS605s were much greater than that for the other probes. This phenomonon was observed at both the 100- and 150-cm depths. The vertical probe orientation caused the wetting fronts to be detected for a much longer period of time than for the horizontally oriented probes. The resultant apparent soil moisture during these recharge periods was necessarily greater. The slightly greater soil moisture measured by the

CS615s than the horizontally oriented CS605s likely is due to localized differences in soils. Soil moisture measured with the 50-cm long CS605s did not fluctuate as much as for the 30-cm long CS605s. This may be an indication that a longer probe provides a more stable response to changes in soil moisture.

Soil-moisture values measured with the CS615s were much more stable and “clean” (less data fluctuation and data loss) than those measured with the CS605s, which were comparatively “noisy” (figs. 5 and 6). Data loss for the CS615s was less than 1 percent, with virtually all losses being unrelated to the probe itself. In contrast, data loss for the CS605s was notable with each of the CS605 probes having lost at least 5 percent of the data during each year of operation. During the first 6 months of 1997, for example, data loss for the CS605s was as follows: 12 percent for the 30-cm long (horizontally oriented) probes; 15 percent for the 30-cm long (vertically oriented) probes; and 22 percent for the 50-cm long (horizontally oriented) probes. During the same time period in 1998 these data losses were about two times greater, indicating a progressive increase of data loss in time.

Data collected with all three of the CS605s at the 300-cm depth were very sparse, with data losses of greater than 80 percent per probe. A comparison of figures 5 and 6, which have the same vertical scales, provides a good indication of the “noise” in the CS605 probes at this depth. Each of the probes at this depth was located below the water table and thus the soil moisture should not have changed significantly over time. Some of the data loss for the CS605s likely resulted from variations in power supply voltage and line noise that caused out-of-range (positive and negative) values. Loss of data with the CS605s critically affects recharge estimates resulting in inaccurate or missing recharge estimates.

During the time when the monitoring system was initially powered by solar-charged batteries, data loss for the CS605s increased during the winter months when air temperatures were below -10°C. This increased data loss was likely due to insufficient solar radiation during the winter to charge the batteries to power the cable

