THE COLORADO SATELLITE-LINKED WATER RESOURCES MONITORING SYSTEM: 25 YEARS LATER

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ABSTRACT

The Colorado Satellite-Linked Water Resources Monitoring System was initiated as a two-year pilot demonstration project in the early 1980's in Colorado's Arkansas River and Rio Grande River Basins. The system was formally established with funding from the Colorado Water Resources and Power Development Authority in 1985. By the end of 1985, an effective monitoring network of 150 stations had been established. The Satellite Monitoring System (or SMS, as it is now called) was turned over to the State Engineer's Office (aka the Colorado Division of Water Resources, CO DWR) to operate and maintain in October 1985. Today CO DWR operates and maintains over 500 satellite telemetry gage stations on rivers, streams, ditches and reservoirs around the State. In combination with satellite telemetry gaging stations operated by the USGS, and gage data from other State and local agencies in Colorado, water resources data from over 900 sites are available in near real time from the Colorado Surface Water Conditions web site (www.dwr.state.co.us). This paper will chronicle the continuing development of this important water resources management tool in Colorado, including changes in technology, information management and delivery, system expansion, coordination with other agencies, and the ever-increasing ways in which the data are used. Although not a SCADA system, many gages on the network provide dual benefit for collection of data for the SMS as well as for direct feed to SCADA systems operated by gage cooperators.

BACKGROUND

Colorado water law has its roots in the gold rush days of the late 1850's and early 1860's, when miners used water to work their claims regardless of the location of the claim relative to the water source. Due to the relative scarcity of water in the Intermountain West and the sporadic nature of the supplies, these early water use rights also were based on the concept of "first in time, first in right". As mining went through its boom and bust cycles, homesteading and development of agriculture followed closely behind. Prior to Colorado statehood in 1876, territorial laws were enacted allowing water to be taken from streams and rivers to lands "not adjoining the waterway", as well as recognition of rights of way to transport water across lands not owned by the owners of the water right.

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The Colorado Doctrine, or the Doctrine of Prior Appropriation, recognizes: a) those that put the water to use first are entitled to get their water first during periods of water shortage, and b) water is a separate property right that can be sold separately from the land. This is opposed to the Riparian Doctrine that ties water use rights to the ownership of lands adjacent to the river or stream. The codification of fundamental Colorado water law is found in Colorado's 1876 Constitution, Article XVI, Sections 5, 6 and 7. These basically state: water within the State of Colorado is a public resource belonging to the citizens of the State; the right is recognized to divert unappropriated waters of any natural stream and apply that water to beneficial use with priority of appropriation determining who gets water first in times of shortage; and, the right is recognized to convey water across public, private and corporate lands upon payment of just compensation.

In 1879, the legislature created a part of Colorado's present water administration system. It provided for the division of the State into ten water districts, nine of these in the South Platte valley and one in the Arkansas. The position of Water Commissioner was created with this legislation for the express purpose of allocating and distributing water according to the doctrine of prior appropriation. The statute as passed by the legislature in 1879 did not provide for stream measurement.

In 1881, the Colorado legislature established the Office of the State Hydraulic Engineer. The purpose of this office was to assist in carrying out the provisions of certain portions of the irrigation laws passed at the same session, and to obtain important information by means of surveys and observations. Primary responsibility was the administration of water rights according to the appropriation doctrine, "first in time, first in right," by maintaining a list of water rights, on each stream, in order of priority. The priority of a water right is determined by both when the water was first diverted and put to a beneficial use and when the right was decreed by the district court. Additionally, the State Engineer shall: "shall make, or cause to be made, careful measurements and calculations of the maximum and minimum flow in cubic feet per second, of water in each stream from which water shall be drawn for irrigation, as may be best for affording information for irrigating purposes; commencing with those streams most used for irrigation; also to collect facts and make report as to a system of reservoirs for the storage of water, their location, capacity and cost; and he shall keep proper and full records of his work, observations and calculations."

These two early pieces of legislation formed the basis of the system of water administration still in use today: measurements of the amount of water in rivers and streams over time provide the data needed and used by water commissioners to administer water rights according to the State's Constitution. Early on this process was difficult. Only infrequent observations of the amount of water in various water courses were possible, only in a few locations, and these observations suffered from inaccuracy and imprecision. In 1883, Colorado's second State Engineer, E.S. Nettleton, designed and developed the Colorado Current Meter, cups or vanes rotating in a horizontal plane around a vertical axis, the speed of rotation of which could be directly related to the velocity of water impinging on the vanes. This design is the basis of the Price AA current meter still widely used today. This advance greatly improved the ability to accurately measure stream discharge. In 1884, Nettleton designed and developed a stream stage recorder for use at streamgaging stations to collect continuous records of stream stage, which could be used to compute records of streamflow. The State Engineer's Office established some of Colorado's earliest stream gaging stations during this period: Cache la Poudre at the Canyon Mouth (1881), Arkansas River at Canon City (1888), and Rio Grande near Del Norte (1889), and are still operated by this office.

In 1887, the State created the position of superintendent of irrigation, the forerunner of today's division engineer, to supervise water commissioners within each division. By the beginning of the 1890's, many stream systems were over appropriated. The need to know stream flow rates over time and in many locations was becoming more widespread.

In 1969, the State legislature passed the Colorado Water Rights Determination Act. This legislation created the Colorado Division of Water Resources (CO DWR) as part of the Department of Natural Resources. The State Engineer's Office was incorporated as the CO DWR. CO DWR is empowered to administer all surface and ground water rights throughout the state and ensure that water is administered according the State Constitution and court decrees. CO DWR employs approximately 257 professional engineers and geologists, information technology professionals, technicians, and support staff to administer water rights, to evaluate and issue water well permits, monitor stream flow and water use, inspect dams and wells for construction and safety, maintain databases of Colorado water information, represent Colorado in interstate water compact proceedings, evaluate impacts of and necessary mitigation for various water use activities, educate the public, and numerous other responsibilities.

Significant development has transpired over the 134 years since Colorado became a State, including development of major urban centers (particularly on the Front Range), economic development, and agricultural development. Interstate compacts and agreements were developed describing how water, which has its source in Colorado, would be shared with downstream States. By the later decades of the 20th century, heavy stress on Colorado's limited water supply and on administration of that water supply was being experienced. Population growth has resulted in greater domestic demand for both surface and ground water. Colorado's water administration has attempted to keep pace. Increasingly complex water court decrees, augmentation plans, exchanges, etc. have been developed and executed.

DEVELOPMENT OF THE COLORADO SATELLITE-LINKED WATER RESOURCES MONITORING SYSTEM

As discussed above, by the early 1980's, Colorado water administrators were experiencing greater and greater need for timely and accurate water resources data at more and more locations Statewide. To help meet this need, a two-year demonstration project was designed and implemented in the Arkansas River and Rio Grande River basins, in which, continuous water resources data were collected at key gaging stations and provided in near real-time via satellite telemetry to decision makers. The project successfully demonstrated that water rights administration, hydrologic records development, flood warning, and water resources management could be significantly enhanced.

