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Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management



U.S. DEPARTMENT OF
ENERGY

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Automated Water Level Measurements in Small-Diameter Aquifer Tubes (11476)

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ABSTRACT

Groundwater contaminated with hexavalent chromium, strontium-90, and uranium discharges into the Columbia River along approximately 16 km (10 mi) of the shoreline. Various treatment systems have and will continue to be implemented to eliminate the impact of Hanford Site contamination to the river. To optimize the various remediation strategies, it is important to understand interactions between groundwater and the surface water of the Columbia River. An automated system to record water levels in aquifer sampling tubes installed in the hyporheic zone was designed and tested to (1) gain a more complete understanding of groundwater/river water interactions based on gaining and losing conditions of the Columbia River, (2) record and interpret data for consistent and defensible groundwater/surface water conceptual models that may be used to better predict subsurface contaminant fate and transport, and (3) evaluate the hydrodynamic influence of extraction wells in an expanded pump-and-treat system to optimize the treatment system.

A system to measure water levels in small-diameter aquifer tubes was designed and tested in the laboratory and field. The system was configured to allow manual measurements to periodically calibrate the instrument and to permit aquifer tube sampling without removing the transducer tube. Manual measurements were collected with an e-tape designed and fabricated especially for this test.

Results indicate that the transducer system accurately records groundwater levels in aquifer tubes. These data are being used to refine the conceptual and numeric models to better understand interactions in the hyporheic zone of the Columbia River and the adjacent river water and groundwater, and changes in hydrochemistry relative to groundwater flux as river water recharges the aquifer and then drains back out in response to changes in the river level.

INTRODUCTION

Over 500 aquifer sampling tubes have been installed at the Hanford Site during the past 14 years. The aquifer tubes are small-diameter, polyethylene tubes located along the Columbia River shoreline that allow sampling of the unconfined aquifer. As many as three tubes are installed at a site, with screened sampling ports at various depths in the aquifer. These aquifer tubes are sampled annually to quarterly and analyzed for various potential contaminants.

The interactions between groundwater and the surface water of the Columbia River is complex, as the river level can rise and fall three to four meters on a daily and seasonal basis. One of the key aids in understanding the interactions between groundwater and river water is hydraulic gradient, which is determined through the use of water level data. Collection of this data is straightforward for monitoring wells, but the aquifer tubes installed in the hyporheic zone are constructed of small-diameter tubing, which precludes using traditional transducers to measure

water levels. No commercially available products that are able to work in this capacity have been identified.

The goal of this project was to develop and test a reliable method to electronically measure and record the static water level in aquifer tubes. This ability would aid in optimizing remedial actions (e.g., pump-and-treat systems) and lead to more accurate groundwater modeling and understanding of groundwater/river interactions.

The Miniature Aquifer Tube Transducer (MATT) system was conceived and designed specifically to be deployed in Hanford aquifer tubes. The system uses an above-ground pressure transducer attached to a small-diameter tube, the end of which is placed inside the aquifer tube and submerged beneath the water level. The transducer tube is filled with silicon fluid to minimize temperature effects and eliminate the possibility of freezing. The transducer is connected to an electronic logging system that records water levels at a programmed rate, and the data are retrieved via UHF radio to a central data repository for analysis. An initial proof of concept was performed under controlled conditions in a laboratory environment, and subsequent field tests were conducted to refine the system. The measurement system was designed to allow manual measurements for periodic calibration, and to maintain the ability to sample the aquifer tubes without disturbing the measurement apparatus. Manual measurements were collected with a miniature e-tape designed and fabricated especially for this test.