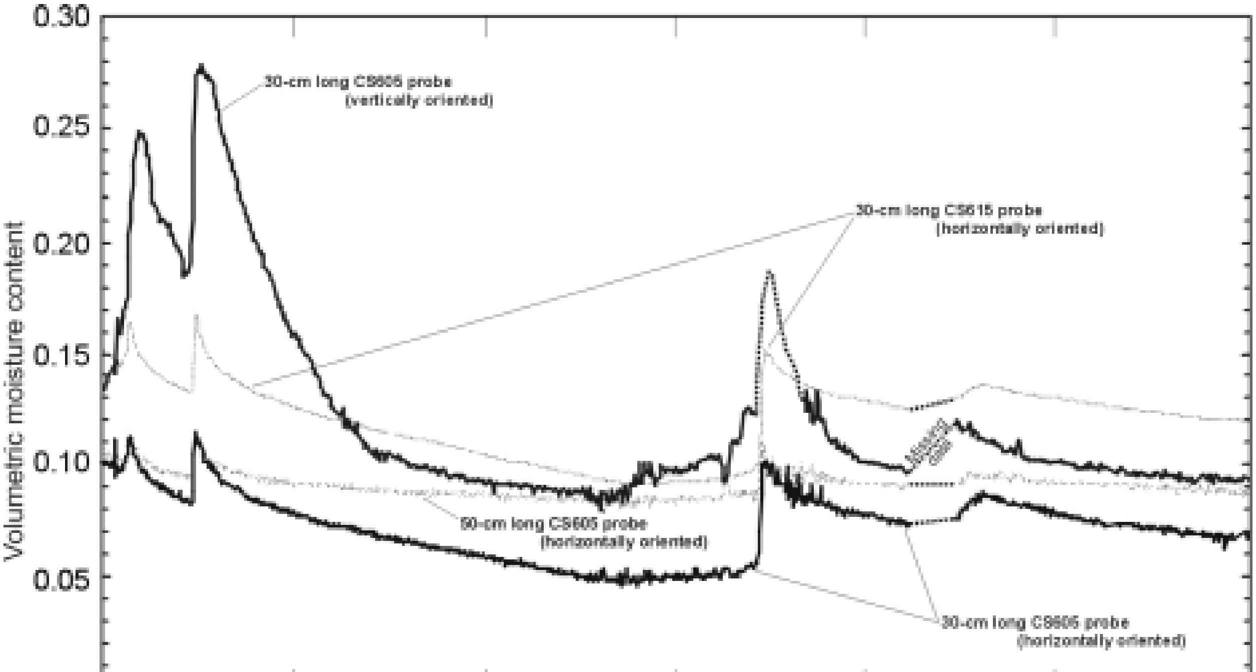

Figure 5. Soil moisture at the 150-cm depth near Well 981 measured with the different probes, July – December 1997.

tester. Conversely, the CS615 probes had sufficient power to make their measurements during the winter months.

The two-pronged CS615 probe was easier to install than the three-pronged CS605 probe, largely because of increased friction and the enhanced likelihood of hitting gravel with the third prong. However, greater care was required during installation of the CS615s to ensure that the internal circuitry was not damaged. The 50-cm long CS605s were most difficult to install because of their greater length, which increased friction and the likelihood of hitting gravel.

Recharge Estimates

Ground-water recharge was estimated using the soil moisture data and by the hydrograph analysis method for all events where precipitation exceeded about 2.0 cm. For the three precipitation events that occurred during the last six months of 1997 (fig. 7), for example, recharge based on data from the horizontally oriented 30-cm long CS615 and CS605 probes were similar. Small-scale soil heterogeneity rather than differences in the way soil moisture is measured by each probe likely cause the slightly different recharge estimates for these probes.