The Colorado Water Resources and Power Development Authority provided initial funding for this project pursuant to Section 37-95-107(5), C.R.S. (1983), by enactment of Senate Joint Resolution No. 20. The Colorado Water Resources and Power Development Authority has, as one of its goals, enhancement of water resources management in Colorado. The Authority provided funding for system establishment and its first year of operation at a total cost of $1.8 million in 1984.

The Authority awarded the contract, under competitive procurement, to the Sutron Corporation, Herndon, Virginia, in May, 1984. The original contract called for Sutron to provide a turn-key system including remote data collection hardware for 82 stations, receive site, central computer, and operating/applications software. In March 1985, the Authority approved an expansion of the monitoring network by an additional 68 stations. This effectively brought the statewide network to 150 stations. The system acceptance test was successfully run on August 8, 1985. The system was formally dedicated on October 4, 1985. At that time, the Authority turned the system over to the State of Colorado under the jurisdiction of the Office of the State Engineer.

Early System Description

The SMS allows the Division of Water Resources to collect, process, store, and distribute many kinds of environmental data transmitted from remote locations. The data set of interest to the Division is the water level at rivers, streams, diversion structures, and reservoirs. The SMS converts these raw water level values into several "products" of use to various "clients". The "products" range from raw data passed on to other computer systems to the official Hydrographic Records of mean daily stream flows. Clients include Division of Water Resources personnel and other water users wanting real-time administrative data, computer systems performing other analyses, and the varied user community of state and federal agencies, municipalities, canal companies, attorneys, and consulting engineers needing access to real-time and historic stream flow data.

The SMS consists of four primary sub-systems: 1) the remote station data measurement, collection, and transmission hardware; 2) the satellite communication links and transmission receive hardware; 3) the computer hardware and software systems; and 4) the computer-based hardware and software for making data available to users.

Data collection, measurement and transmission hardware was generally installed in existing stream, diversion, or reservoir gauging stations, and included on-site sensors, a programmable Data Collection Platform (DCP) and radio transmitter electronics, a power supply, and a radio antenna. The primary sensor for measurement of stream stage or water level was either a float actuated incremental shaft encoder operating in a stilling well hydraulically connected to the stream or reservoir, or, a manometer or other type of pressure transducer, or a direct discharge meter. Often air temperature sensors and other meteorological sensors were also present. The DCP is a programmable device that collects, processes, and stores data from up to 16 sensors. It also controls the timing of the satellite radio transmissions. Most sites are powered by 12-volt batteries re-charged by solar panels. If available on site, 120 volt AC power was used and converted to 12 volt DC current. Environmentally secure enclosures were used to protect the equipment from extreme weather and unauthorized access.

In the early years of operation, remote site hardware consisted of a Sutron 8004 DCP (Fig. 1) that would measure data every 15 minutes from a 0-5 volt shaft encoder and then transmit the values every four hours at a data transmission rate of 100 bps. Transmission time windows were one minute in length. The DCP was programmed using command driven software by connecting a portable computer via an RS-232 port. Very little diagnostic insight about DCP operational performance was provided. The 8004 was limited to storage of 32 data values per connected sensor. In most cases, this amounted to 8 hours of 15-minute data. With scheduled transmissions at 4-hour intervals, this provided replicate data in case of a missed transmission. A DCP could be programmed to detect if stream stage or water level conditions exceeded programmed threshold levels. When such conditions occurred, transmission of such random events on a separate channel for random messages could be enabled, providing real-time alarm warnings. A major operational issue was the need to maintain accurate time (GMT) in the DCP in order to keep satellite transmissions within the required transmission time window for the specific gage site. Many transmissions were missed due to incorrect GMT time entry, and, over time DCP clocks would drift. Additionally, transmission circuits would drift requiring bench re-calibration.

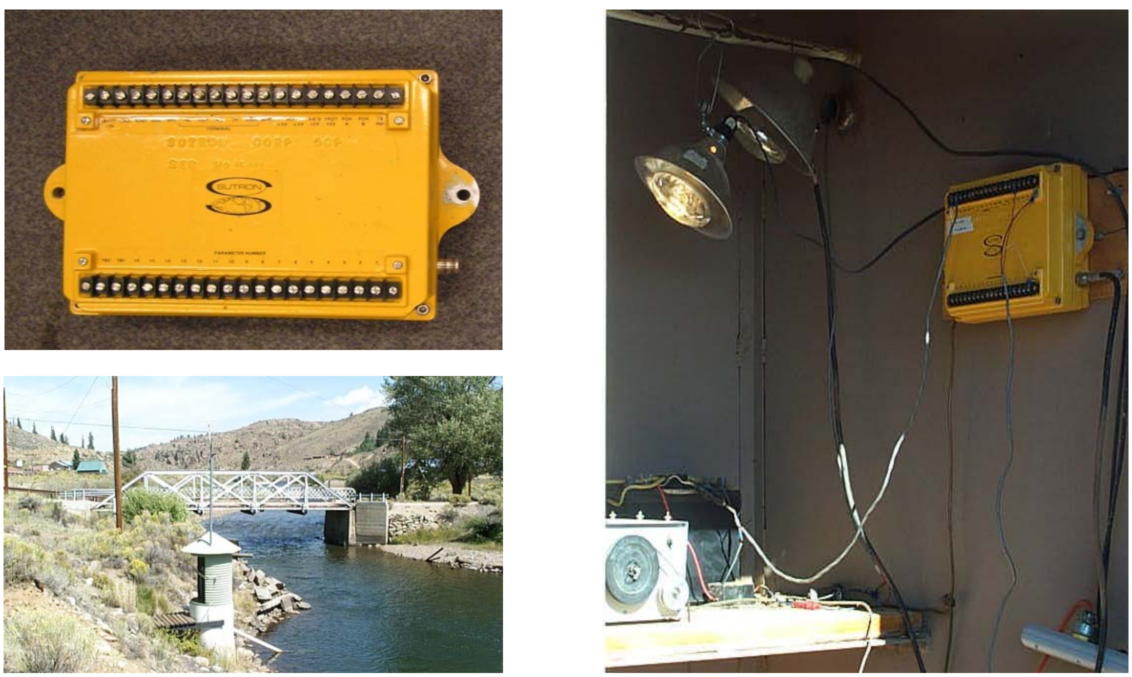

Figure 1. Early Colorado SMS DCP and gage installation.

The system was expanded in the 1990's using Sutron 8200 DCPs. The 8200 could measure and log data from several different types of shaft encoders and could store up to one year of data in internal memory. New bubbler-type pressure transducers were introduced in the field to replace mercury manometers. The DCP was programmed by menu driven software, but now had a one line display and front panel keypad for configuration and viewing of data. Many transmissions were still missed due to clock and transmission circuit drift.