Purpose and Scope

The MATT project was conducted by the Remediation Science and Technology group in CH2MHILL Plateau Remediation Company's (CHPRC's) Soil and Groundwater Remediation Project, a prime contractor to the U.S. Department of Energy, Richland Operations Office. A need to measure water level in aquifer tubes was identified by groundwater project leads to aid in modeling efforts and help optimize expanded pump-and-treat systems in Hanford's 100 Area. Research indicated that no off-the-shelf products were available to accomplish this task, so CHPRC personnel developed the technology from concept to field testing in three phases: (1) design, (2) bench-top proof-of-concept testing, and (3) field pilot testing. The first phase included formulating a conceptual design, procuring equipment, and initial bench-top setup of the system. The bench test served both to prove that the MATT design would accomplish the goals of the project and to refine the design for field testing. The field testing was performed as a pilot test of the conceptual design developed during bench testing, and to verify the field applicability of the MATT system. The MATT was installed in three aquifer tubes in the 100-K Area along the Columbia River to monitor water level fluctuations during the summer and fall of 2010.

The specific short-term objective of this project was to develop a reliable system to electronically measure the water level changes in near-shore aquifer tubes. The aquifer tubes at the Hanford Site are constructed with 0.635 cm (0.25 in.) outer diameter polyethylene tubing, with an inner diameter of 0.43 cm (0.17 in.). The tube is connected to a 15 cm (6 in.) long, cylindrical steel screen that is installed at depths ranging from 0.9 m (3 ft) to 9 m (30 ft) below the ground surface.

The ultimate goal is to use data from the system to (1) gain a more complete understanding of groundwater/river water interactions based on gaining and losing conditions of the Columbia River, (2) record and interpret data for consistent and defensible groundwater/surface water conceptual models that may be used to better predict subsurface contaminant fate and transport, and (3) evaluate the hydrodynamic influence of extraction wells in an expanded pump-and-treat system to optimize remediation.

Concept and Design

The concept for this project was to design and implement a system that produces data of similar quality to the submersible pressure transducers used in conventional wells. The following factors were considered in the MATT conceptual model and configurations of the MATT systems were tested in the laboratory and field:

- Configure geometry to allow easy insertion of the sensor tube into existing aquifer tubes.
- Install at or near ground surface for ease and accuracy of servicing and calibration.
- Accurately measure water level changes through the range expected in an aquifer tube (up to 4 m [12 ft], equating to a pressure change of approximately 35 KPa [5 psi]).
- Evaluate the accuracy and reproducibility of water levels measured by the MATT system through periodic manual measurements, with an accuracy goal of less than 2.5 cm (1 in.).
- Ensure that routine water sampling activities can be easily performed through the sampling port with the sensor tubing installed in the aquifer tube, without affecting the calibration of the pressure transducer.
- Determine a calibration factor to convert transducer signals to water table elevations.
- Confirm that the pressure transducer is detecting only pressures associated with water level elevation while compensating for barometric pressure.
- Use electrical components compatible with existing Hanford Site water level instrumentation.
- Demonstrate robustness and reliability of the MATT system when exposed to Hanford environmental conditions, meteorological forces, and ecological/wildlife impacts.
- Ensure that the MATT readings return to baseline conditions following removal and re-installation during water level verification measurement activities.
- Strive for cost effectiveness by using off-the-shelf parts that have been fully tested and have well-defined operating parameters.

MINI AQUIFER TUBE TRANSDUCER TESTING

The MATT system was tested in the laboratory and the field. Objectives for the laboratory tests were to prove the viability of the conceptual design and to refine the system design for field

testing. The main objective of the field tests was to determine the accuracy and precision of monitoring water level changes in aquifer tubes under real conditions.

The heart of the MATT system is the transducer, which is a configurable gauge-type pressure transducer obtained from Honeywell Sensotech Division, Model FP2000. These units are designed with a submersible sensor tip on one end and an electrical cable that includes a dry vented line on the opposite end. The vented line is used to detect atmospheric pressure and compensate for the effects of changing barometric pressure on the water table.

Each transducer is connected to a fluoropolymer (FPA) sensor tube with an outside diameter of 0.32 cm (0.125 in.) and an inside diameter of 0.16 cm (0.063 in.). One end of this tubing is attached to the pressure transducer sensor tip using a threaded/compression adapter fitting. The other open end of the FPA tubing is inserted into the aquifer tube and positioned to be approximately 2.5 cm (1 in.) above the hose barb at the top of the aquifer tube screen. The small diameter of the sensor tube leaves an open cross-sectional area of 0.15 cm^2 (0.023 in.^2) in the aquifer tube, which is approximately 45 percent of the original area of the tube and large enough to allow groundwater samples to be collected without the need to disturb the transducer system.

