

# INSIGHTS INTO HYDRODYNAMIC AND GEOCHEMICAL PROCESSES IN A VALLEY-FILL ARD WASTE-ROCK REPOSITORY FROM AN AUTONOMOUS MULTI-SENSOR MONITORING SYSTEM<sup>1</sup>

Ken Wangerud, Roelof Versteeg, Gail Heath, Rich Markiewicz, and Alex Richardson<sup>2</sup>

**Abstract.** Acid mine site remediation is a significant problem, both in the U.S and globally. Due to the volume of acid producing rock the only practical solution is minimizing acid production by reducing or eliminating water flow through the rock. Typically, this is achieved through emplacement of a cap over the waste rock. The Ruby Gulch repository at the Gilt Edge Mine NPL Site is such a capped waste rock repository. Eliminating discharge from valley-fill capped waste-rock repositories is difficult and multiple factors can cause continuing oxidation and ARD discharge. Consequently, early in the cap-cover design EPA and the Bureau of Reclamation design-build team recognized the need for a long-term monitoring system which would provide actionable information on the repository performance and behavior. Specifically, the following objectives were defined for a monitoring system: 1) provide information on the integrity and performance of the newly constructed surface cover and diversion system; 2) continuously assess the waste's hydrological and geochemical behavior, such that rational decisions can be made for the operation of this cover and liner system; 3) provide easy and timely information access on system performance to a variety of stakeholders; and 4) generate information and insights which can be used to enhance future cover and monitoring discussions between EPA, the Bureau of Reclamation and DOE Idaho National Laboratory. A long-term monitoring system was designed and integrated into the multi-layered geomembrane-rock-soil cap-cover over the 65-acre, 450'-high, sulfide waste-rock dump to provide information to meet these objectives. The system consists of tensiometers, lysimeters and thermocouples in four wells, a 523-electrode resistivity system installed below the cap and in the wells, a weather station, and a precision outflow-meter at the toe-discharge of the repository. Continuous data from this system as well as auxiliary manually collected samples are parsed into a web accessible central server. Automated and on demand data processing allows for 2-D, 3-D and 4-D resistivity tomography and user controllable data mining. The philosophy underlying this system is that it should provide both for effective automated and autonomous data collection and for a cost effective way for multiple stakeholders to use this data.

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<sup>2</sup> Ken Wangerud is a Remedial Project Manager in the Superfund Remedial Program at the Environmental Protection Agency, Region 8, Denver, CO 80202. Roelof Versteeg is a Senior Advisory Scientist at the Idaho National Laboratory (INL), Idaho Falls, ID 83415. Gail Heath is a Principal Scientist at the INL, Idaho Falls, Idaho 83415. Rich Markiewicz is a scientist at the Bureau of Reclamation, Denver, CO. Alex Richardson is a scientist at the INL, Idaho Falls, Idaho, 83415.

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## Introduction

The Gilt Edge Mine NPL Site is located near Lead-Deadwood in the northern Black Hills of South Dakota USA. The 275-acre site (Fig.1) was developed in a small district that had been mined intermittently since 1876 using underground methods. Under a 1986 permit, Brohm Mining Company (BMC) developed three open pits, a cyanide (CN) heap leach pad, Au-processing facilities, and a 12-million cubic yard valley-fill waste rock dump. Early permit applications had not mentioned acid-generating minerals, but sulfide heavy-metal laden materials were abundant. BMC ceased mining operations in 1998 and abandoned the site in 1999, leaving South Dakota Department of Environment and Natural Resources (DENR) responsible for treating ARD and site reclamation. The U.S. Environmental Protection Agency (EPA) placed the site on the National Priorities List in 2000 and maintains site controls and ARD treatment while carrying out remediation planning and construction sulfide waste materials and exposed bedrock generate acid-SO<sub>4</sub><sup>-2</sup> leachates containing As, Cd, Cu and Zn which, if uncontrolled, would further impair groundwater and surface water, impacting receiving water fisheries and threatening downstream municipal water supply.



**Figure 1. Gilt Edge Mine NPL Site; east-facing terraced and capped waste-rock repository**

## Ruby Gulch Waste Rock Repository

During mining waste rock was dumped into the narrow and steep valley, extending to the bottom of the “Y” (Fig.2). With 29 inches annual average precipitation, the dump discharged approx. 30-million gallons per year of pH 2.8 metal-toxic ARD-leachates. The ARD is intercepted in an impoundment at the dump-toe for pump-back to a reservoir for treatment. Therefore, installation of a cap-cover system to prevent infiltration and divert runoff from the dump was a priority. An interim-remedy Record-of-Decision was to construct an in-place containment-isolation repository, with perimeter diversion and drainage channels to convey runoff around the repository. EPA retained the U.S. Bureau of Reclamation (BurRec) to



**Figure 2. 1988-view of dumps into upper legs of**

carry out remedial design and construction. BurRec teamed with the DOE Idaho National Laboratory (INL) for design and installation of a monitoring system that was designed and installed concurrently with the repository cap-cover.

Repository Construction. Reshaping of the 12-million cubic yard dump required moving excess materials into the north-tributary (Fig.3 and Fig.4), increasing the waste footprint to 70-acres.



**Figure 3. Hauling and reshaping valley fill.**



**Figure 4. Hauling rock into N-valley tributary.**

The valley-fill was reshaped to a maximum 3.5:1 grade with lateral-drain benches spaced approx.150-feet up the slopes (Fig. 5); repository height from toe to crest is approx. 450 feet. The benches collect runoff, conveying flows on 3% grades to steep down-gradient perimeter channels exiting the site. The lateral-drain v-shaped bench bottoms have 18-inch perforated pipes placed just above the geomembrane liner near the base. The benches are filled with 18-inches of drain rock and are topped with 20-foot wide flat-bottomed riprapped channels sized to safely convey a 100-year storm runoff into the perimeter diversion channels.

Perimeter diversions that were blasted and excavated into more-fractured bedrock were bedded with bentonite, and geo-composite membrane was laid prior to riprap placement.