The communications link for data transmissions from the remote site DCP is a Geostationary Orbital Environmental Satellite (GOES). This is a federal satellite operated by the National Oceanic and Atmospheric Administration-National Environmental Satellite, Data, and Information Service (NOAA-NESDIS). The GOES satellite is in equatorial, geostationary orbit 22,500 miles from the earth surface in space. The Division of Water Resources originally installed a Direct Readout Ground Station (DRGS) to receive this data directly from the GOES satellite. In the mid 1990’s, this method was converted to what is called a local readout ground station which receives and processes data transmitted on a domestic communications satellite. The NOAA Data Collection System (DCS) receives all GOES transmissions at its Command and Data Acquisition Station at Wallops Island, Virginia then retransmits the data over one channel to a domestic communications satellite visible from all of North America. This satellite (DOMSAT) broadcasts back to earth with much more power than the GOES system. The more powerful signal allows use of a much smaller 1.8-m diameter antenna and much simpler electronics. Since the DOMSAT multiplexes all data on one channel data from any remote site can be received without additional electronics.

The first main computer used on the SMS was a Digital Equipment Corporation (DEC) VAX 4000-300. This system gathered data from the DRGS electronics and from the DOMSAT receive system running on a PC. Real-time software automatically processed converted, and stored the incoming data. The conversion calculations used the most up-to-date stage-discharge relationships for a given stream gage and hydrographic shifts, as determined by actual measurements, to reflect changes in the stream channel characteristics. The system processed meteorological information in a similar manner. Every morning the system processed the previous day's data and calculated mean values, minimums, maximums, and other statistics, placing the results in a separate database. To preserve the integrity of the data, the original raw satellite data were archived unedited in a separate database. An internally developed system extracted a subset of the original data for editing and hydrologic streamflow record development. Other programs allowed users to access data and to control the system.

Several methods of communications access and data dissemination were supported in the early years. Using a PC and a modem, users anywhere in the world, with proper authorization could access the system. In 1995, CO DWR installed newer, high speed 28.8kb modems. This provided users with a better level of service through much higher data transfer rates. Eventually applications were developed allowing users to connect to the system and access data through the Internet.

The Colorado Satellite-linked Water Resources Monitoring System received national merit awards in 1985 and 1986. The National Society of Professional Engineers selected the system as one of ten outstanding national engineering achievements for 1985. The

Council of State Governments selected the system as one of eight of the top innovative programs instituted by state government in the nation for 1986. At the time, Colorado was the only State in the nation to operate a statewide monitoring system of this type.

On-Going Development

The interest in real-time data collection for monitoring water resources and other natural resources data grew at an incredible rate due to the need for such data and the cost effectiveness of this approach to data collection, processing and dissemination. Table 1 shows the growth of the SMS at five-year intervals since inception. Various federal agencies (primarily the US Geological Survey), water conservancy districts, municipalities, and private entities operate satellite-linked data collection stations in Colorado in addition to the State-operated network.

Table 1. Growth of the number of gaging stations (operated by CO DWR and by other agencies) included in the Satellite Monitoring System since inception.

Year	CO DWR	USGS and Other Federal, State, Local Agencies	Total
1985	52	98	150
1990	57	101	158
1995	229	176	405
2000	324	264	588
2005	462	276	738
2010	518	384	902

During the past decade alone there have been significant advances in technologies employed in the SMS for data collection, data processing, and data presentation to end users. The year 2000 (Y2K) brought about the end of the use of the VAX main frame and DB2 database on the SMS due to incompatibility issues. At that time the satellite monitoring database was migrated to SQL Server 2000 and initial data processing was accomplished on a redundant set of workstations. Each workstation was connected to one of the satellite dish receivers at CO DWR. Data from the receivers was processed and decoded, and then the processed data was fed into both an internal data system, and out through a set of TCP/IP sockets. Alert, Decode, and Diagnostics sub-systems (hosted on the main application/database server), each ‘listened’ on their respective sockets for feeds from the decoding software. These received and then processed the data messages into the main database, where the processed information was used by other sub-systems and applications. The USGS and NCWCD sub-systems (hosted on the development server), received and processed data from their respective cooperator agencies and also stored the data in the main database.

The Data Processing sub-system performed additional calculations or summaries as necessary. This final processed data was then made available to the web reporting database, applications, and tools. Internal Data Viewing and Management Applications were used by CO DWR personnel to manage aspects of the Data Processing sub-system, check the status of field equipment, or retrieve real-time stream-flow results from the database archive. The Hydrologic Management System, a PC client-based software tool, allowed CO DWR hydrographers to update rating tables, shifts, and shift curves used when calculating streamflow results, and the SatMon Telemetry Editor allowed IT personnel to update decoding information. Real-Time Archive and Diagnostics Reporting Systems were intranet based web applications that allowed users to retrieve flow data from the database, as well as to check the status of field equipment by reviewing reports of the diagnostic data sent with each satellite transmission.

In 2000, a simple web site was created for public access to hydrograph displays and tabular data of current stream conditions and up to the last 10 days of historic data. Additional historic data requests required the user to contact CO DWR. In 2004, an internal Alert notification system was added so that specific threshold stream and reservoir conditions could be monitored and notification alert messages generated when thresholds were met or exceeded.

Several improvements were made to the data processing and presentation sub-systems during 2007-2008. These included:

- Extensive upgrade and re-formatting of the stream flow web site allowing enhanced viewing and analysis of current conditions and historic data
- Development of web-based applications for system administration
- Migration of the satellite monitoring database to SQL Server 2005
- Added gage data from a new cooperative program (discussed below) with water conservancy district gages for display on the CO DWR web site
- Upgraded satellite data decoding to a near industry standard LRGS process developed by Ilex Engineering. This new system can capture data from both satellite and/or Internet sources
- Developed and implemented Windows services to process incoming data to improve system stability and integrity
- Added historic data retrieval and analysis features to the web site
- Allowed users to define custom station lists

Current SMS Configuration

Due to near saturation use of available channels on the GOES satellite system, in 2001 NOAA-NESDIS began a process to convert from 100 bps transmissions within one-minute windows every four hours to “high data rate” transmissions at 300/1200 bps in 6 to 15 second windows every hour. This conversion process was formally implemented in 2003, and NOAA-NESDIS has allowed a 10-year period for upgrades. As a result the capacity of the GOES satellite system has increased significantly. For the CO SMS, upgrades have typically involved complete replacement of remote site equipment. Upgrade costs have been in the range of $4000 to $5000 per gage.