Changing water levels in the aquifer tube are reflected as pressure changes in the MATT sensor tube. These pressure changes are registered by the transducer diaphragm, which is attached to a piezoelectric sensor that emits an electrical signal transmitted to the data logger. The signal is translated to a groundwater elevation value using calibration data from the vendor and laboratory testing.

Laboratory Testing

The MATT system was configured and tested in the laboratory to evaluate its ability to record accurate and reproducible groundwater level measurements and identify any factors that may influence results. The purpose of these laboratory tests was to refine the design of this system to the point where it could be demonstrated in the field.

For the laboratory tests, the sensor tubing was submerged in a simulated aquifer tube positioned in a transparent vertical pipe containing water. Water was added or removed from the pipe to mimic groundwater changes and evaluate transducer response. The temperature of ambient air and simulated groundwater was manipulated to simulate changing environmental conditions and evaluate any effects on the MATT system.

The following is a list of the objectives of the bench-scale tests:

- Design a simulated, saturated, semi-confined aquifer and aquifer tube system to visually observe and quantify water level changes and aquifer tube response in a controlled environment.
- Design a system to allow groundwater sampling through the aquifer tube without disturbing the MATT system.
- Quantify response and accuracy of the MATT system to changes in simulated water levels.
- Evaluate the effects of temperature changes on the system.

- Ensure that the pressure transducer is detecting only applied pressures while compensating for barometric pressure.
- Provide quality assurance of the feasibility and reliability of a conceptual design for the MATT and PPET system.
- Verify that water samples can be easily collected from aquifer tubes while the MATT system is in place.
- Determine how routine sample collection activities affect zeroing and calibration of the pressure transducer.
- Identify any unanticipated influences on MATT readings.

Sensor Tube Fluid Testing

Early in the laboratory tests, it was noted that water level signals from the MATT system varied significantly with ambient air temperature (Fig. 1[a]). The cause of this was determined to be due to volumetric changes in the air-filled sensor tubes. Subsequent to this realization, tests were performed with deionized water, propylene glycol solution, and silicone oil to determine the medium with the most accurate and reliable response to water level changes, while displaying the lowest sensitivity to changes in air temperature on the MATT system.

In the tests using water and propylene glycol, the MATT signals also were found to vary with temperature. Observation of the tubes over several days revealed formation of bubbles due to exsolution of gasses from the fluid. Three different viscosities of silicone oil were then tested; these were seen to be relatively unaffected by temperature changes (Fig. 1[b]). Silicone oil with a viscosity of 3 centistokes (cSt) was chosen as the preferred fluid for field testing.

Hydraulic Head (Water Level) Sensitivity Results

The water level in the graduated water column was manually adjusted at various points in the testing by removing and adding water using a peristaltic pump. The water levels were measured using graduated markings on the water column and the conventional transducer submersed in the water column. During each head sensitivity test, air temperature was kept as stable as possible (<2.5° C [5° F) change).

The hydraulic head sensitivity test results show that all three MATT systems had an average sensitivity of 0.17 mV/cm (0.43 mV/in.) of water under constant temperature. This relationship holds regardless of the fluid filling the sensor tubes.

Determination of MATT Precision

The results of bench tests show that the transducer response to water level changes is independent of the fluid contained in the sensor tube. As noted above, the greatest factor affecting accuracy and precision is ambient temperature and its influence on the sensor tube fluid.

