MANAGING A CAPPED ACID ROCK DRAINAGE (ARD) REPOSITORY USING SEMI-AUTONOMOUS MONITORING AND MODELING[1]

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Abstract. Effective ARD repository management requires ongoing assessment of remedial integrity and operational performance in such a manner that short and long term risks and cost are balanced and optimized. Such management requires actionable information on the behavior of the repository. This information will typically be derived from diverse data (physical, chemical and hydrological), forward and inverse hydrological, geochemical and geophysical models and cost/benefit models. With the increase in volumes of data and complexity of analysis, end users face increasing challenges in obtaining information in a timely and cost effective manner. A web accessible workflow environment for performance monitoring, designed at the Idaho National Laboratory (INL), was implemented for a capped ARD repository (the Ruby Gulch Repository) and is part of the Gilt Edge Superfund site in South Dakota. This repository is instrumented with a geophysical, hydrological and environmental sensor network. Data from this network are transmitted automatically every two hours to a server. At the server, the data are automatically parsed in a relational database and analyzed using automatically executing scripts. The resulting information is both transmitted through automated reports and accessible by users through a web application. The combination of near real time reporting and analysis and integration with analysis tools provides for actionable information on short and long term repository behavior. The structure of a web accessible workflow system for performance monitoring is well suited for both managing data, creating information and providing access to information for diverse users.

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Introduction

A fundamental challenge in ARD site management is the balancing and optimization of short and long term risks and costs. Meeting this challenge requires continual assessment of remedial integrity and operational performance. This challenge exists regardless of the approach taken to prevention or mitigation of acid mine drainage (AMD) or the size of the site.

In order to perform this assessment site managers need an understanding both of the relevant dynamics of a site as well as the processes which are responsible for these dynamics. For instance, it is not enough to know of diurnal variability in for example AMD production: what causes this variability must also be known. In addition, this understanding is needed timely and should be obtained in a cost effective manner.

This understanding will typically be derived from a combination of data – hydrological, geochemical, geophysical and operational – data analysis and reduction as well as multiple analytical and numerical models. In an ideal scenario this understanding (as well as the methods and data used to arrive at this understanding) would be at the fingertips of site managers as well as other relevant stakeholders.

In many cases, despite extensive and expensive data collection, site managers do not have access to either this understanding, data, or methods. The reasons are several: data acquisition and management are fragmented (for instance, in many cases hydrological and geochemical data are collected by different groups, and are stored and managed differently), data reduction and modeling are performed by technically proficient staff at consultant firms, and the primary data product to which managers have access is a status report and interpretation based on months-old data.

Associated with the challenge of obtaining timely and actionable information is the challenge of dealing with increasingly large amounts of data – made possible by low cost sensors and automated acquisition systems – as well as increasingly more complex applications for data reduction and modeling. Requiring each user to become an expert in data management, data reduction and modeling is not feasible.

To increase efficiency and reduce cost of performance monitoring, INL scientists have focused over the past several years on the design and implementation of a web-accessible workflow environment for performance monitoring. The need for this system was driven both by mining problems as well as the general need for performance monitoring for contaminated sites (ASCE 2003). In this paper we discuss the implementation of this system at the Ruby Gulch Waste Rock Repository of the Gilt Edge Mine Superfund Site. Note that we define "performance monitoring" as "*the generation of information on site performance through data acquisition and analysis.*" Thus, our definition focuses on information generation, not on data collection. Note that the focus of this paper is on the underlying structure of our system and the software implementation of linking models and data. A companion paper in this conference (Wangerud, Versteeg et al. 2006) discusses the sensor components of this system and some of its results.

The Gilt Edge Mine Superfund Site

The Gilt Edge mine site is located southeast of the town of Lead in the Northern Black Hills, Lawrence County, South Dakota. Several owners and operators had conducted underground mining for Au, Cu, and W since 1876. In 1986 Brohm Mining Company obtained a permit to conduct large-scale open pit mining.

Under the permit, BMC developed three open pits, a large cyanide (CN) heap-leach pad, and a 12 million cubic yard valley-fill waste rock dump. Early permit applications did not mention acid generating materials, though sulfidic metal laden rock was abundant.