Currently, the typical configuration at CO DWR SMS gaging station consists of a Sutron Satlink2 high data rate (hourly transmissions at 300 bps) DCP along with a serial digital interface (SDI) shaft encoder or a bubbler type pressure transducer called a Constant Flow Bubbler. The Satlink2 DCP is programmed using Windows-based software. DCPs are typically configured to collect and log data every 15 minutes. Data are store in flash memory for up to 3 years. The Satlink2 provides the user the option of also installing up to four analog sensors (such as air temperature) and includes a separate input for a tipping bucket rain gage. Several gages in key areas are setup to log and transmit these additional parameters.

By virtue of the implementation of high data rate transmission and shorter time windows in which to successfully complete transmissions (6 to 15 seconds) DCP clock reliability has had to improve. This has been accomplished through use of GPS synchronization that acquires GMT time every hour to ensure accurate DCP clock time. Transmissions occur once every hour at an assigned time given by NESDIS. Four hours of data are transmitted each hour, with three of the four hours being redundant data.

The Satlink2 DCP may also be programmed for alert levels. High threshold alert levels are used to monitor potential flood threats, low threshold alert levels provide protection for low flow instream water rights, and rate of change threshold alerts are used to monitor flows at gages below reservoirs. Once an alert level is detected the DCP will then transmit data values on a separate random channel. These may be viewed real time on the web site or activate an alert messaging service described later.

Sutron has been the primary supplier of data collection platform and satellite telemetry equipment since the SMS was initiated in 1985. This attempt to standardize on equipment has resulted in the following benefits:

- equipment compatibility issues are non-existent or minimal
- staff efficiency in terms of training requirements is improved
- staff develop better understanding of equipment operation, maintenance and troubleshooting when from a single source rather than multiple sources,
- costs of ancillary equipment, parts, pieces, tools to support a single line of equipment rather than multiple lines are reduced
- diagnostics test equipment costs are reduced

CO DWR is currently in the final stages of a multi-year program to upgrade satellite equipment at gaging stations throughout Colorado to high data rate. It is expected the upgrade process will be completed during 2010. Part of the upgrade process has included installation of: a) proper grounding and isolation equipment to improve operational reliability at field sites, b) improved gage power supply equipment (better batteries and solar panels), c) more accurate 400 count per rotation SDI shaft encoders to replace older 200 count per rotation shaft encoders, and d) Sutron Constant Flow Bubblers to replace older bubbler type pressure transducers for better performance and operation diagnostics. Figure 2 presents photos of several upgraded gage stations showing the improved components.

Improvements and upgrades to the SMS data processing and presentation sub-systems have continued as well. Once data have been transmitted to the GOES satellite, the

Figure 2. Photos of CO DWR gaging stations showing equipment upgrades.

NOAA CDA station at Wallops Island decodes the data from the transmission and then makes it available in 2 ways: by rebroadcasting data to the domestic satellite (DOMSAT), and by streaming to the Internet where users may access and capture the data stream via a Local Readout Ground Station (LRGS). There are multiple LRGS stations around the country that access satellite transmissions through a Direct Readout Ground Station (DRGS) and make the transmissions available through an LRGS to the Internet.

Data messages are received at CO DWR through an LRGS. The LRGS is a Windows Server 2003 PC. It is configured to receive transmissions primarily through a DOMSAT receiver connected to the satellite dish on the Centennial Building. A new feature is if the receiver signal fails, then the LRGS will automatically switch to a TCP/IP connection and retrieves data messages through a USGS LRGS system (the Emergency Data Distribution

Network) in Sioux Falls SD. A second LRGS platform sits in a “hot-standby state” as an emergency backup. Figure 3 is a diagram illustrating the current configuration of hardware components used in the SMS from remote field sites to the LRGS server in Denver.

Data are decoded by the LRGS software and stored as text files on the local server. Each LRGS decodes and stores 30 days of data transmissions. Processing is performed by a series of applications running as Windows services. The Data Loader Service takes files decoded by the LRGS and pushes them to the SMS database. The LRGS server also runs applications as “Windows services” to retrieve and process data from cooperator agencies which, in turn, are stored in the SMS database. A USGS Data Service processes data from the USGS web site and stores the data. A NCWCD Data Service processes data via a web service and stores the data. The Data Processor service takes the initially processed data, and performs additional calculations such as discharge. A Diagnostics Service processes “raw” data from files decoded by the LRGS and pushes them to the SMS database. Data in these files is used to diagnose common problems with satellite transmissions. A separate windows service application performs additional data processing, and data is disseminated through a variety of means. Figure 4 is an illustration of the current configuration of computer hardware used to process and prepare data for presentation to end users.

Additional data processing systems and services have recently been implemented. The SMS Monitor Service is a Windows service that periodically checks each component in the data processing system. If any one component has failed to execute within a specified period of time, a notification email is sent to the system administrator. This service has added to the operational integrity of the system. The Alert System has been re-written as a Windows service which allows “subscribers” to be notified when transmitted data meets certain threshold criteria. These two services reside together on a Windows Server 2003 PC. In 2009, data analysis features were added to streamflow web site to replace an internal tool used by Water Commissioners called SatMon Tool. Also in 2009, a web service was created to provide data access by data cooperators on the SMS.

A few operational data processing statistics illustrate the volume of data handled by the SMS in its current configuration:

- 10,700+ satellite transmissions decoded per day
- 105,500+ data values stored per day
- 32,000+ diagnostics data values (signal strength, battery voltage, error codes, etc.) decoded per day
- 45,000+ data values from external providers processed and stored per day.

OPERATION OF THE SMS

The Hydrographic and Satellite Monitoring Branch of the CO DWR is charged with the operational responsibility of the SMS. The Branch’s primary efforts are directed towards collection and dissemination of accurate, high quality 'real-time' surface water (stream and reservoir) data to support CO DWR's water rights administration mission. The Branch currently operates and maintains nearly 520 gaging stations throughout Colorado, and coordinates with the USGS and other State and Federal agencies that operate approximately an additional 380 gaging stations in the State. Primary objectives