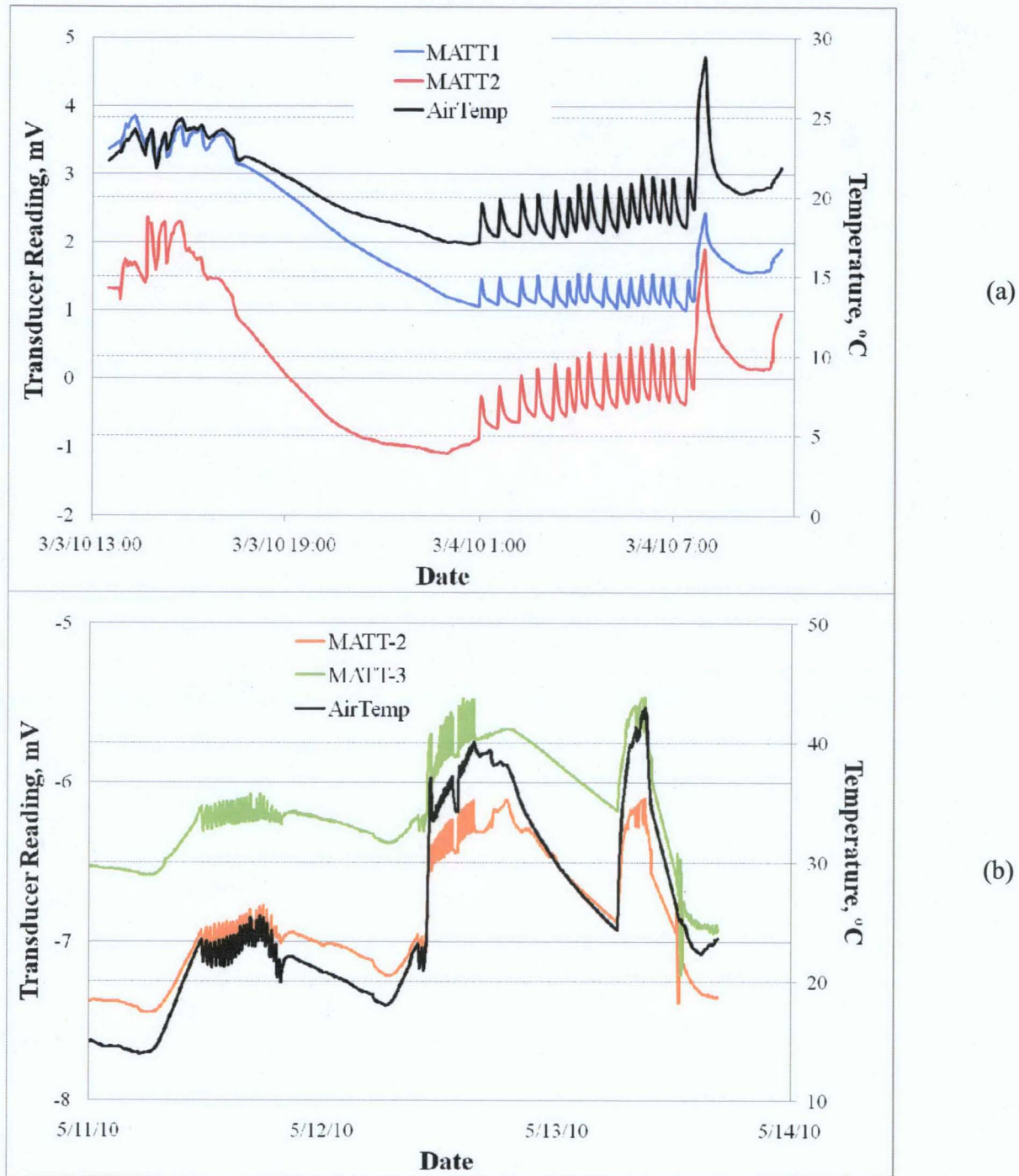


Fig. 1. Graph of data from MATT units filled with (a) air, and (b) 3 cSt silicone oil

Under the controlled water column experiments the MATT data is convincingly reproducible, with standard deviations from the water level tests less than 6.5 percent of the transducer signal. That indicates that deviation of the signal under controlled temperature is <1 mm (<0.1 in.).

Measuring Water Level in Aquifer Tubes

To verify water level elevations and calibrate the MATT units in the field, the ability to measure true static water levels is required. Conventional electronic water level meters (e-tapes) are too large to fit inside aquifer tubes, so a miniature e-tape was designed and fabricated to perform these measurements.