During 1998-1999 BMC had serious financial difficulties and told the State that it could not continue site control. The South Dakota Department of Environment and Natural Resources (DENR) maintained necessary water treatment operations at the site, using the State's Regulated Substance Response Fund, until August 2000 when emergency response operations were turned over to EPA.

EPA's superfund program placed the site on the National Priorities List (NPL) in December 2000. More detail about the site can be found at
http://geophysics.inel.gov/h2/giltedge/pages/index.php

Site Contaminants

Sulfide waste rock and exposed ore (which generate leachates to surface and ground water) release dissolved metals, including As, Cd, Cu, and Zn. Nitrates and high levels of SO_4^{-2} are also present in the contaminated residues. Copper, Cd and Zn appear to be the major polluting risks to the habitats of Strawberry and Bear Butte Creeks. Uncontrolled releases threatened down-stream wells and local municipal water supplies. Containment and treatment of site water was thus necessary.

Site Remediation

The Superfund Remedial Program designated the following Operable Units (OU) as distinct management units in overall plan for the site (Fig. 1):

- OU1 – Gilt Edge Mine Site (the overall 258 acre area)
- OU2 – Interim Water Treatment Operations
- OU3 – Ruby Gulch Waste Rock Repository Project (70 acres)

The Ruby Gulch Waste Rock Repository

The Ruby Gulch waste rock repository consists of approximately 12 million cubic yards of sulfidic waste rock and spent heap leach ore. These cover about 70 acres and occupy two headwater tributaries that join (at about the center of the repository mass) to form the main Ruby Gulch Drainage

The Ruby Gulch Waste Rock Repository Record of Decision called for regrading the waste rock dump and covering it with a composite geomembrane cap, drainage system and soil cover. Clean materials for the soil cover were imported from a nearby highway project. These actions were meant to greatly reduce the generation of acid rock drainage. The regrading, drainage system and liner emplacement occurred between 2001 and 2003 and are described in detail in a companion paper in this volume (Wangerud, Versteeg et al. 2006)