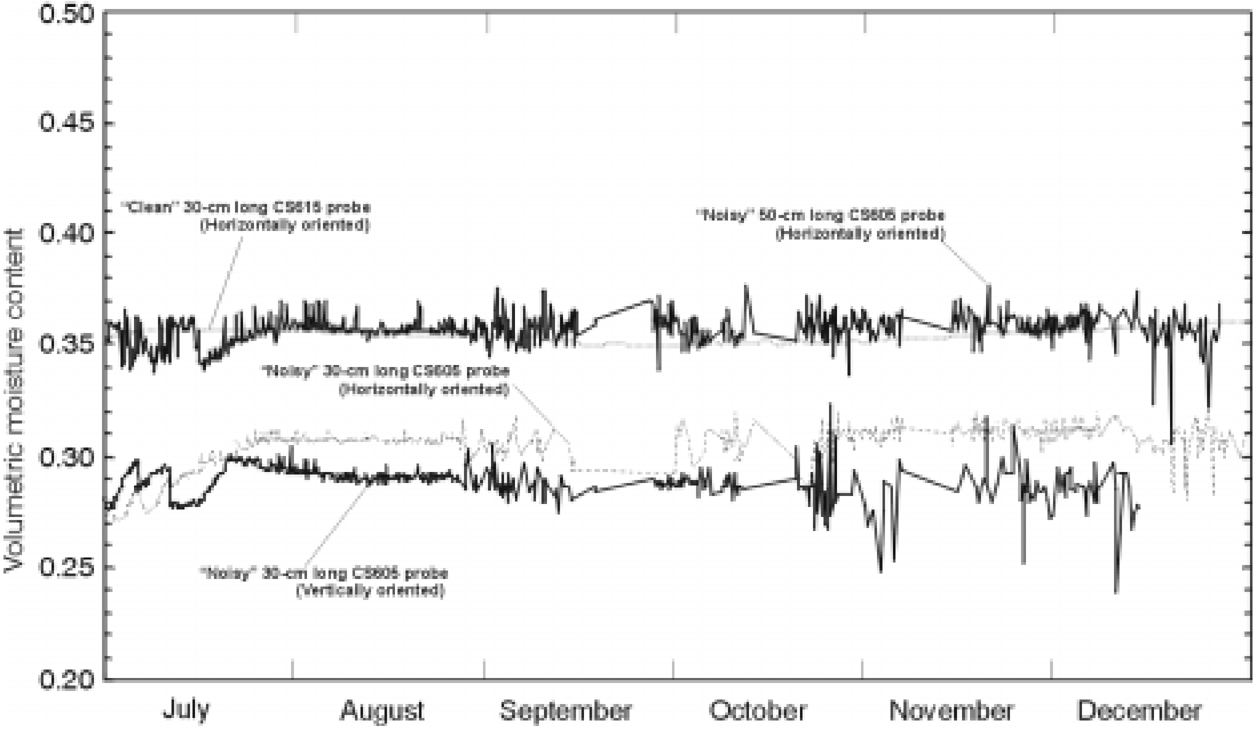

Figure 6. Soil moisture at the 300-cm depth near Well 981 measured with the different probes, July – December 1997.

Recharge based on the vertically oriented 30-cm long CS605 probes during the early July event was about 70 percent greater than for the other probes (fig. 7). This greater recharge for the vertically oriented probe was typical during the study. The vertical probe orientation caused the wetting fronts to be detected for a much longer period of time than for the horizontally oriented probes, which generally resulted in a higher estimated recharge rate. This was not always the case, however, as evidenced by the less than average recharge estimate for the vertically oriented probes during the mid October 1997 event (fig. 7). These inconsistent results are further evidence that the vertical probe orientation is not appropriate for recharge estimation at this site.

The method of hydrograph analysis was applied to the three recharge events that occurred during the second half of 1997. Because the two July precipitation events occurred only about two weeks apart (fig. 5) the effects of both events were superimposed in the ground-water hydrograph response (figs. 7 and 8). Thus, only one recharge estimate is presented for the two July events. The well used for hydrograph analysis at the 981 site was installed in August 1997. Thus, data from a nearby datalogger at Well 812 were used for estimating recharge during the July recharge event (fig. 8). Use of water-level data from the two different wells shown in figure 8 may have introduced some error when comparing the recharge estimates for this time period.

Recharge estimates based on hydrograph analysis were generally 20-40 percent less than estimates based on the soil-moisture probes for events in 1997 and 1998. For example, total recharge based on hydrograph analysis for the three 1997 events shown in figure 7 was 11 cm or about 30 percent less than estimates based on the horizontally oriented probes. The several limiting assumptions behind both of the recharge estimation methods are the most likely causes for the differing estimates. Application of other methods such as tritium/helium (Solomon and others, 1993) is being employed at the site to obtain a more accurate recharge estimate.