The miniature e-tape consists of small-diameter tubing containing two insulated conductors and a terminal electrode assembly (probe). The probe contains two electrodes that are insulated from each other and separated by an air gap. The tubing is connected to the electronics module of a commercially available electronic water level meter, electronics module, and reel. To use the e-tape, the probe is pushed into the aquifer tube until the electrodes contact the water surface. This allows electrical current to flow between the electrodes, which generate an audible and visual signal to alert the user that water has been encountered.

The miniature e-tape was tested and refined in the simulated aquifer tube/water column apparatus used for testing the MATT units.

Statistical Interpretation

Multiple regression, ANOVA, and deconvolution techniques were used to analyze data collected during tests with silicone oil. This investigation found that only air temperature is highly correlated to the MATT signal response, with an R^2 value of 0.936. The R^2 value for signal response to tank temperature, which is an attenuated response to air temperature, was 0.29. The R^2 value for signal response to barometric pressure was 0.0004, signifying no correlation. Correlation between the MATT signal response and water level in the simulated water column, which was held constant during the test, was also very low, with an R^2 of 0.04.

Results of this work indicate that applying temperature corrections to the signal response data yields reproducible water level results to about 0.3 cm (0.12 in.). The regression formulae for air temperature effect on signal response are presented in Equations 1 and 2.

$$\text{MATT2_corrected} = \text{MATT2(ft)} - 0.00533943 * (\text{AirTemp} - \text{AirTempi}) - 0.00152617 * (\text{TankTemp} - \text{TankTempi}) \quad (1)$$

$$\text{MATT3_corrected} = \text{MATT3(ft)} - 0.0042445 * (\text{AirTemp} - \text{AirTempi}) - 0.000456441 * (\text{TankTemp} - \text{TankTempi}) \quad (2)$$

Where:

AirTempi = initial air temperature

TankTempi = initial tank temperature.

Summary of Bench-Scale Tests

Bench-scale tests were conducted to evaluate the feasibility of testing and deploying MATT systems in aquifer tubes along the Columbia River shoreline, and refining the configuration and procedures for installing and operating the system. The greatest challenge was to minimize the

effects of ambient temperature changes to signal response to obtain accurate and precise measurement of water table depths as measured in aquifer tubes.

The initial tests were performed with air in the sensor tube and transducer sensor tip. Signal response varied up to 3.4 mV at constant head over an 11.8° C temperature range (0.29 mV/° C). This equates to an apparent change of 20 cm (8.0 in.) in water level, or 1.7 cm/° C (0.38 in./° F). These large deviations would not be acceptable for field measurements, where existing conventional transducers have a conservatively reproducible accuracy of 1.85 cm (0.65 in.).

Test phases 2 and 3 were performed with water and propylene glycol filling the transducer tubes and tips. Little response to temperature was observed during these tests until the second or third day, at which point gas began to exsolve from the liquids forming gas bubbles in the sensor tube (and likely also in the transducer sensor tip). Signal response varied up to 16.8 mV for water and 14.5 mV for propylene glycol, with the latter exhibiting less variation over the range of temperatures (0.73 mV/° C for water and 0.33 mV/° C for propylene glycol).

Test phase 4 was performed with three viscosities of silicone oil, which effectively mitigated gas exsolution and resulted in signal response variations to temperature that were low and predictable. The least-viscous oil (3 cSt) was determined to have the lowest change in signal response to temperature, with an average of 0.064 mV/° C. This equates to a calculated water level change with temperature of 0.38 cm/° C (0.082 in./° F).

The most important conclusions from the bench-scale test results are as follows:

- The MATT system displays a signal response to air temperature changes.
- MATT signal response variations are influenced by the physical characteristics (i.e., thermal expansion coefficients) of the fluid used to fill the transducer sensor tube.
- Sensor tubes filled with 3 cSt silicone oil produce the lowest signal response to air temperature changes
- Under isothermal conditions the MATT system registers accurate and reproducible water level measurements
- Sensor tube length does not noticeably influence the pattern or range of signal variations with air temperature changes.
- Water samples may be easily collected from the sampling tube with the transducer sensor tube remaining in place.