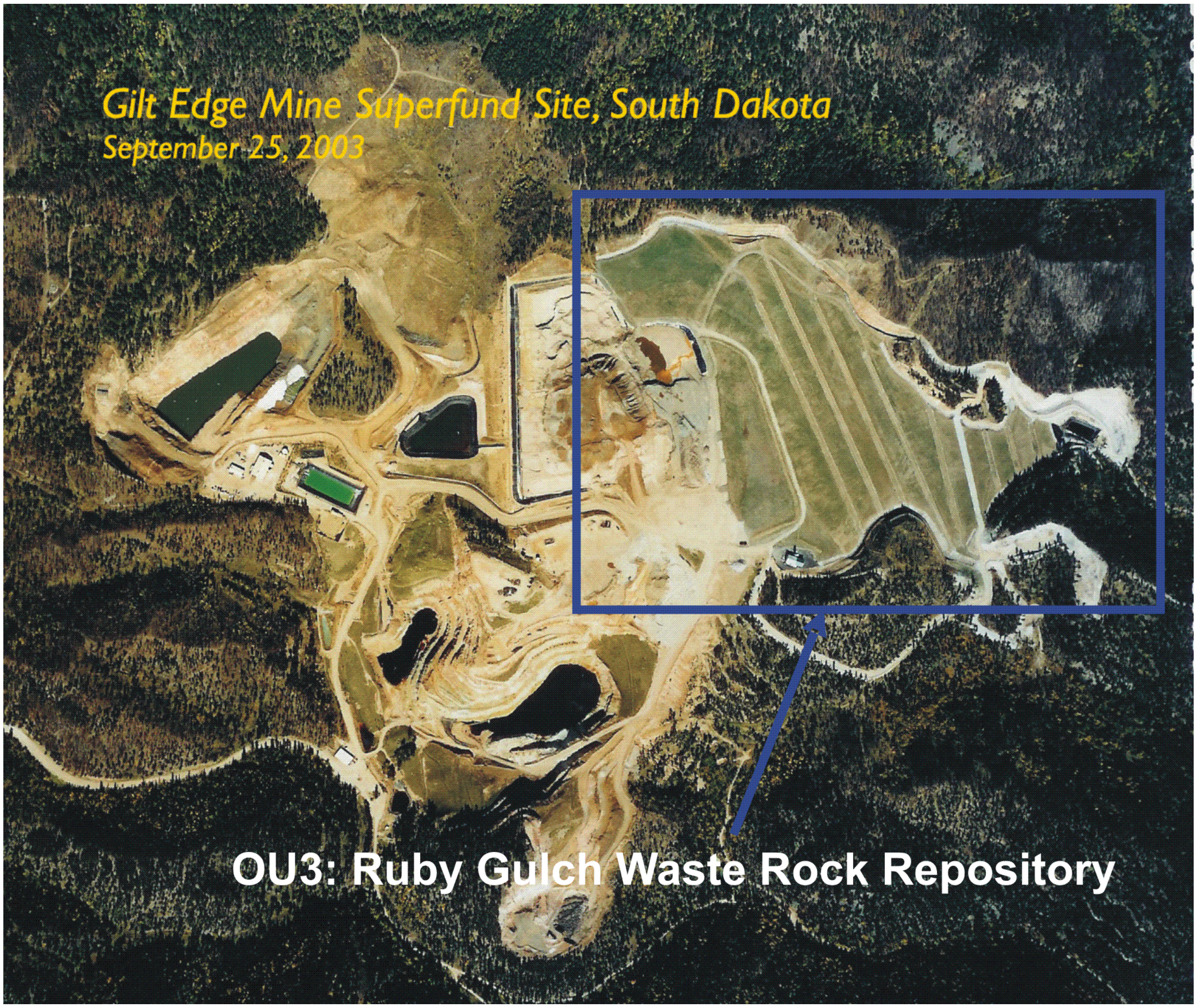

Figure 1. Gilt Edge Mine site and location of OU3

Implementation of performance monitoring at the Gilt Edge Site

The core challenge in performance monitoring is how to perform it in a cost effective, timely, rigorous and scientifically defensible manner while meeting multiple stakeholder needs. Stakeholders typically include regulators, owners, scientists and the general public. These interests bring about information objectives that include regulatory, performance, process or impact related. Typically, each of these information objectives has a different time criticality.

For instance, information with projected long term impacts can take longer to generate than information related to operational effectiveness and deviations of the system from a baseline condition (e.g. associated with a transient event). However, there is a commonality for all these objectives in that the information generation process should be transparent, reproducible (Schwab, Karrenbach et al. 2000) and auditable.

- For the Ruby Gulch Cap and Cover system, the primary stakeholders are EPA and SDENR Their objectives are to: ensure integrity of cap and diversion system
- understand system hydrological and geochemical behavior so that rational decisions can be made for the operation of the cap and liner system
- provide timely, relevant information to stakeholders (public, SDENR, EPA) on the dump
- obtain insight into the effects of "barometric-pumping" phenomena in O_2-loading and oxidation-reduction reaction kinetics, and
- enhance future cap designs.

Performance Monitoring Components

Performance monitoring has five components or steps:

1. Data acquisition
2. Data management
3. Data processing
4. Data interpretation/result generation
5. Result delivery

Historically, these steps were all performed separately: field technicians would collect data and samples and transcribe data into notebooks; laboratories would analyze data and submit results to contractors; data reduction and processing would be done by technically proficient staff using a number of software applications; and results would be delivered to stakeholders in hardcopy reports complete with graphs, tables and texts interpreting these results. Data management typically consisted of keeping all notebooks in one office, all data in a number of spreadsheets, and all reports on the bookshelf. The result was a cumbersome, expensive process that was inefficient in meeting monitoring objectives. Also, commonly, samples were collected but never used, there were inconsistencies in field data that were never detected, and final monitoring results were sometimes faulty and impossible to duplicate.

Over the last ten years, many advances have enhanced monitoring efficiency. For instance, data acquisition and data transfer for numerous physical sensors are easily and cheaply automated; data storage in relational databases (as opposed to spreadsheets) are common; a range of application packages exist for data analysis and interpretation; and results can be distributed electronically on forms that allow limited user interaction with the data (e.g. through web based GIS Systems).

However, while data acquisition and data management practices have improved, data access, data processing, interpretation and result delivery have not become easier: specifically, expert knowledge is typically still required to obtain specific information from a monitoring system. In addition, as the amount of data and the complexity of analysis steps continue to increase it becomes more difficult to make sense of such data and results efficiently. Many sites have hundreds of wells, each of which is sampled periodically and analyzed for multiple constituents. Thus, with increasing site complexity and data density it has become increasingly more complex to obtain reliable information.