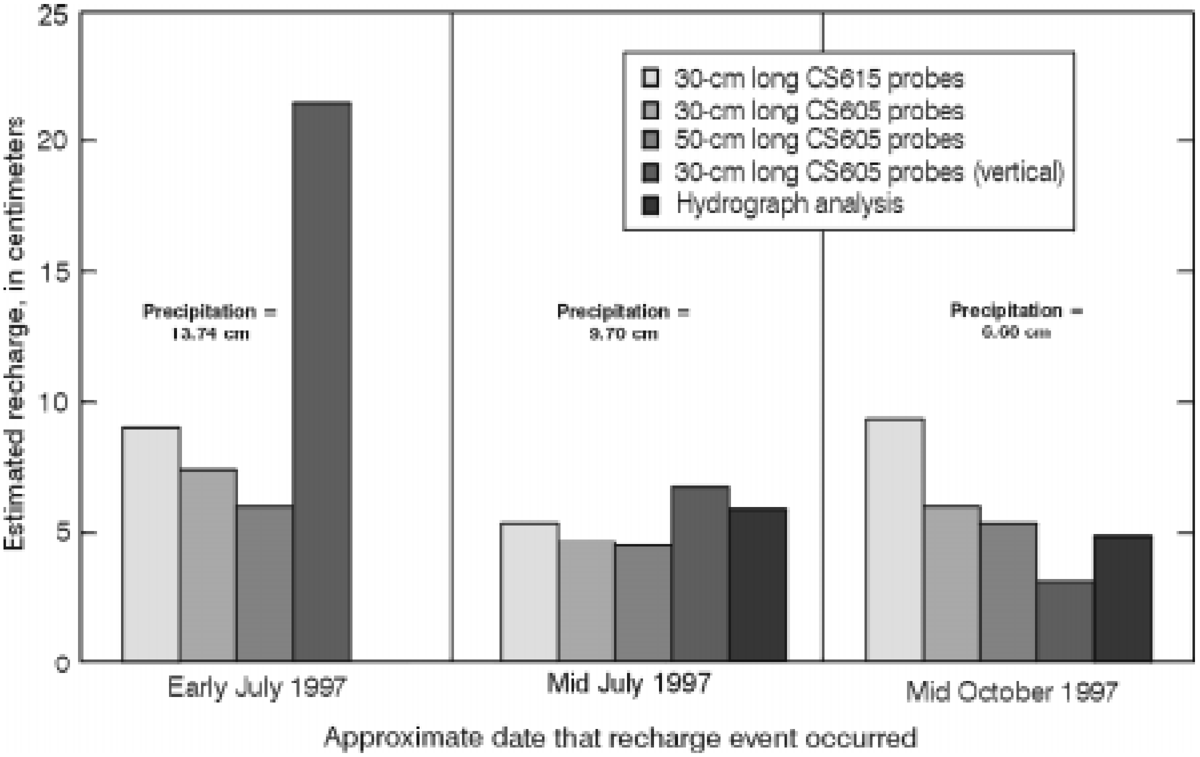

Figure 7. Recharge estimates based on the different probes near Well 981 compared to estimates based on hydrograph analysis, July – December 1997.

Model Analyses

Computer simulations indicate that the rate of dissolution from an oil body is linearly related to the recharge rate. Water permeabilities estimated from a multiphase flow model (Essaid and others, 1995) were used in MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) and MODPATH (Pollock, 1994) simulations to evaluate steady state water movement through the oil body. When there is no recharge, most of the ground water flows around the oil body and does not come in contact with the oil. However, recharge water flows downward through the oil body and increases the contact between ground water and the oil, increasing the rate of dissolution.

SUMMARY AND CONCLUSIONS

Ground-water recharge is an important factor affecting the Bemidji, Minnesota crude-oil spill site where about 400,000 liters of crude oil remained in the ground after remediation was completed following the 1979 pipeline break. An automated data logging system was used to measure unsaturated zone properties relevant to estimating recharge and evaluating their effects of the dissolution of oil. The performance of several different soil-moisture probes manufactured by Campbell Scientific Inc. was evaluated. Analysis of the temporal variation in soil temperature was both qualitatively and quantitatively useful in estimating the timing, depth, and duration of recharge events.