The repository cap is a highly-engineered (but generally conventional) cover-drain system consisting of layers (installed top-to-bottom) as follows (Fig. 6, 7, and 8):



**Figure 5. Geomembrane laid and drain-rock placement on slopes and benches.**

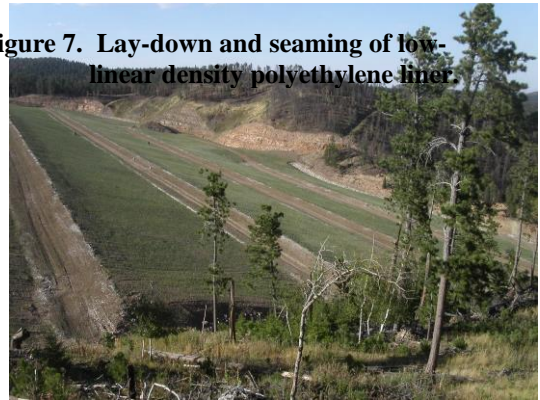




**Figure 6. Diversion bentonite bedding, geo-composite liner, and riprap**



**Figure 7. Lay-down and seaming of low-linear density polyethylene liner.**



**Figure 8. Fall 2003 view onto center area of completed repository cap-**

- 6 inches of topsoil, mulched and seeded to native grasses and forbs;
- 30 inches of rocky subsoil containing 30-40% soil fines (less than 2 mm);
- 18 inches of clean ¼ -1 inch drain rock;
- 80-mil structured low-linear density polyethylene membrane & geotextile;
- minus 1-inch roller-compacted spent-ore from the heap leach pad, placed onto the coarse waste-rock mass as a liner-bedding .
- In case fluid- or gas-additive mitigation methods are developed in the future, perforated pipe runs were placed into the dump surface under the benches, with end-access through water-tight riser-boots in the membrane. It should be noted that two areas of the valley-fill have remained “open” and uncapped. An 8-acre area overlying the uppermost portion of the pre-mining SW-tributary will not be capped until remediation decisions for adjoining areas (the Heap Leach Pad and Sunday Pit) are made. The toe of the valley fill has remained open, pending completion of design for a seismic resistant toe-buttress and new ARD-storage facility. Construction of a capped toe-buttress and a buried ARD-vault will be completed by end-2005, and should substantially reduce chimney-effect airflows into the repository mass.

Determining the extent to which remedial objectives have been met, and understanding changes in repository conditions affecting both short- and long-term effectiveness of remedial actions (both hydrodynamics and geochemistry) under changing conditions and variables, requires monitoring a variety of conditions. As previously mentioned, the design and concurrent installation of the Ruby Repository Monitoring System was a critical part of the overall construction-project. The components and initial operation of this monitoring system is the focus of this paper.

### **Ruby Repository Monitoring System**

#### **Construction and Design Considerations.**

Wide-ranging repository factors (structural and geotechnical conditions, geology and mineralogy, changing hydrology and hydrodynamics, changing geochemistry and kinetics) meant that numerous variables must be addressed by a monitoring system. Monitoring of large repositories with multiple-objectives often requires numerous sampling wells; for this 70-acre dump, 20-50 multi-horizon piezometers and/or well-nests were initially considered. However, this approach had substantial limitations and risks, including:

- very difficult drilling and well-completion conditions (with high risk of delays to cap-cover construction startup), and
- engineering recommendations that membrane penetrations involving deep-set wells be absolutely minimized.

The design team decided that a monitoring system utilizing a limited number of highly-instrumented wells, supplemented with arrays of electrodes for electrical resistivity tomography, could be developed which would substantially minimize major liner penetrations, and yet provide a spatially comprehensive means to achieve monitoring objectives related to hydrodynamics.

#### **Monitoring Objectives.**

Ruby Gulch had not undergone extensive pre-mining hydro-geological investigations. Prior bedrock wells had indicated only slight groundwater presence; however, mid-valley spring-seeps had reportedly been observed during spring-melt and wet-years. Absent definitive groundwater studies, and given the urgency of capping the dump, EPA was interested in a monitoring program that could obtain information related to a variety of ARD formation and repository conditions:

- measure repository outflow accurately;
- utilize automation to minimize field sampling;
- evaluate remedy effectiveness by assessing internal hydraulics and geochemical changes within the repository;
- detect membrane leakage (especially along mechanically- and hydraulic-stressed bench-zones);
- detect inflows to the repository from possible “leaky” perimeter diversion-drains;
- observe bedrock groundwater levels and potential inflows to the repository;

- gain insight into internal moisture and flow regimes;
- identify geochemistry of repository condensates, pore-water and pore-gas;
- gain insight into “chimney-effects” and “barometric-pumping” phenomena in O<sub>2</sub>-loading and oxidation-reduction reaction kinetics;
- monitor temperatures within the dump mass related to air-flux and sulfide-oxidation and redox conditions.

### Monitoring Approach and Design.

The design of monitoring systems should be driven by current and future information needs, constrained by operation & maintenance (O&M) costs. Information needs differ for a range of different stakeholders (including site owners, site operators, regulators, legislators, scientists and the general public). A sensible approach to monitoring integrates the five elements of monitoring: (1) data acquisition; (2) data management; (3) information generation; (4) information distribution; and (5) information use. Such an approach should also consider the short and long term costs of data collection, data aggregation, and information distribution. For instance, there is a significant (but hard to quantify) cost associated with periodically re-aggregating dissimilar datasets (e.g., with different sampling periods) for cross plotting and analysis.

In developing this monitoring system, these elements were carefully integrated into a structure shown in Fig. 9. Data is collected automatically in the field (from multiple, distributed sensors and through different acquisition approaches). Data is transferred (using web-services) to a central server, where it is parsed into a relational database. Data qa/qc, data-management and processing occur automatically. Users can obtain results either automatically through periodic reports or manually through a standard web-browser. Intensive data processing is done through web-services on a HPC cluster. Processing and analysis of this data occurs both automatically and on demand, and users have access to all the data through a standard web browser.