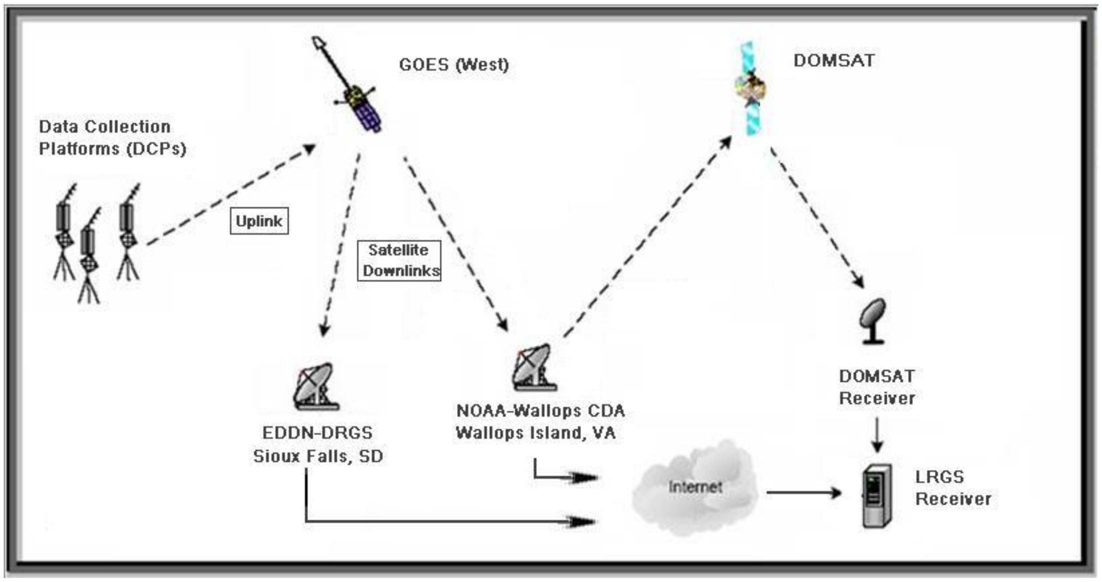

Figure 3. Diagram illustrating the hardware components of the Satellite Monitoring System.

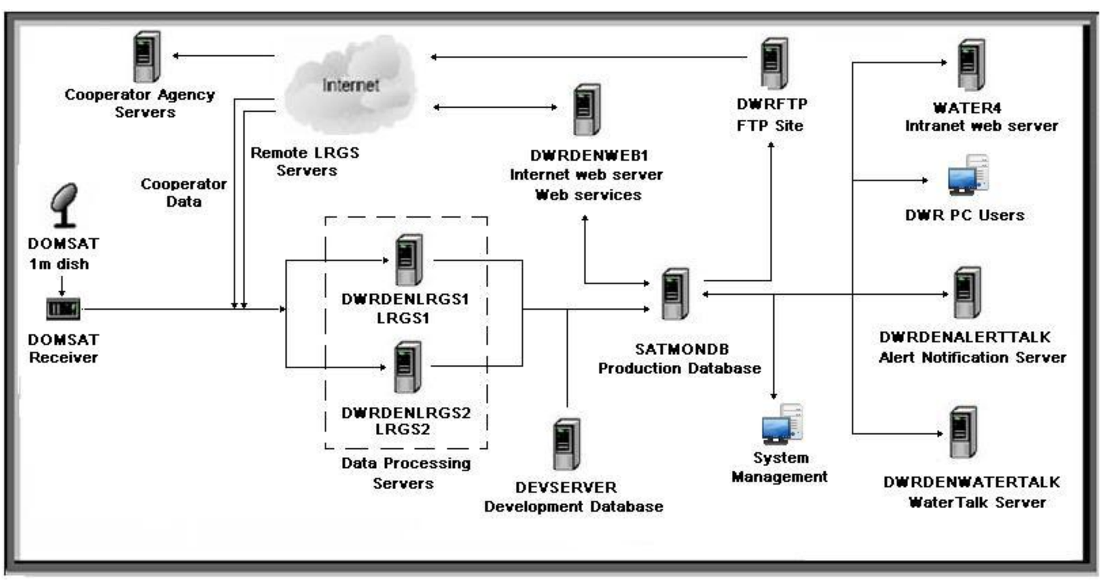

Figure 4. Diagram illustrating the hardware components of the Data Processing System.

of this work are: 1) to conduct streamflow measurements at stream gaging sites along the State's natural rivers and creeks, and at major ditch and canal diversions, to maintain accurate stage-discharge relationships and 2) maintain water level (stage) sensing and satellite telemetry equipment to minimize operational downtime and missing data. The purpose of this work is to provide accurate water supply data at key locations to CO DWR water administrators, who, in turn, must distribute and allocate water according to the principals of allocation and public safety as established in the Colorado Constitution, court decrees, and Interstate Compacts while maximizing beneficial use.

Basic statutory authority vesting the State Engineer with streamflow measurement and monitoring responsibility is given in Colorado Revised Statutes (CRS) Section 37-80-102(1)(h), which gives the State Engineer general supervisory control over measurement, record-keeping, and distribution of the public waters of the state. Flow measurements are performed on rivers, streams, creeks, major ditch and canal diversions to support increased water administration accuracy and efficiency.

CRS Section 37-80-110(1)(i) authorizes the State Engineer to collect fees for water measurement work done by his office "for rating any ditch, canal, reservoir inlet or outlet, at the request of the owner thereof or of any agent or employee having control of the same". Section 37-80-117 requires owners/operators of canal and ditch diversions to cooperate with authorized hydrographers to regulate flows in the canal or ditch when it has been deemed necessary to perform rating measurements to make a rating of any weir or flume or measuring section of any canal or ditch.

CRS Sections 37-84-112 to 37-84-122 discuss responsibilities of water users and owners of ditches, canals, measurement structures, reservoirs and other facilities for diversion and use of water with respect to specifications, construction, and maintenance of such facilities. Section 37-84-114 requires the state engineer or division engineer rate the measuring flumes and weirs referred to in these sections, and maintain records thereof. Section 37-84-122 describes the penalties when any division engineer, or his deputy or assistant, willfully neglects or refuses, after being called upon, to promptly measure water from the stream or other source of supply into the irrigating canals or ditches, in his division.

Authority to house and operate the satellite monitoring system within the State Engineer's Office was given in CRS Section 37-80-102(10). Section 37-80-111.5(1)(c) created the satellite monitoring system cash fund and authorized the State Engineer to set and collect fees by rule and regulation for the use of the equipment and programs of the satellite monitoring system authorized pursuant to Section 37-80-102 (10). Moneys in the satellite monitoring system cash fund may be expended by the State Engineer for the purposes of Section 37-80-102 (10), subject to appropriation by the general assembly.

The Hydrographic Program is implemented substantially in accordance with the State of Colorado DWR Hydrographic Manual. This manual provides standard operating procedures to be followed by all CO DWR hydrographers and provides the basis for the technical guidance and administrative management for consistent, reliable and sound streamflow measurement and record development. Many of the standard operating procedures for streamflow measurement; gaging station design, construction and maintenance; and streamflow record development are directly attributable to US Geological Survey streamflow measurement and computation methods (USGS Water Supply Paper 2175: Measurement and Computation of Streamflow).

Maintaining database integrity is an important operations goal. Real-time data are of no value unless the data are accurate. Considerable effort is expended to ensure that remote hardware and sensors remain in calibration. While other entities operate about 43% of the stations in the State's monitoring network, they generally are not using the data to make real-time water administration decisions. This difference in the use of data makes efforts to keep equipment calibrated more difficult. Those entities more concerned with historic data do not have the same sense of immediacy as the CO DWR with its interest in water administration. State hydrographers visit SMS gage stations as frequently as every week, but generally at two to four week intervals. On-site flow measurements and any necessary adjustments to the equipment are made.