In summary, while there have been many technological enhancements to each of the individual monitoring elements (including the ability to perform complex analysis and run intricate numerical models on standard desktops), these have paradoxically not resulted in transparent, reproducible or easily accessible results. One example of this are the recent issues at the Yucca Mountain site (Wald 2005). One way to resolve this is by implementing performance monitoring as a workflow.

A workflow is defined by the Workflow Management Coalition (Coalition 1999) as "*the automation of a business process, in whole or part, during which documents, information or tasks are passed from one participant to another for action, according to a set of procedural rules".* Following this, a performance monitoring workflow system can be defined as "*the automation of performance monitoring (including data acquisition, management and reduction) according to a set of procedural rules*".

A Workflow System For Performance Monitoring

A workflow system for performance monitoring should have the following attributes:

- Ease of use by users with broad and varying degrees of expertise. Users may access such a system on either a daily or monthly basis, and such a system should provide users with rapid access to relevant information.
- Ability to perform information generation in an auditable, transparent and reproducible manner.
- Ability to integrate existing systems and applications for data acquisition, data analysis, and result generation. This is driven by both the investment in existing data gathering and management efforts, as well as the regulatory acceptance of desktop-based analysis and modeling codes.

Based on these considerations, we implemented a workflow system for performance monitoring that follows the general structure of scientific workflow systems and has the attributes listed above. Our system at Gilt Edge is a web application, meaning that it can be accessed and controlled through a standard browser (Fig. 2). The system consists of a heterogeneous, automated data acquisition infrastructure, a centralized server which periodically receives data (using web service calls) from each of the acquisition components, several linked databases which hold both the field data, calibration values and processing instructions, and a suite of tools (encoded in PHP, a general purpose scripting language (www.php.net)) which perform data processing and visualization. A visual interface to the data is encoded using dynamic java script and html/css.