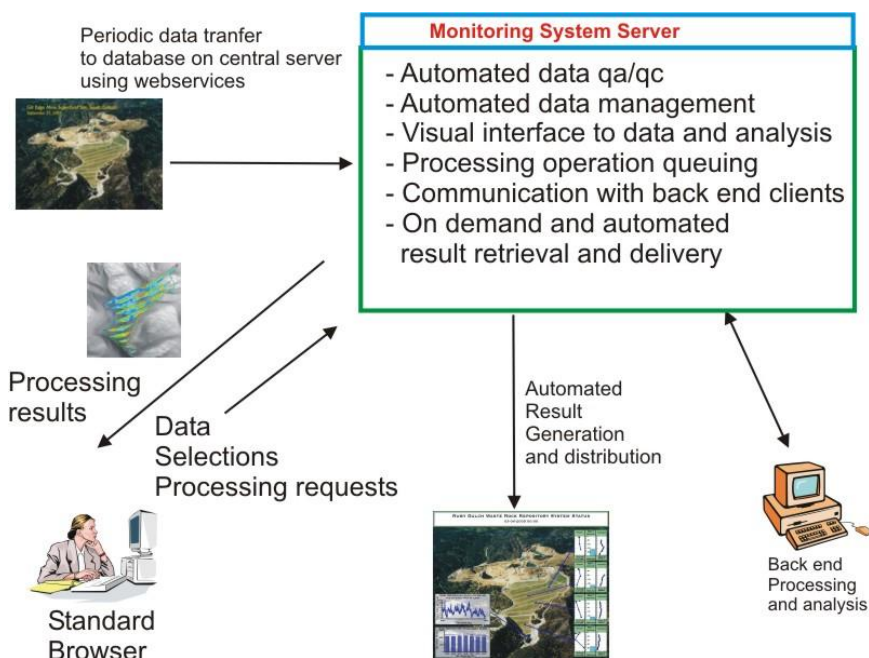
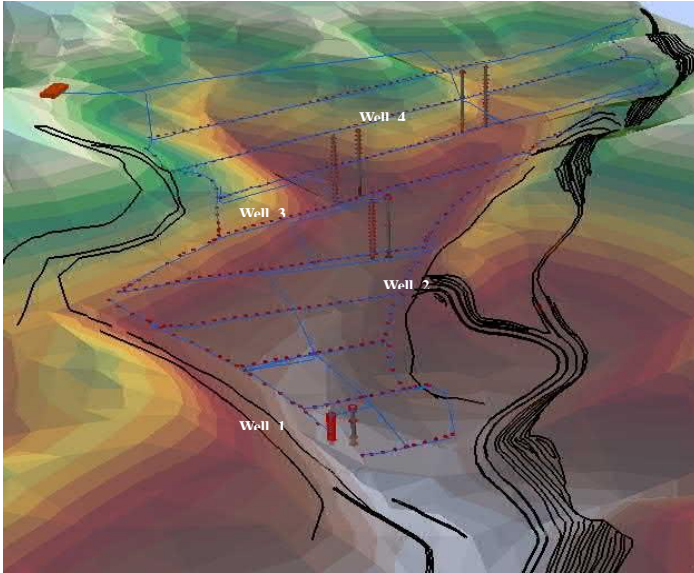


Figure 9. Components of INL developed monitoring system. Data is collected automatically and autonomously, transferred to a central server, processed, and provided to users.

On-site System Components. Data in the Ruby Gulch monitoring system comes both from automated sensors (which collect data autonomously) and from manual sampling efforts. Fig. 10 shows the general layout and position of the system components within the completed (Fig. 11) repository.



**Figure 10.** Ruby Gulch pre-dump topography, showing placement of the monitoring wells and resistivity electrode arrays (red) and power and data-communication lines (blue); resistivity-unit, multi-plexers, computer-controls and modem equipment housed inside water treatment plant (upper-left).



**Figure11.** Fall 2003 view (facing west) of the capped repository; five lower slope-segments and benches drain to diversions at right, bypassing ARD impoundment and exiting out lower Ruby Gulch; five upper slope-segments and benches drain to diversions at left, exiting into adjacent drainage to the south .

Automated Sensors. The monitoring system autonomously collects continuous data using the following sensors:

- A weather station operated by DENR to which INL has added software and modem access to data. This weather station collects data on temperature, humidity, wind-speed and direction and barometric pressure, as well as rainfall in the summer months. Data is currently collected at one-hour intervals, and is automatically retrieved once a day.
- An outflow meter at the bottom of the Ruby Repository. This outflow meter collects data (using a Doppler ultrasonic sensor mounted above an H-box flume) on the discharge flow-rate. Measurement-data is taken at 30-second intervals and is transferred (and available) within two hours of collection.
- Temperature sensors in four well boreholes. These boreholes go through the rock waste into the bedrock. Each borehole has 14 temperature sensors (thermocouples) which are evenly distributed over the borehole. Data from these sensors is collected at five-minute intervals, and is transferred (and available) within two hours of collection.



- Advanced tensiometers are located within boreholes and measure matrix potential (related to water saturation). Data from these sensors is collected at five-minute intervals, and is transferred (and available) within two hours of collection.
- A multi-electrode resistivity system. This system consists of electrodes distributed along the surface of the repository rock (1-2 feet below the geomembrane-liner) and in the boreholes. These electrodes are connected to a multi-electrode resistivity system which can use any group of four electrodes for a resistivity measurement. This system allows the collection of 2D and 3D resistivity profiles, which can be inverted to yield spatial distributions of electrical resistivity. These distributions (and changes in these distributions) can be interpreted in terms of moisture (changes) and temperature. The resistivity system collects data continuously at the rate of one measurement per 2.5 seconds. This data is transmitted at the completion of a suite of resistivity measurements (known as a schedule). A schedule typically contains several thousand measurements.

Manual Sampling and Data. In addition to the autonomously collected data, gas-ports and porous-ceramic cup-lysimeters in the wells are sampled monthly (starting in June 2004). Gas analysis is done in the field for CO<sub>2</sub> and O<sub>2</sub>. Water samples are sent to a laboratory for analysis. In addition to this data there is a substantial amount of historical data (collected by BMC and DENR) which has been aggregated into the database.





**Onsite Installation.** Due to anticipated construction schedules, the entire Ruby Gulch project was implemented as a phased design-build undertaking for both the cap-cover-diversions and the monitoring system. Both aspects of the project had to be integrated, and the BurRec and INL science and engineering design teams worked collaboratively, each carrying out various aspects of the monitoring system design, fabrication and installation. INL geohydrologists and drilling contractors did well-design and installation (Fig. 12) INL geophysicists and electrical engineers headed up the resistivity system design and system specifications, while BurRec technical specialists headed up fabrication and installation of the near-surface resistivity electrode arrays (Fig. 13.). EPA requested that an operating-term of 20-year minimum be achieved, resulting in the development of robust system components. 10x10x1/4-inch electrodes were made using Type 316 corrosion-resistant stainless steel. BurRec technical staff designed and fabricated a high-density polyethylene sealed-connector for attaching the wires to each plate (Fig. 14). Shallow trenches were dug into the dump-rock, and wiring harnesses were bedded in sand for protection. The electrodes were bedded into the waste rock-mass using a bentonite and metal-salt mixture for higher assurance of electrical contact with the dump rock. INL technical staff coordinated design, specification, and equipment acquisition and installation for all of the “above-ground” system operations-and-control components.