System diagnostics data help in monitoring the operation of the remote data collection hardware. Computer generated reports tabulate the transmission characteristics and a database analysis for each station for the previous day. Reports list the number of received, scheduled, and missed transmissions, any message length errors, transmission time errors, errors in transmission quality including power and frequency, any deficiency in remote power supplies, and the number of missing values and parity errors for each station. Remote equipment operating problems can be detected before they produce fatal errors.

Hydrographic field personnel receive training from the SMS Electronics Specialist in the operation and maintenance of system hardware. Training is directed at system diagnostics, hardware calibration, and basic repairs. Each Division is supplied with sets of replacement hardware. If a component malfunctions and cannot be repaired in the field, it is replaced and sent to the Electronics Specialist’s repair facility in Denver. If repair is not possible there or if the item is under warranty, it is then returned to the manufacturer for repair.

DATA ACCESS

The system was developed as a tool to help the Division of Water Resources administer and enforce user water rights and interstate compact agreements. Software systems and tools for accessing and retrieving stream flow data have been developed to support CO DWR personnel, outside agencies and the public. These systems provide both real-time and historic stream-flow information by a number of different means and formats. Users can access data from the system by different avenues depending on their need.

Colorado Surface Water Conditions Website

Raw and processed data are available to users at the Colorado Surface Water Conditions web site (www.dwr.state.co.us). This website queries the SMS database and provides users with current surface water conditions and provisional, historic data (both graphic and tabular). In addition to stream flow data, many gaging stations provide other environmental parameters such as precipitation, air or water temperature. Also, many of the state's reservoirs are included in the system to provide water surface elevation and storage contents in acre-feet of storage. The current conditions web site is an ASP.NET 2.0 application that connects to the SMS database to generate on-the-fly data pages to the web user.

Since 2008, the web site has offered a number of important features for the retrieval and analysis of surface water data. A "My Stations" section was added to the web site that allowed users to create a custom set of gaging stations. This custom set allowed users to quickly view gaging stations of special interest. That same year a feature was also added to allow users the ability to "overlay" data from multiple gaging stations, or multiple years of data from the same station. This feature provides users with the ability to compare multiple data sets.

Most recently, a feature was added to allow users the opportunity to view statistical information from a set of gaging stations. Statistics include daily averages, 24 hourly values (for user defined 24-hour period), and daily minimum and maximum values. Users may download these statistical values for further analysis. In 2009, the web site had 4,671,884 hits.

Links are also provided to historic data for published stream flow gages on the Colorado Decision Support System website (http://cdss.state.co.us/DNN/default.aspx).

WaterTalk

The telephony based application WaterTalk, provides data via a call-in telephone based system. WaterTalk is an automated water information phone line used to access specific stream flow data at stream gages located throughout Colorado. The system is comprised of a Dialogic telephony card mounted in a PC running Windows Server 2003. The telephony application, Active Call Center, runs as a Windows service to monitor incoming calls from the Dialogic card. When a call is detected, a series of scripts are executed to "walk" the caller through the system and retrieve the desired information. In 2009, WaterTalk processed 75,475 telephone requests.

In the process, the caller dials into the system and selects one of seven valid water divisions in the State. The system verifies the water division selected, and then asks the user to enter the code number for a station identifier within that division. If a valid code was entered, the system returns information pertaining to that station, including the descriptive name, date and time of the latest data reading, and the value at that time. In addition to selecting a valid water division, a user may select division 0, which in reality returns the latest data value recorded in the Satellite Monitoring System. This allows administrators to remotely test whether the system is up to date and functioning properly.

webHMS Web Site

The SMS system includes a web site to provide administrative functions. The webHMS web site was developed to provide Hydrographic Branch personnel with a user interface for gaging station management. Via this interface, staff can assess system status and perform system administration functions. These include managing gaging station data processing including shift and stage-shift relationship activation, rating curve application, and setting of message flags regarding station data quality and status. Satellite telemetry setup and configuration including how the gage data are to be decoded can be performed. Staff can access and evaluate satellite transmission diagnostic data including remote site GOES transmitter operational status, remote site battery voltage, remote site self-timed and random transmission activity, etc. Statistical reports summarizing the status of the system can also be generated.

ColoradoWaterSMS Web Service

The ColoradoWaterSMS web service was created to expose data from CO DWR stream flow and climate stations throughout the State. The web service was developed using Visual Studio .NET and resides on the same web server as the current conditions web site.

The goal of this service is to expose useful non-proprietary, non-security-sensitive data to our cooperators and anyone else interested in consuming it, and allows the user to develop their own program to consume and display data. Web services are for machine-to-machine communications, exchanging XML messages between the entity requesting information (client), and the entity providing information by responding to these requests (server).

SYSTEM APPLICATIONS

Water Rights Administration

The primary utility of the Colorado satellite-linked monitoring system is for water rights administration. The availability of real-time data from a network of key gauging stations in each major river basin in Colorado provides an overview of the hydrologic conditions of the basin that was previously not available. By evaluating real-time data for upstream stations, downstream flow conditions can typically be predicted 24 to 48 hours in advance. This becomes an essential planning tool in the hands of the Division Engineers and Water Commissioners. The "river call" can be adjusted more precisely to satisfy as many water rights as possible, even if just for short duration flow peaks caused by precipitation events. Access to real-time data makes it possible to adjust the "river call" to match dynamic hydrologic conditions. If additional water becomes available, additional junior rights can be satisfied. On the other hand, if water supplies decrease, then water use can be curtailed to protect senior rights.

The administration of water rights in Colorado is becoming increasingly more complex due to increased demands, implementation of augmentation plans, water exchanges, transmountain diversions, and minimum stream flow requirements. For example, the number of water rights has increased from 102,028 in 1982 to over 173,000 in 2007, and increasing numbers of water rights has continued to the present. Water rights transfers approved by the water courts are becoming increasingly complex. This is especially evident where agricultural water rights are transferred to municipal use.

There is considerable interest in monitoring transmountain diversions, both by western slope water users and the eastern slope entities diverting the water. Transmountain diversion water is administered under different laws than water originating in the basin. In general, this water may be claimed for reuse by the diverter until it is totally consumed. Forty transmountain diversions are monitored by the SMS.

Water exchanges between water users are becoming increasingly frequent. These exchanges can provide for more effective utilization of available water resources in high demand river basins, but can be difficult to administer. The satellite-linked monitoring system has proven to be an integral component in monitoring and accounting of these exchanges.

Many municipalities and major irrigation companies have reservoir storage rights. Generally, these entities can call for release of stored water on demand. The Division Engineer must be able to delineate the natural flow from the storage release while in the stream. He/she then must track the release and ensure that the proper delivery is made. The SMS has demonstrated to be effective in this area.