Careful removal and re-installation of the MATT sensor tube in the aquifer tube during manual water level measurement activities does not affect the baseline calibration of the transducer.

Field Test

The field test was conducted in aquifer tubes installed along the Columbia River shoreline in the 100-K Area (Fig. 2). The MATT systems were deployed in three adjacent aquifer tubes, which are completed at different depths. This location was chosen to assist modeling the capture



Fig. 2. Location of miniature aquifer tube transducer field test

effectiveness of pump-and-treat systems in this area by monitoring near-river groundwater levels before and after expanded systems begin operation in late calendar year 2010. The location is approximately 175 m (574 ft) upstream of an automated water level monitoring network station that measures elevation of the Columbia River.

Field Installation

The MATT installation consists of three plastic electrical junction boxes and a tripod-mounted programmable data logger, radio transceiver, radio antenna, and solar panel (Fig. 2, inset). The junction boxes contain the MATT pressure transducers, thermocouples for measuring temperature, and connections to the aquifer tubes. Polyvinyl chloride (PVC) conduit and pipe encloses and protects the transducer and thermocouple cables and the aquifer tubes.

The MATT boxes are insulated with rigid foil-faced polyisocyanurate foam board to help moderate temperature fluctuations that may affect transducer readings. The boxes are attached to horizontal steel reinforcing rods (rebar), which are secured using stainless steel wire to vertical rebar driven into the ground. This attachment system assures the boxes will remain in place when the river rises.

The MATT enclosures were placed so the aquifer tubes emerged from the ground directly into the bottom of the boxes (Fig. 3). To form an airtight connection between the aquifer tube and the transducer sensor tube, a push-to-connect type 0.635 cm (0.25 in.) tee fitting and 0.318 x 0.635 cm (0.125 x 0.25 in.) Chemfluor® adapter fitting is used, which also allows collection of water samples without removal of the MATT sensor tube. The adapter fitting is positioned on the MATT sensor tube so that the end of the tube is 2.5 cm (1 in.) above the end of the hose barb on the aquifer tube screen implant.