**Figure 13. BurRec fabricated and installed 52-miles of wire for the electrode-arrays.**

Electrode-array wires were run to a membrane-boot/riser centrally-located on each bench (Fig. 15.); following seaming to the geomembrane, lay-down of the drain-rock and other above-membrane components of the cap-cover could proceed.

For the wells containing pressure-transducers, lysimeters, and pore-gas ports (tubing placed down-hole into a 1-foot sand layer to retrieve air samples), fabrication and installation of the internal well-head



**Figure 14. Near-surface electrode connection and pl;**



mechanical and electrical components proceeded (Fig. 16).

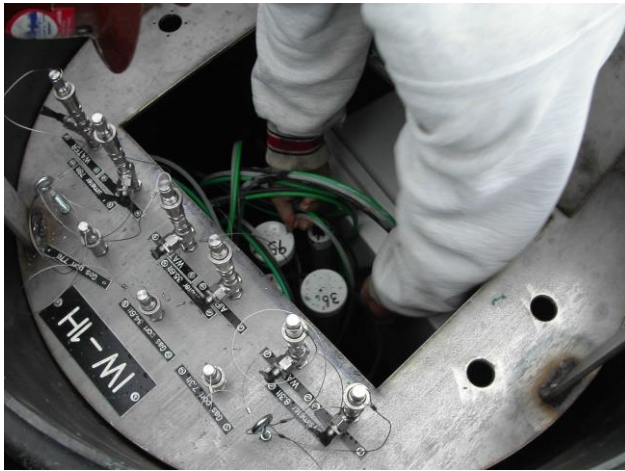


Figure 15. Wiring harness riser; note well-heads in background.

Figure 16. Completed well-head, with connectors for down-hole samples, and housing for Adams-units for digital instruments.

Swagelok connectors enable rapid connection for field sampling. The lysimeters are installed so that air-pressure is applied to one connector, forcing the liquid sample up-hole for retrieval through the paired connector. The porous-ceramic cup lysimeters are able to draw-in fluid samples, enabling insight into the chemistry of waters within unsaturated zones. Air samples are retrieved by attaching a peristaltic pump to the connector, applying a vacuum to remove/purge in-line air, and subsequently retrieve a gas-sample from unsaturated portions of the dump mass.

At above-ground junction-boxes on the repository, the electrode-array wires and data-lines from the wells are connected to multi-conductor “trunk-lines” leading to the control-center within the water treatment plant at the top of the repository (Fig. 17). The power-supplies, multi-plexers (circuit-boards for programmable switching control of electrode pairs), computers programmed (and remotely reprogrammable) for autonomous data collection, and modems for data-transmission are housed in a wall-cabinet (Fig. 18). A nearby weather station operated by

DENR had a software package and modem added, enabling weather-data to be provided hourly to the EPA-INL system.



**Figure 18. Multiplexers connected to resistivity unit and computers.**

**Figure 17. Multi-conductor cables for connecting electrodes to multiplexers and resistivity instruments.**



## Off-site Components and Information-Delivery.

As shown on Fig. 9 earlier, access to the monitoring system information occurs through a standard web browser. Access to the system is through the DOE-INL system at (<http://geophysics.inel.gov>) and Fig. 18a shows the front-end of the monitoring system access. Figure 18b shows the web-page where access to all time-series data for each sensor, monitoring-instrument and location is engaged. Users can engage a broad range functionalities. These include the ability to access and graph all data in the system in user selectable combinations, abilities to create on-demand animations, and the ability to set alerts on ranges of parameters being monitored at the repository. Alerts are delivered either by phone or by email. In addition, users can request automatically generated reports at user specified intervals, and can view time-lapse imagery of ERT data.

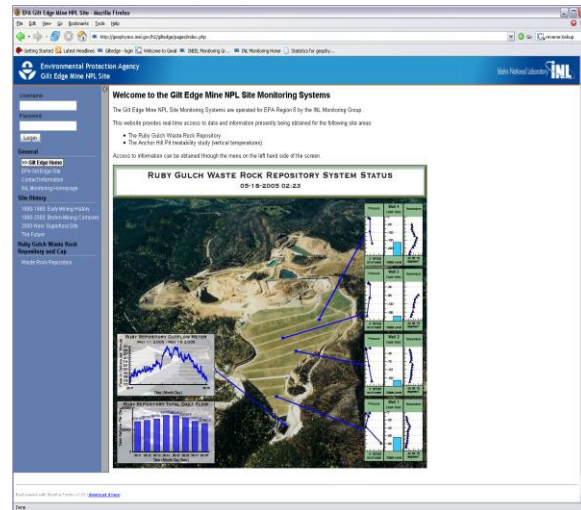


Figure 18a. Home-page to the INL & EPA Gilt Edge Mine Monitoring System website.

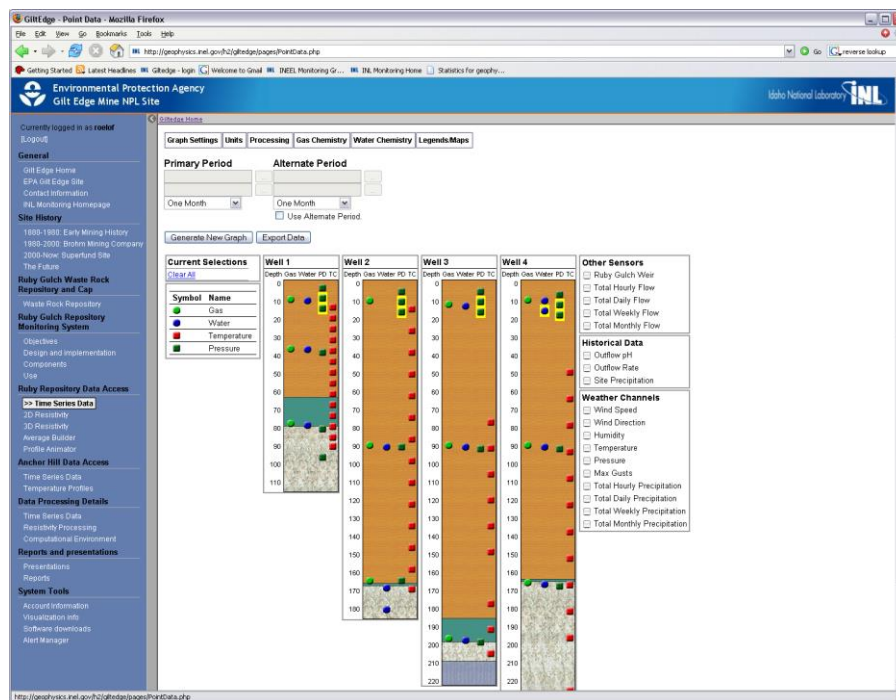


Figure18b. Web-page for access to time-series data for the Ruby Gulch Monitoring System.