The utility of the SMS in the administration of interstate compacts is an especially important application. The State Engineer has the responsibility to deliver defined amounts of water under the terms of the various interstate compacts, but not to over-deliver and deprive Colorado of its entitlement. Data collected from over twenty gage stations operated by both the CO DWR and the USGS are incorporated in the statewide monitoring network and utilized for the effective administration of these interstate compacts.

The majority of the large, senior water rights in Colorado belong to irrigation companies. These rights are often the calling right in the administration of a water district. The direct diversion rights exercised can affect significantly the hydrology of the river. Dozens of major irrigation diversions are monitored by the system.

Water rights have been acquired by federal and state agencies to guarantee minimum stream flow for both recreational and fisheries benefits. As well, instream flow water rights have been developed by the Colorado Water Conservation Board to ensure minimum instream flows are maintained in critical stream reaches around the State. The availability of real-time data is essential in ensuring that these minimum stream flows are maintained.

Hydrologic Records Development

Specialized software programs provide for the processing of raw hydrologic data on a real-time basis. Conversions such as stage-discharge relationships and shift applications are performed on a real-time basis as the data transmissions are received. Mean daily values are computed automatically each day for the previous day. Data values that fall outside of user defined normal or expected ranges are flagged appropriately. Flagged data values are not utilized in computing mean daily values. Missing values can be added and invalid data values corrected by the respective hydrographer for that station using data editing functions.

Data can be retrieved and displayed in various formats including the standardized US Geological Survey-Water Resources Division annual report format adopted by the Colorado Division of Water Resources for publication purposes. An advantage of real-time hydrologic data collection is in being able to monitor the station for on-going valid data collection. If a sensor or recorder fails, the hydrographer is immediately aware of the problem and can take corrective action before losing a significant amount of data.

It is essential to understand that real-time records can be different from the final record for a given station. This can be the result of editing raw data values because of sensor calibration errors, sensor malfunctions, analog-to-digital conversion errors, or parity errors. The entering of more current rating tables and shifts can modify discharge conversions. Corrections to the data are sometimes necessary to compensate for hydrologic effects such as icing. Human error can also result in invalid data. The final record for those gauging stations operated by non-state entities, such as the US Geological Survey-Water Resources Division, is the responsibility of that entity. Modifications to the real-time records for these stations are accepted by the State of Colorado.

The Hydrographic Branch develops historic streamflow records in coordination with other State and Federal entities and the water user community. At the conclusion of each water year, the State Engineer’s Office compiles streamflow information and measurements conducted throughout the year for publication. Published streamflow records describe the mean daily discharge, the instantaneous maximum, lowest mean discharge, and monthly/ annual volumetric totals for a specific location on a river or stream. These annual streamflow records are computed using two critical sources of information: streamflow measurements made throughout the water year to calibrate the stage-discharge relationship at a specific site, and, the electronic record of stream stage collected by the satellite monitoring system. Using these data a continuous record of streamflow for the water year is computed. Streamflow records undergo a rigorous data quality control/quality assurance program to ensure the product is accurate. The Division of Water Resources Hydrographic program computes and publishes over 240 streamflow records annually. Published historical streamflow data are extremely valuable in support of water resources planning and management decision-making, assessment of current conditions and comparisons with historical flow data, and hydrologic modeling.

Water Resources Accounting

Currently, the SMS is being utilized for accounting for the Colorado River Decision Support System (CRDSS), the Colorado-Big Thompson Project, the Dolores Project, and the Fryingpan-Arkansas Project Winter Water Storage Program among others around the State. The ability to input real-time data into these accounting programs allows for current and on-going tabulations.

Dam Safety

Dam safety monitoring has developed in recent years into a major issue. Numerous on-site parameters are of interest to the State Engineer in assessing stability of a dam. At this time, the system monitors reservoir inflow, water surface elevation and reservoir release or outflow at more than fifty reservoirs in Colorado. These data provide a basis for evaluating current operating conditions as compared to specific operating instructions. The installation and operation of additional sensor types could provide essential data on internal hydraulic pressure, vertical and horizontal movement, and seepage rates.

COORDINATION AND COOPERATION

Formal streamgaging programs are administered by the CO DWR and the USGS Colorado Water Science Center, and have support from more than 60 cooperating organizations. Streamgaging programs are closely coordinated between the CO DWR and the USGS with funding and coordination assistance from the Colorado Water Conservation Board, to help ensure the data are comparable and easily accessible to everyone, including the provision of real-time data on the internet. Other organizations, including the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers, Northern Colorado Water Conservancy District, Denver Water, the cities of Aurora and Colorado Springs, and the Urban Drainage and Flood Control District, also collect streamflow information to support their project needs and make those data available to water users and managers. Coordination occurs on many levels; high level coordination, data chief coordination, and field staff coordination.

The CO DWR Director/State Engineer, the CWCB Director, and the USGS Colorado Water Science Center Director meet annually to discuss respective program and set policy directions that concern all entities. Topics include current projects, litigation involving water-quantification issues, and ongoing evaluations of the adequacy of the gage-network operations and coverage. Coordination of equipment purchases to upgrade streamgages is also discussed at these meetings. Coordination agreements allow the State to buy specialized equipment directly through the USGS Hydrologic Instrumentation Facility.

Coordination meetings also occur between the CO DWR Lead Hydrographers, the CWCB Gaging Coordinator, and the USGS Data Chiefs two times per year. These meetings enable our agencies to work cohesively and to effectively coordinate our work efforts at the operational level. Mutual objectives, opportunities, and conflicts are discussed and coordinated to facilitate better operations for all three agencies. Training opportunities are also shared between agencies at these meetings. Streamflow data coordination is one of the ongoing agenda items at the Data Chief Coordination meetings. Data are shared between the agencies and the public via websites and direct data feeds. Streamflow records from 15 gages sites operated by the CO DWR are reviewed and published by the USGS.

Day-to-day coordination occurs between the staff of all three agencies. Contact is made as needed and mutual support routinely is offered among the agencies. Help includes equipment repair and maintenance, and streamflow data troubleshooting. For example, if a hydrographer discovers a problem with another agency's gage while on site, a temporary repair will be made so data are not lost.

A recent cooperative program between CO DWR, Northern Colorado Water Conservancy District (NCWCD), Lower South Platte Water Conservancy District (LSPWCD), and Saint Vrain and Left Hand Water Conservancy District (SVLHWCD) has resulted in obtaining and presenting streamflow data from 65 additional gage stations at diversion, recharge sites, augmentation sites, and return sites for display on the CO DWR website. These gages are configured with Sutron Stage Discharge Recorders (basically a programmable shaft encoder with onboard datalogging and communications interface) and cell phone telemetry. Both the SDR unit as well as this cell phone telemetry paradigm were largely developed and refined by cooperative efforts between CO DWR and Sutron Corp. and NCWCD.