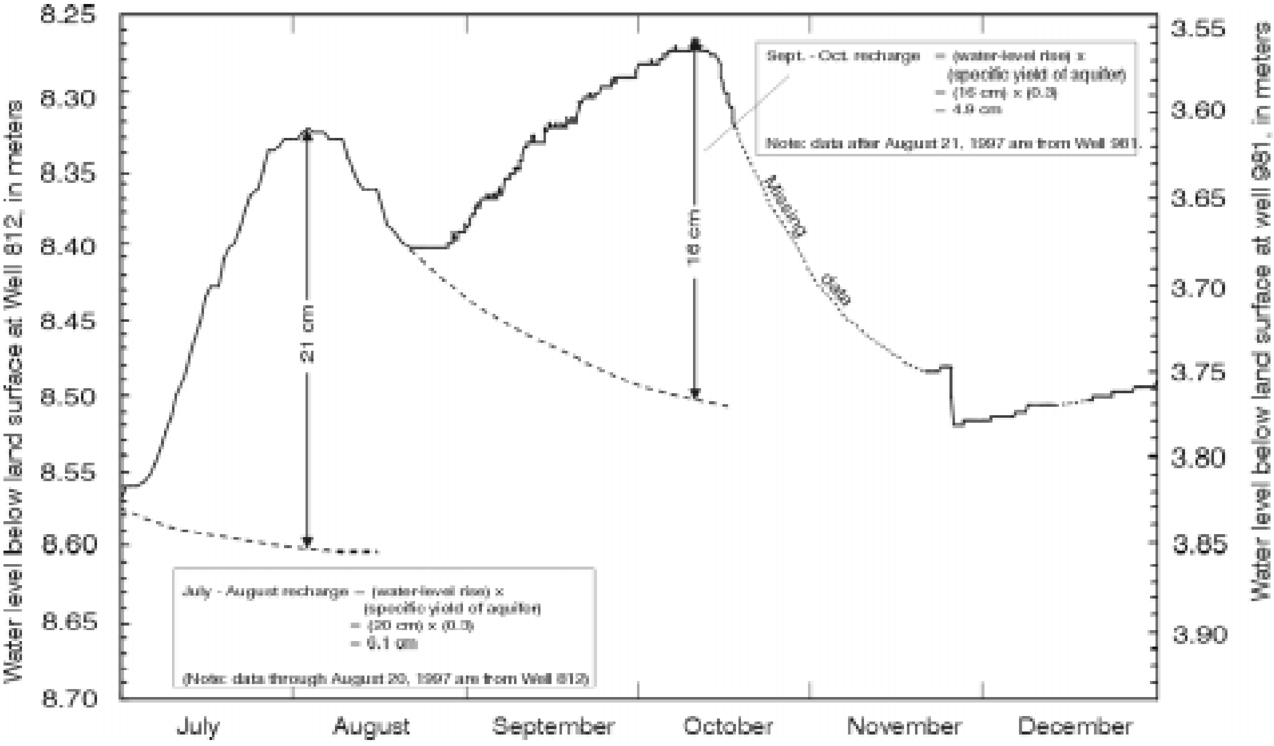

Figure 8. Water-level hydrograph and recharge calculations, July – December 1997.

Laboratory and field testing of the soil-moisture probes indicated that the Campbell Scientific CS615 probe was better suited to estimating recharge at the Bemidji crude-oil spill site than the CS605 probes, given the local soil and climatic conditions. Field testing indicated that the CS615 probes are better suited to the needs at the Bemidji site for the following reasons: (1) the CS615 probes provided a dependable and accurate means for long-term monitoring of soil moisture in the glacial outwash being studied; (2) the CS615 probe is somewhat easier to install in sandy soils than the standard CS605 probe; (3) data from the CS615 probes had less “noise” than data from the standard CS605 probes; and (4) the CS615 probe provided dependable and accurate data using limited power under the extreme weather conditions typical of northern Minnesota. The greater soil moisture measured by some of the vertically-oriented CS605 probes is somewhat surprising. Further laboratory or field research into this phenomenon may be warranted, the results of which would have transfer value to unsaturated-zone research using similar instrumentation.

Based on results of the preliminary testing, an array of CS615 soil-moisture probes, thermocouples, and zero-maintenance tensiometers were installed in the unsaturated zone near Well 9015 (north oil pool) in the fall of 1998. Seven CS615 probes and thermocouples were installed between the depths of 0.5 and 6.0 m. Four zero-maintenance tensiometers were installed between the depths of 1.0 and 2.5 m. The soil moisture and pressure data will be used to estimate ground-water recharge based on the zero flux plane method and to evaluate the effects of the dissolution of oil.

Computer simulations indicated that the rate of dissolution from the oil body is linearly related to the recharge rate. Additional multiphase flow model analyses are being conducted to quantify this increased dissolution. Additional multiphase flow model analyses are also being conducted to evaluate how dissolution is affected by recharge that varies in relation to the presence of crude oil in the unsaturated and saturated zones, discontinuous lenses of lacustrine silt and clay, and topography. The VS2DT code (Lappala and others, 1987; Healy, 1990) is also being used to estimate recharge rates and to evaluate the movement of water through the oil.

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