Figures 19a-c show some of the data-results and information graphs generated using this system.

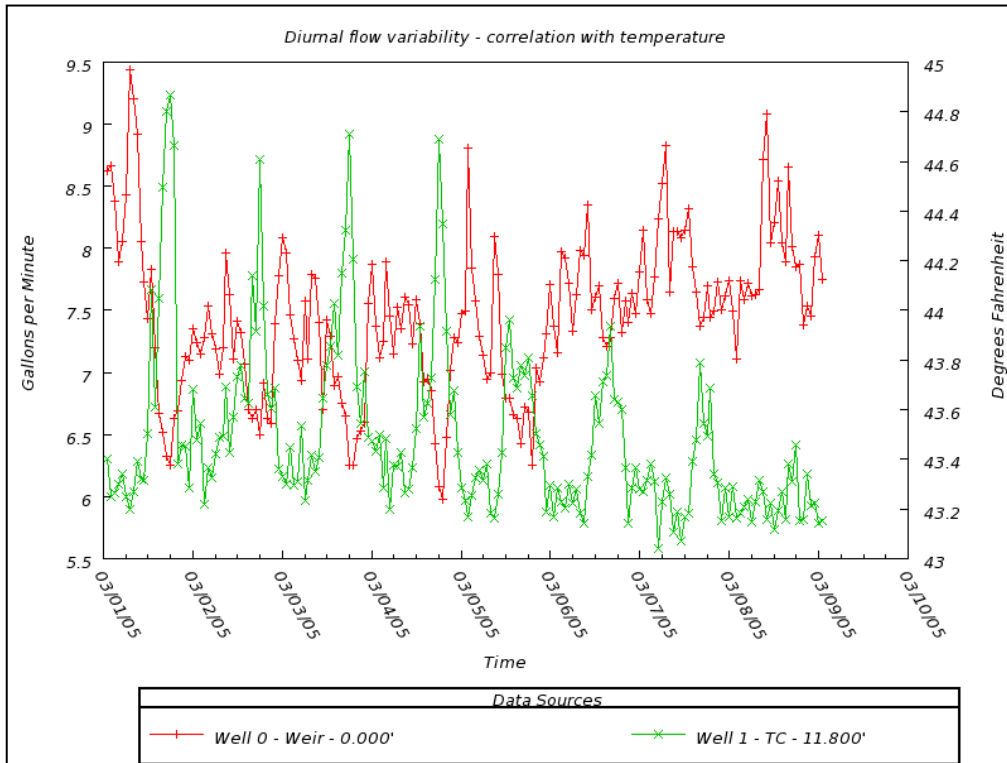


Figure 19a. Auto-plot of discharge volumes vs. rainfall.

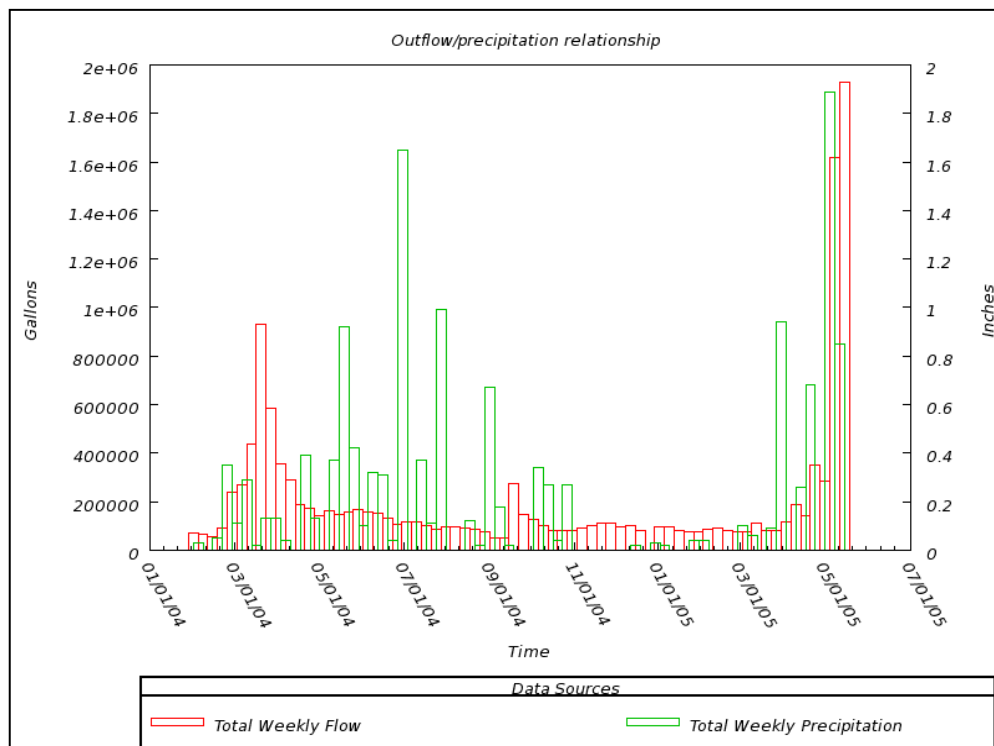


Figure 19b. Auto-plot of total weekly flow vs. precipitation.