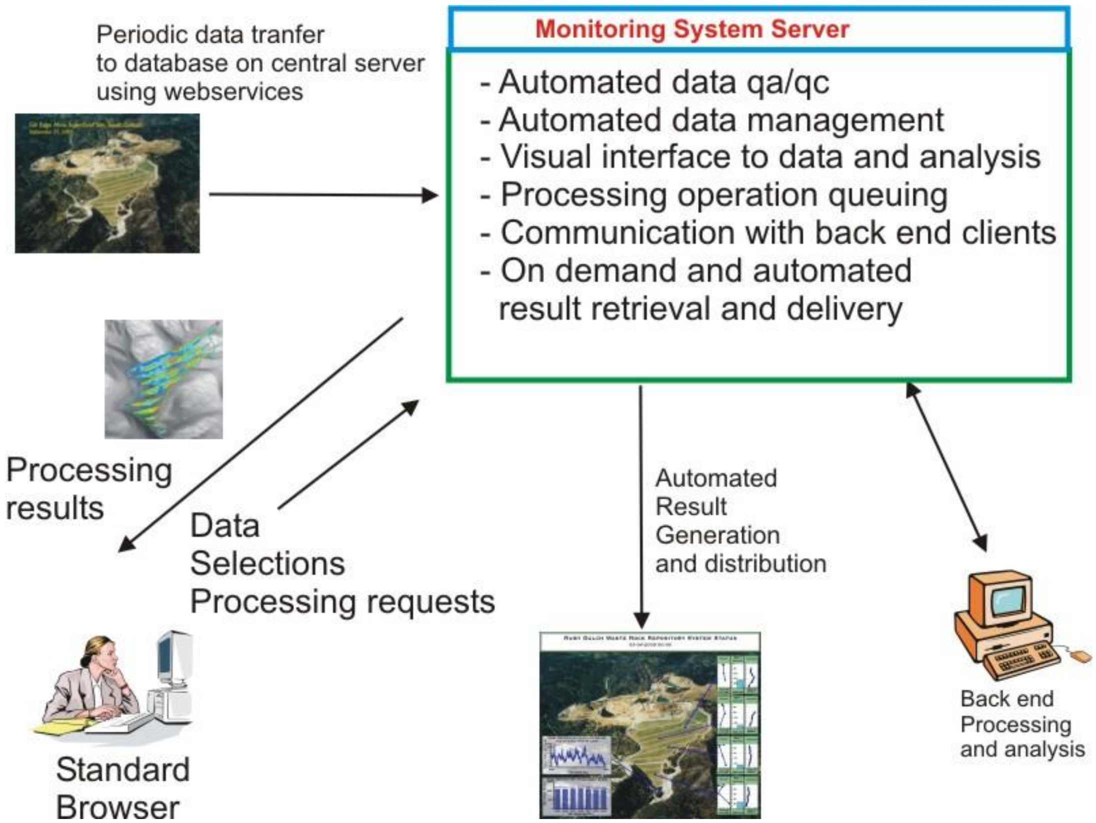

Figure 2. Outline of web-based workflow environment for environmental site monitoring. The example shown is for the Ruby Gulch Repository monitoring system (Versteeg, Heath et al. 2003; Versteeg, Ankeny et al. 2004)

Our implementation has a number of elements that differentiate it from traditional workflow systems. For instance, instead of using a dedicated workflow language we use PHP. This is partly driven by the implementation of our workflow system as a web application and partly by the fact that PHP does allow us to treat data and operators in an abstract manner. Thus, in this structure we can easily define and implement operations such as "calculate a least squares fit to data from the temperature sensor located in well 1 at 20 feet," and delegate the underlying operations (retrieve data, pass the data to the statistical routine, and retrieve and visualize results) to underlying modules. Note that PHP does not have intrinsic workflow language attributes such as parallelism of task execution or task synchronization – these have to be coded in explicitly.

Our implementation of this workflow system also differs from packages such as Kepler (Fricke, Ludaescher et al. 2004) and myGrid (Oinn, Addis et al. 2004) in that users have a finite set of workflows which the user can execute on a large catalog of datasets. In other systems users can compose their own workflows. However, as workflow composition requires substantial understanding of the underlying IT structure, we chose a model in which novel workflows are defined centrally, and in which users can modify parameters and data within existing workflows.

Another important feature in our system is tight integration between data acquisition, data management and data analysis. Within environmental monitoring, the chain of custody for data and processing is extremely important. Through the integration, we can provide reproducibility of results (Schwab, Karrenbach et al. 2000) as well as transparency in result generation.

A fourth feature is the use of stand alone applications for result generation (Versteeg, Rowe et al. 2005), which allows us to access existing third party applications (for graphing, statistics, modeling and inversion) using standard, platform-independent protocols.

The final feature is the implementation of this system as a web-accessible system. This is done for several reasons. First, it removes the need for users to install desktop software and the attendant need to install and maintain databases. Second, it provides a common interface and access point for all users. Third, such an interface allows for the easy capture of all the parameters used to generate a particular result. Or, as we capture user parameters as they generate a result, we can encode these parameters in association with the result, providing instant reproducibility as well as transparency.

Back End Implementation of the Performance Monitoring Workflow System for the Ruby Gulch Rock Repository

Data for our workflow system are provided by an autonomous network of hydrological, geophysical and environmental sensors. Details on the sensor network and examples of system output are provided in (Wangerud, Versteeg et al. 2006). Once data are transmitted (automatically) from the sensor network to the server they are automatically analyzed and become available for users to investigate. A data flow providing some technical details of our system is shown in Fig. 3.

1. The flow of data and information follows the following steps. Note that the numbers of each step correspond to Fig. 3. Data are collected in flat files by a standalone acquisition program at the monitoring site. Each file is encoded in XML (e**X**tensible **M**arkup **L**anguage) and is self-describing. Data are periodically transmitted to the server via web services.
2. As soon as the data are received, automatic qa/qc is performed on the data according to a pre-defined workflow. If problems exist with the data (or if no data are received for a specified period of time), an alert is generated to the project administrator(s).
3. Data selection interfaces are generated on demand. These interfaces are implemented in DHTML (dynamic html with javascript), and are accessed through a web browser. (Fig. 4). This allows for a rich interface in which data selection can be narrowed down by the user through the browser. In this structure AJAX methods (asynchronous javascript and XML) (Garrett 2005) are used to provide additional data selectors. Other approaches to client side data selectors could include java applets (Dadhania, Greenwald et al. 2004).
4. A user selects a data source, a time period, and a workflow to apply to the data. Once the user submits the request, the raw data is calibrated using calibration relations appropriate

for the time period, and the data enters the workflow. The appropriate workflow is then executed using the data and parameters selected by the user.