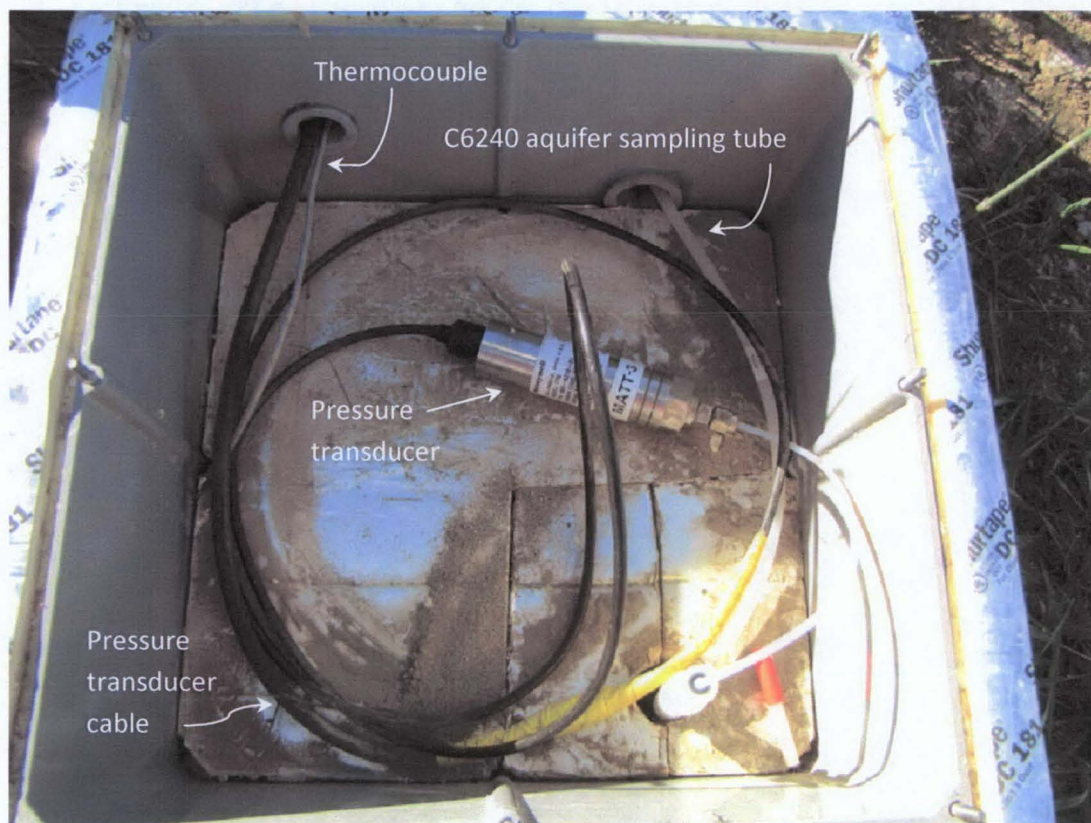


Figure 3. MATT Components Inside Containment Box.

The PVC electrical nonmetallic tubing (ENT) and pipe connected to the MATT boxes encase the transducer cable, thermocouple cable and the aquifer tube water sample extension. The ENT is connected to the data logger enclosure. The PVC pipe extends upslope a few feet beyond the tripod. Both ENT and PVC pipe are secured to rebar stakes with stainless steel wire.

The data logger was programmed to collect data at 15-min intervals from all three MATT transducers and thermocouples, and ambient air temperature. Water level was manually measured every one to two weeks; inspection of all components of the MATT system was also performed at this time. All pertinent activities and data were recorded on Field Activity Reports.

The MATT field systems were inspected approximately weekly during the field test. Tasks performed during inspection included assessment of system integrity (e.g., signs of disturbance of boxes or lines), downloading data, removing and inspecting sensor tubes, and measuring groundwater levels with the miniature e-tape. It was not unusual to observe that silicone oil had leaked from some of the sensor tubes, creating air bubbles in the tubes that had a tendency to migrate up the lines. Since these bubbles had the potential of influencing the MATT readings they were removed by refilling the sensor tubes with silicone oil.

The MATT data from the field tests are shown in Fig. 4, along with physical measurements from the miniature e-tape. These data demonstrate that the units maintain calibration over the course of nearly three months (with the exception of a September excursion by MATT-2, attributed to a leaking fitting).