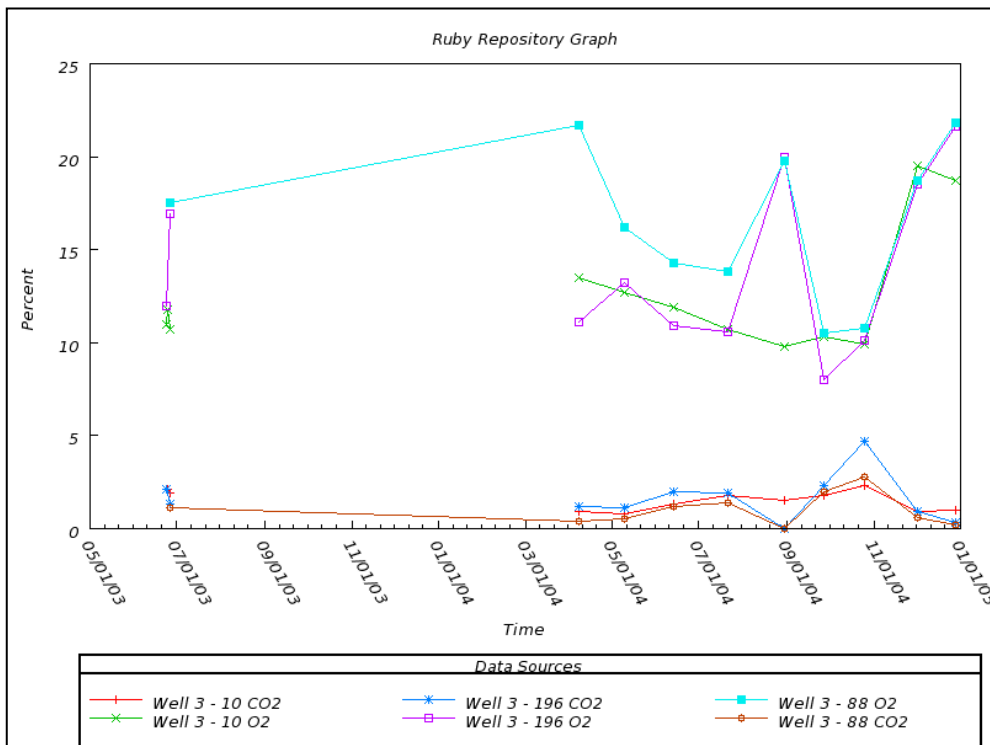


Figure 19c. Auto-plot of oxygen and carbon-dioxide levels in Well 3.

### Repository Monitoring Observations

Repository construction (except for the toe-buttress) was completed in spring 2003 and the remainder of that year was dedicated to system validation and calibration- and quality-assurance testing to check and verify the as-built system. Field-sampling of wells began in 2004, and electrical resistivity data collection was undertaken in 2-D mode along the bench arrays. Preliminary evaluation of the integrity of the northwest diversion channel was performed through a slug-test, and flow observations were made utilizing the adjacent electrode arrays. 3-D resistivity-data collection and processing began in 2005, and the ERT results shown are from the spring 2005 precipitation cycle.

The monitoring system has been collecting data since January 2004 (historical data is available since 1996 for precipitation, and repository outflow and pH). Time has not allowed a complete evaluation of all data. Actually, the volume of data that is available goes beyond the immediate needs and evaluation and interpretative wherewithal of the project-team. The data-bank can also be a rich source of data for other interested scientific and engineering investigators.

Current observations allow us to form an image of some of the processes occurring in the repository, including:

- Obtaining time-lapse tracking of the changes in moisture-density and motion in the repository using ERT (Fig. 22-25). The continuously operating electrical resistivity system collects a 3D dataset every 39 hours and 40 minutes. These data can be inverted



to yield both absolute and difference maps of electrical resistivity. The difference maps of electrical resistivity correlate to changes in moisture, and can thus be used to investigate the source and origin of water entering the repository

- Observing diurnal variations in the outflow which are inverse to variation in internal repository temperature. Our current conceptual model relates this to daily inflow from air into the repository resulting in both uptake and precipitation of moisture. A question is whether this mechanism removes or adds to the net outflow. However, it could be possible that these phenomena are in fact related to ongoing geochemical reactions that are not yet explained.

Between 2000 and 2004, the Site experienced below-normal precipitation conditions similar to those experienced throughout the western U.S. Overall outflow from the waste-rock dump was markedly reduced during this period. The “spike” in discharge in spring 2003 was thought to be attributed to flow entering the repository through a bench-drain that had to be re-constructed. However, a marked “spike” in repository discharge during spring 2005 was noted and was somewhat unexpected (Fig. 20). Deliberations and monitoring system data analysis is continuing to ascertain what may be the principle cause(s) for this occurrence.

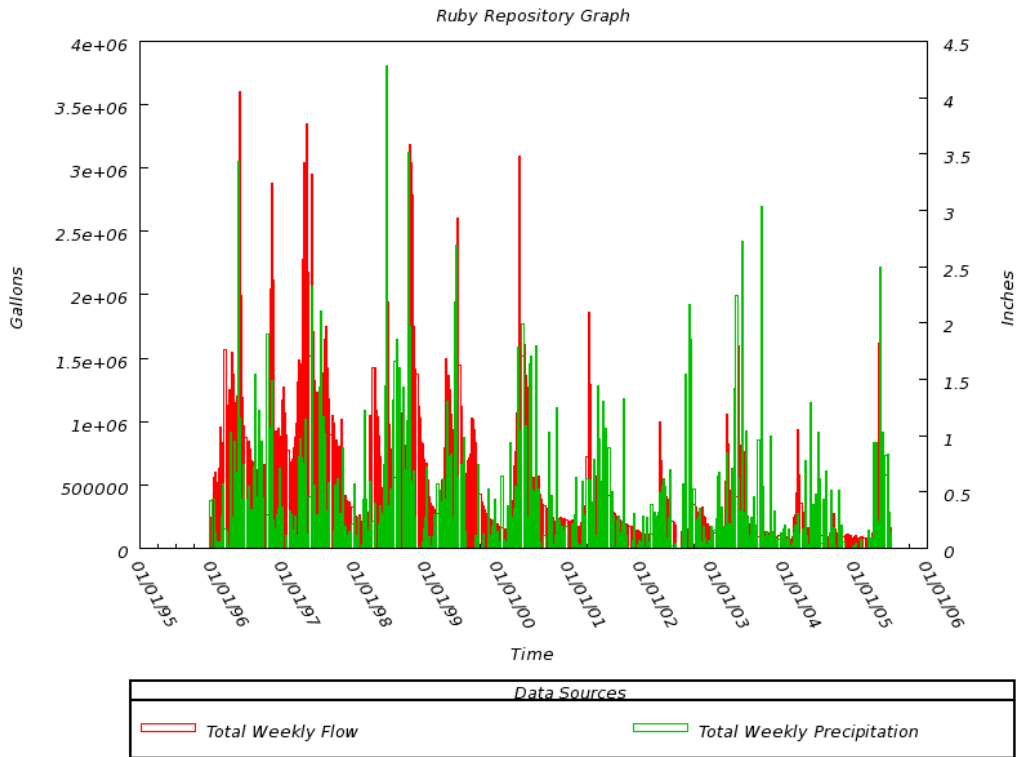


Figure 20. Auto-plot of Ruby outflow vs. precipitation 1996-2005.

Spring 2005 repository outflows and precipitation can be seen in more detail in Fig. 21.