5. At the completion of the workflow, results are returned to the client to be displayed to the user, typically in a separate browser window as a PNG (**P**ortable **N**etwork **G**raph, a standard graphical format) encoded graph.

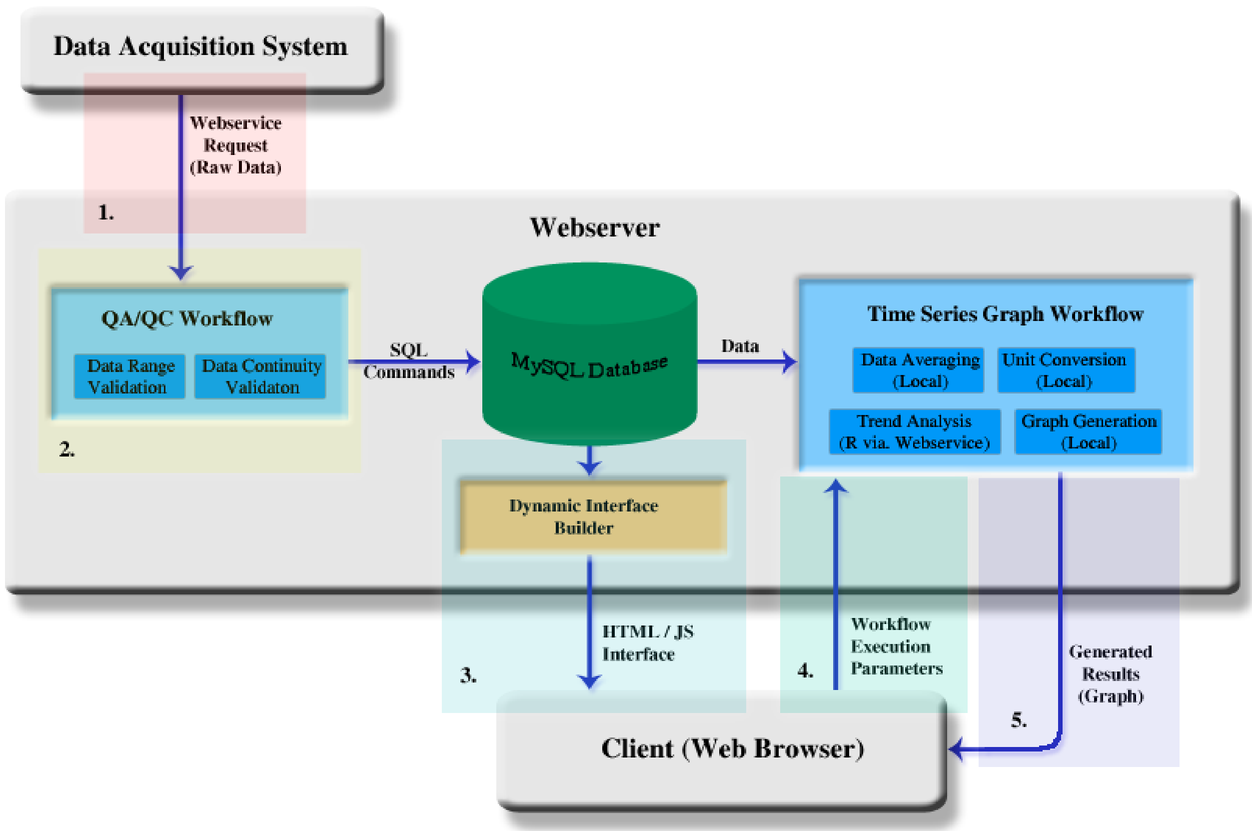

Figure 3. Example of data and information flow in our workflow system

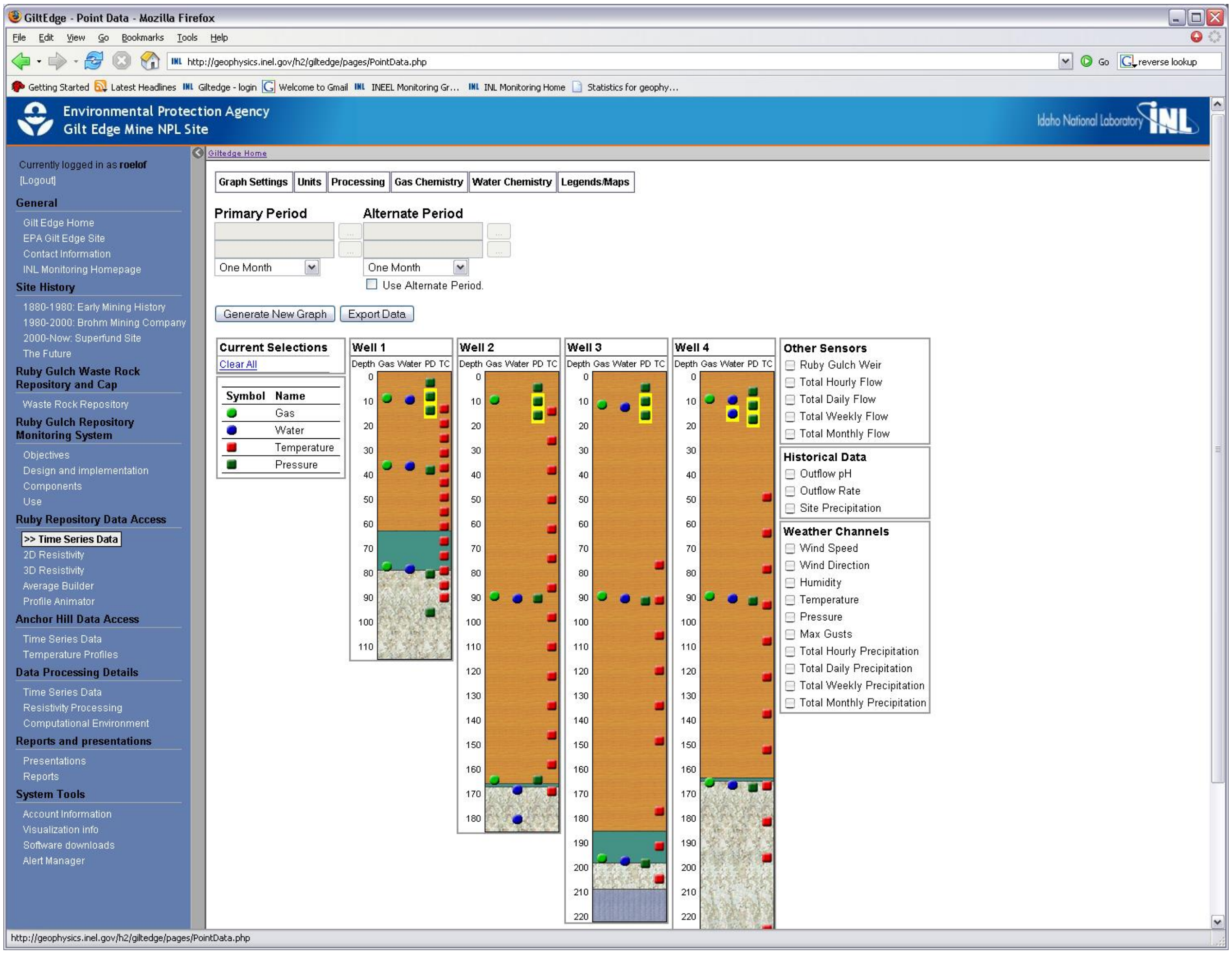

Figure 4. Data selector interface. This interface is created dynamically from the sensors/channels that exist in the database.

Summary: System Management Using a Web-Based Performance Monitoring System

The combination of automated acquisition, data analysis and result generation through well defined workflows provides for a system which allows the generation and timely delivery of actionable information on system performance. For instance, users get alerts when unusual events occur, and can follow the temporal evolution of electrical resistivity imagery of the dump and examine correlations between multiple parameters. Adding additional workflows to the system (e.g. the generation of an automated report which performs trend analysis or correlation on data and reports the results) is relatively simple as the system is modular: as long as an analysis can be described exactly, it can be implemented. As there is complete transparency, reproducibility and an easy interface to get at data and results from this system have shown to meet and exceed end user needs.

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