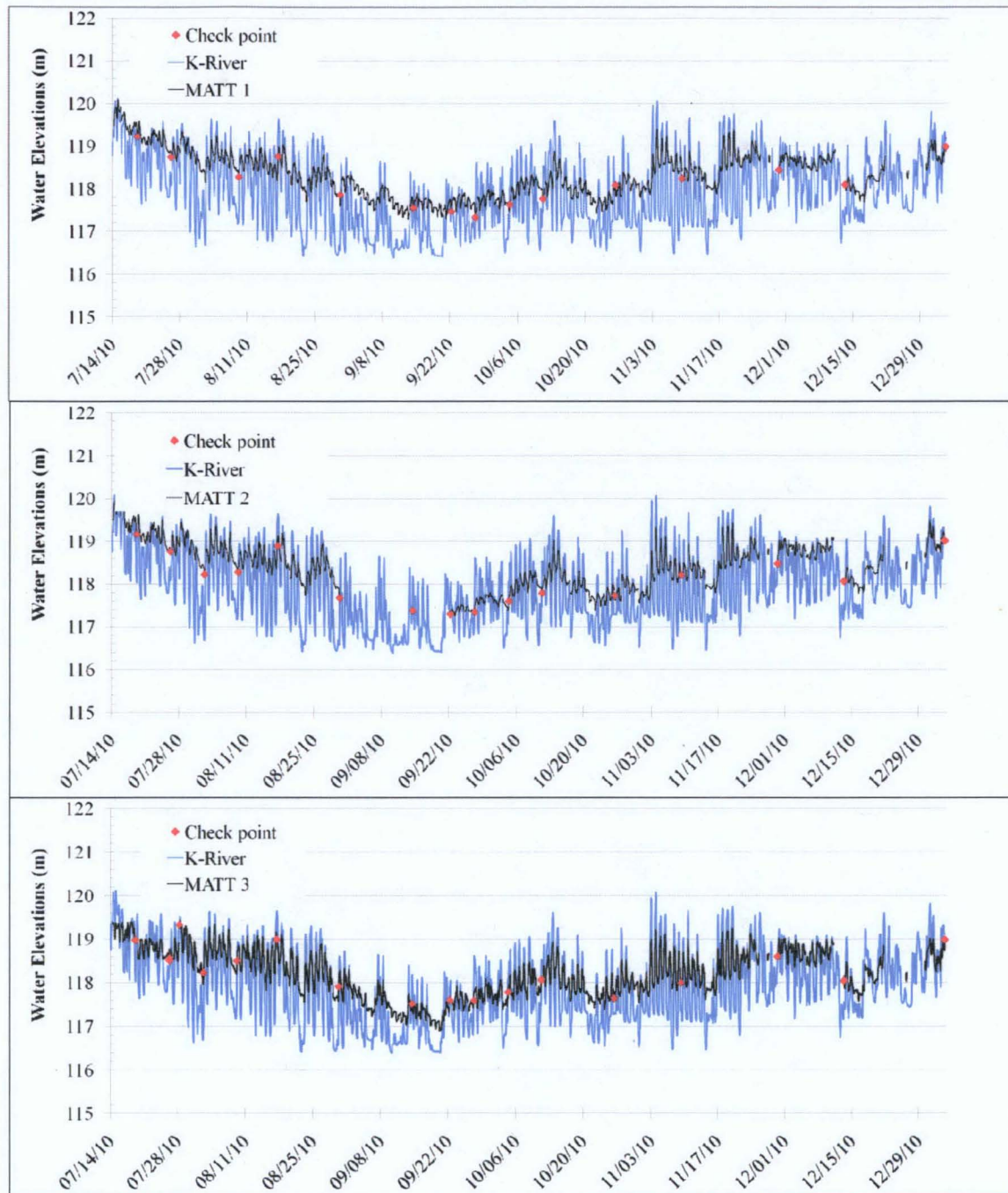


Fig. 4. Plot of water level elevations from MATT field units. River elevations and manual measurements are also shown.

CONCLUSIONS

The objective of this project was to develop a reliable system to electronically measure the water level changes in near-shore aquifer tubes. The ultimate goal is to use data from the system to (1) gain a more complete understanding of groundwater/river water interactions based on gaining and losing conditions of the Columbia River, (2) record and interpret data for consistent and defensible groundwater/surface water conceptual models that may be used to better predict

subsurface contaminant fate and transport, and (3) evaluate the hydrodynamic influence of extraction wells in an expanded pump-and-treat system to optimize remediation.

To meet these goals, a conceptual design for the system was formulated and the necessary equipment was assembled and tested in the laboratory. Experiments were performed in a simulated groundwater column to evaluate sensitivity to water level changes and to minimize outside influence on readings. It was found that filling the transducer sensor tubes with a low-viscosity silicone oil eliminated bubble formation in the tubes, which was the established cause for temperature influences on the groundwater level readings. Further tests were performed to assure groundwater samples could be collected without disassembling the transducer system, and that a manual measurement device designed and fabricated especially for this system could accurately measure groundwater levels in aquifer tubes.

After the laboratory tests, the system was tested in the field to determine the accuracy and precision of monitoring water level changes in aquifer tubes under real conditions. Three transducer units were deployed in adjacent aquifer tubes completed at different depths. Data collected over nearly four months indicates that the MATT system reliably measures and records water levels in aquifer tubes and the readings are not significantly influenced by ambient temperature fluctuations.