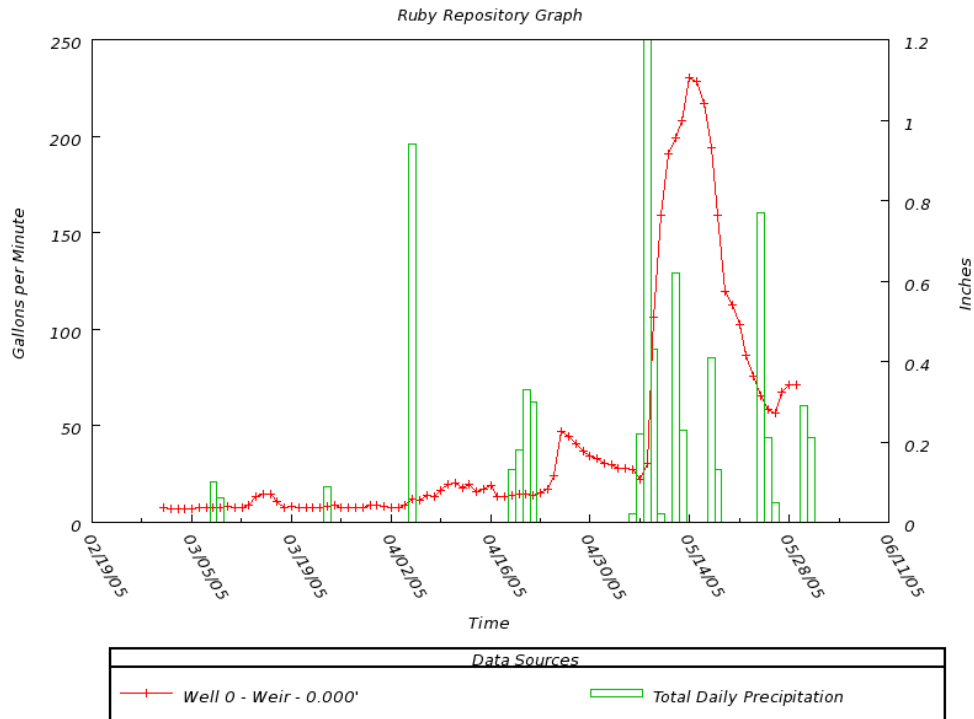


Figure 21. Repository discharge and precipitation April-May 2005.

Beginning with baseline 3-D resistivity data starting in February 2005, evaluation of moisture-density conditions within the repository related to precipitation events and flow conditions has begun. Subsequent resistivity data-sets were collected on 40-hour cycles throughout the repository area. Fig. 22 to 24 show the comparisons in resistivity (changes in moisture-densities) within the repository and underlying Ruby Gulch between March-May 2005. March imagery indicated little changes from baseline and was typified by the image shown in Fig. 22. However, in late-March and April moisture increased markedly (Fig. 23.)

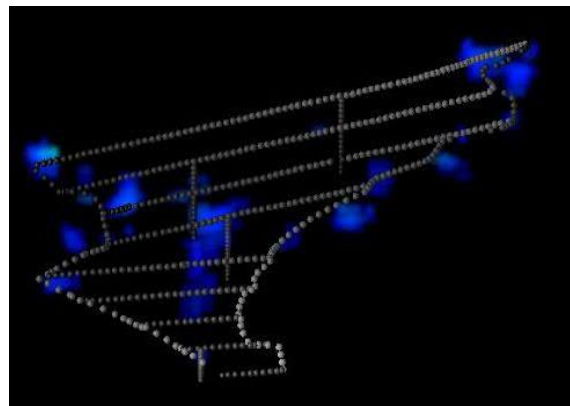


Figure 22. Relatively low densities during March.

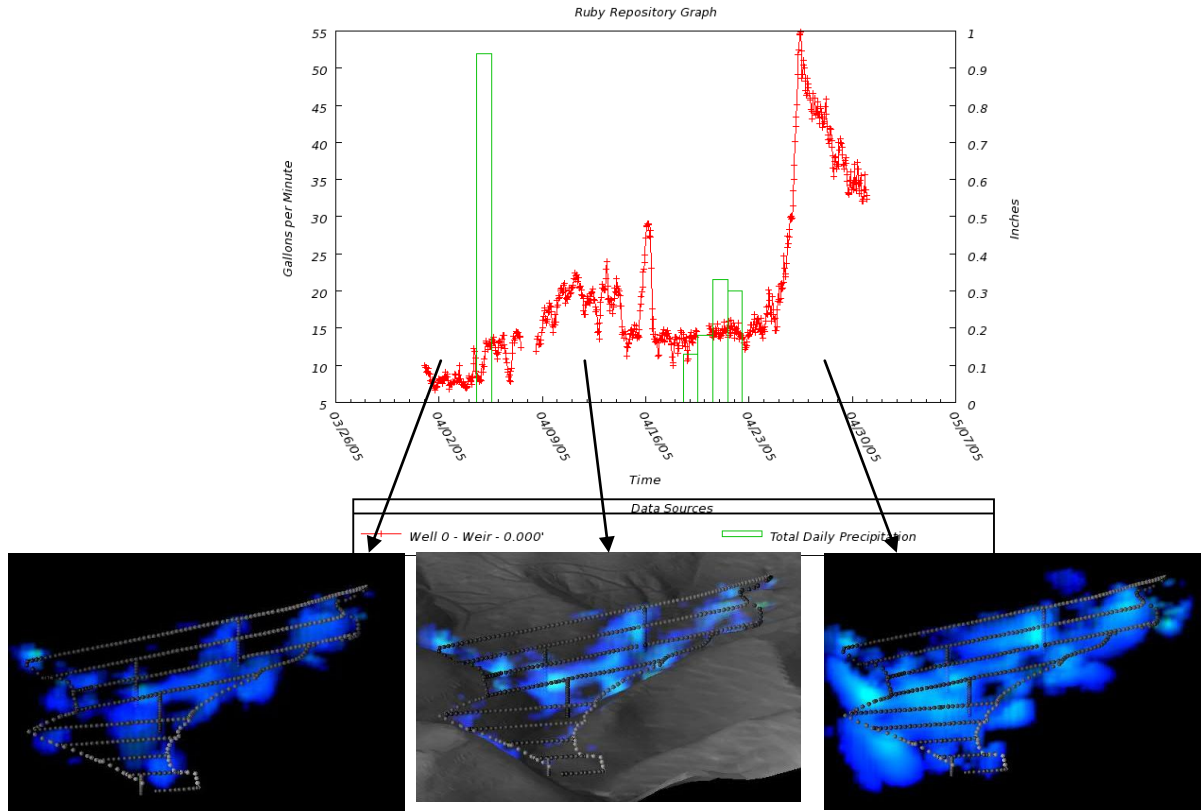


Figure 23. April 2005 precipitation and repository discharge (system auto-plot), shown with 3-D images of moisture-plumes indicating increasing water-density within, around, and beneath the repository mass.

Rain events and inflows during May from presently undefined sources appear to have taken the repository to levels of saturation that clearly were manifested in outflow discharges. (Fig. 24.)



Note the much higher scales required to plot the May data on this figure.

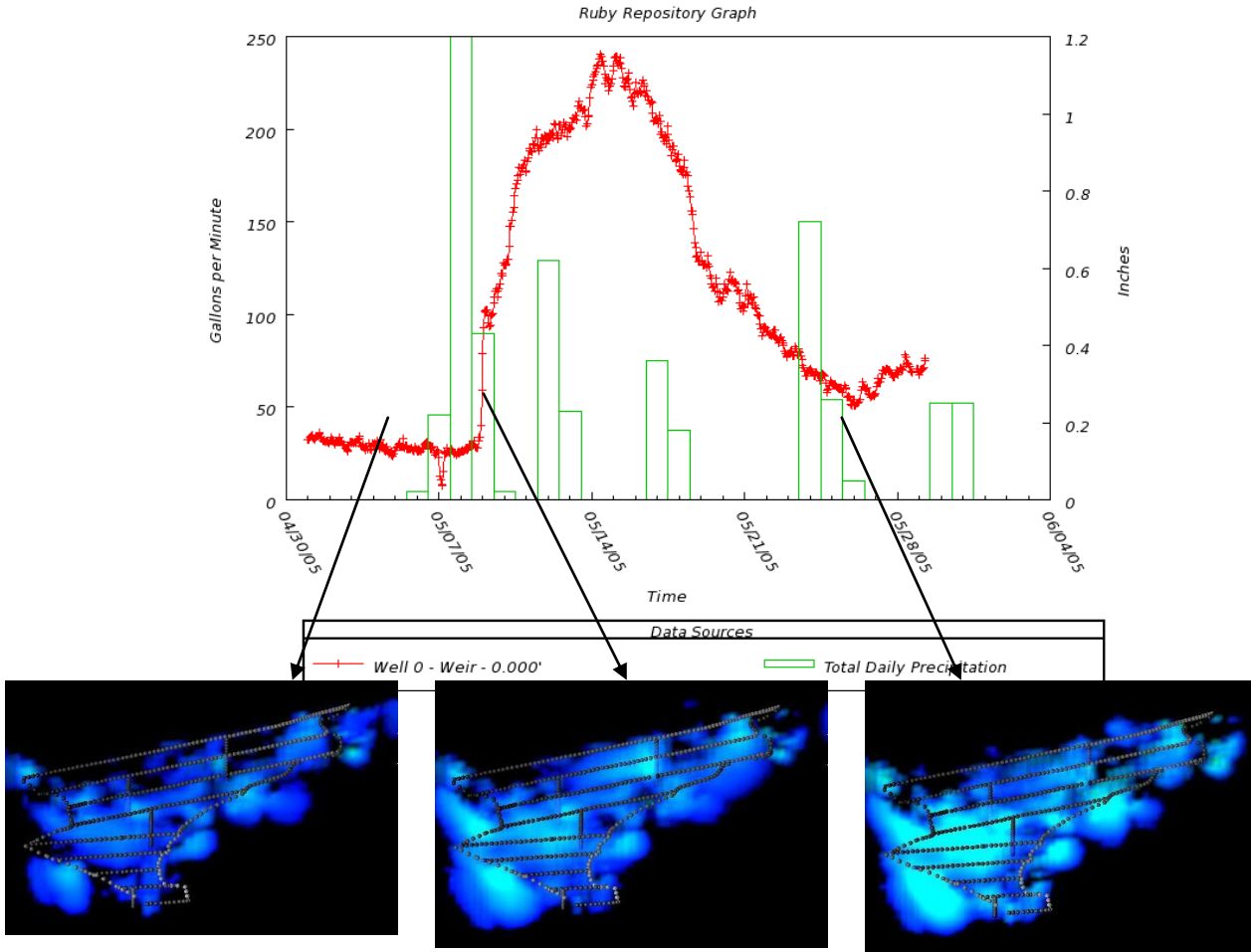


Figure 24. May 2005 precipitation and repository discharge (system auto-plot), shown with 3-D images of moisture-plumes indicating large buildup of water-density, particularly at depth and beneath and around the repository mass; this may indicate groundwater upwelling into the base of the repository, and into the sides from surrounding higher terrain.

Taken together, observations to date illustrate both the complex hydrogeological processes of this repository and the need to further refine both our data processing and model interpretation. In the future we expect to couple these observations to numerical models to arrive at a more detailed understanding of the conditions and trends within this repository. This information would then be used for management decisions.

## **Summary and the Road Ahead**

In order to maximize the performance of a monitoring system while minimizing cost all the components of a monitoring system should be carefully designed and integrated. The approach developed by INL, and implemented at the Gilt Edge Mine site combines the following, distinct features:

- Automate mundane tasks (data collection, data download, data management),
- Integrate data from diverse sensors through a common interface. This allows users to examine relationships between e.g. geophysical, hydrological and geochemical data, thus allowing enhancements of conceptual models
- Ensure that critical events are captured (data acquisition systems failing, transient events occurring), and are communicated automatically to the appropriate operational and regulatory staff,
- Provide for data access through a common, web accessible interface allowing for rapid, user-driven investigation. This shifts the focus from talking about data to talking about the meaning of data.

As this system is fully automated, the operational costs of using this system are minimized and data use is maximized. From a result point of view, the system has demonstrated both its ability to capture system behavior and the complexity and dynamic nature of the hydro-geological processes in the repository. The current results provide a basis from which to develop customized data driven hydro-geological models of the subsurface processes at the Ruby Gulch waste rock repository which can be used for future management decisions

## **Implementation of this Approach for Other Sites**

The same web based approach has been implemented for other environmental sites, including a landfill in South Eastern Idaho and an infiltration site at the INL. While none of these has the complexity of the Gilt Edge site (in terms of types and number of sensors) the five basic components of monitoring are constant for all sites, and as the back end of these systems all share a common code base it is now relatively straightforward to setup a web based monitoring system from the ground up. Note that while full integration of automated data acquisition in a web based monitoring system makes sense for many reasons, integration of existing acquisition approaches (including data-loggers and manual sampling efforts) in such systems has been shown to be relatively easy. Or, this approach scales from inexpensive monitoring systems (with only a few sensors) to complex systems with hundreds or thousands of sensors.

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