Data are transferred from the remote SDR sites to computer base stations in the NCWCD and LSPWCD offices on an hourly basis similar to the current SMS transmission interval and on-demand as needed, where the data is processed and made available so that the SMS system can access and transfer the data via an FTP service client. Data is then archived in CO DWR databases and displayed in a similar fashion to traditional SMS sites. Figure 5 is a photo of a cooperative program SDR/cell phone telemetry gage.

This system deviates substantially from the SMS system discussed earlier in that discharge computations are computed, processed, and logged wholly within the SDR unit rather than being computed based on parameters stored in the satellite monitoring database. Additionally, data transmission and data retrieval are not initiated from the field unit; rather the base computer stations call out and individually poll the sites at specified intervals. Special routines are in place to redundantly call a remote site if data transmission failed or if a data set is incomplete.

This program paradigm has proven to be a cost effective solution for obtaining data from multiple remote sites of mutual interest because of the lower initial capital inputs. As a result of the lower capital inputs and further development of the SDR units, simple automation has started to be installed or considered on some of these sites via the Sutron Ditch Master package.

Figure 5. Cooperative Program SDR/cell phone telemetry streamgage.

Another recent cooperative development has been to marry or merge multiple users of a gage to a single sensor capable of multiple data outputs (SDI-12 / RS-485 / SCADA). Historically, cooperative gages at which multiple users or entities were involved required multiple instruments to accomplish the same task due to their output requirements. Thus, a single gage may have several sensors performing the same task reporting to different systems. For example, a float-actuated shaft encoder would report stage values to a DCP via SDI-12, which is placed next to another float-actuated shaft encoder producing an analog signal to a Supervisory Control and Data Acquisition (SCADA) system. This paradigm caused the two data sets to differ, primarily due to instrument calibration issues. Moreover, many of the analog sensors had poor resolution.

Starting in 2007, a cooperative pilot program was developed embarked upon between the USBR and CO DWR within the East Slope of the Colorado Big Thompson (CBT) system, whereby gages that were cooperatively operated by the USBR and CO DWR were migrated to a single stage sensor system. Typical installations employed a Design Analysis Waterlog H-334 Absolute SDI-12 shaft encoder (65,536 counts/rev). The H-334 unit simultaneously produces a SDI-12 and analog (4-20mA) output. Stage determined via the optical/magnetic sensor determines stage in user defined units, and then scales and produces the output signal via an internal digital to analog converter. Subsequent installations within the CBT system have used a Sutron SDR-001-4 unit which can simultaneously produce output signals via SDI-12 and 4-20mA analog similar to the H-334 unit, but also maintains an internal log of recorded stage as well as all user interactions with the unit.

For sites employing a pressure transducer, the single sensor approach was accomplished by utilization of a Design Analysis H-416 SDI-12 to 4-20mA converter unit (Figure 6). The H-416 unit is designed to passively listen for to the SDI-12 bus for a user defined address and parameter. Once the SDI-12 value is captured by the H-416 unit, it scales and produces an output current based on user-defined threshold values.

Employment of the signal sensor paradigm has proven to be a positive solution for all parties involved. Data obtained via digital and analog avenues agree much closer than ever before. USBR staff had previously had to visit gages up to three times a week to ensure calibration now only weekly visits are made and adjustments are rarely needed.

Because of the success of this pilot program employed along the East Slope portion of the CBT project, cooperative USBR-CO DWR gages throughout the West Slope of the CBT, as well as Fryingpan-Arkansas projects have been, or are in the process of being converted to the single sensor-dual output paradigm[5]. Moreover, similar cooperative gages within the Denver Water, NCWCD systems have started to employ the techniques demonstrated within the East Slope CBT system.

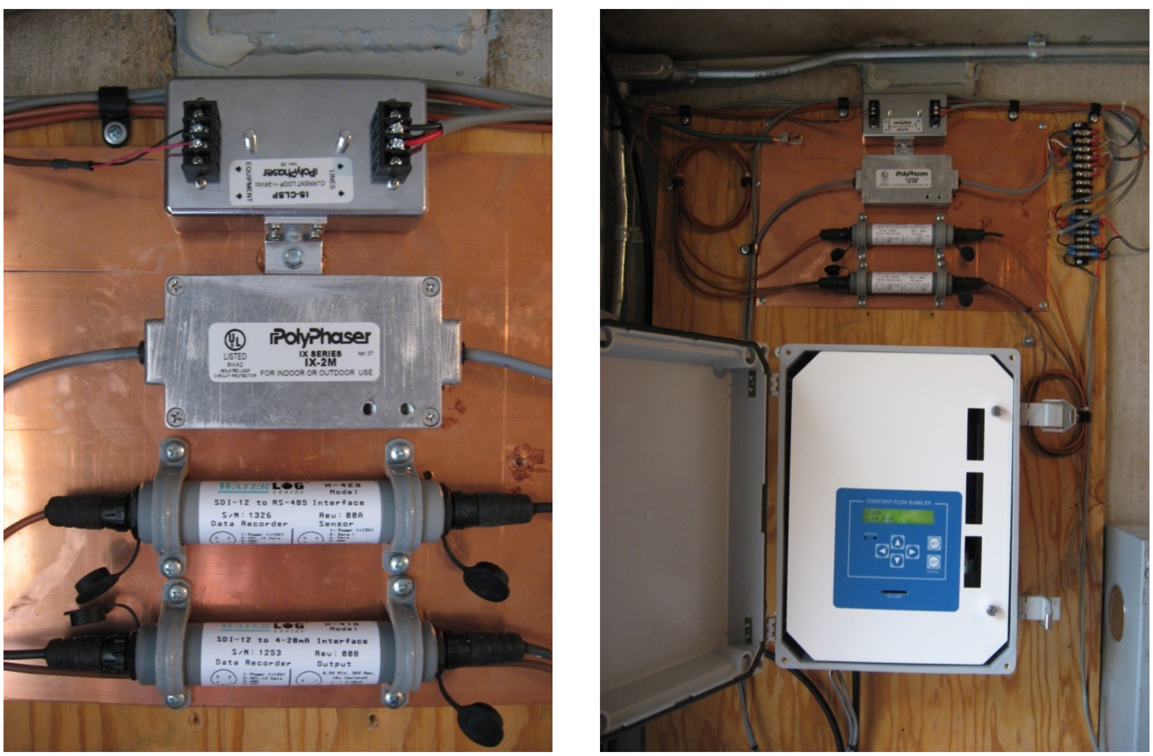

Figure 6. Photos showing a Sutron CFB connected to a Design Analysis H-416 SDI-12 to 4-20mA converter module.

[5] The authors wish to acknowledge the efforts of Mr. Mark Henneberg, formerly Hydrologic Technician, Eastern CO Area Office, US Bureau of Reclamation, Loveland CO, and currently US Geological Survey, Grand Junction CO for his extensive work to make the single sensor-dual output paradigm a reality.

SUMMARY

The satellite-linked monitoring system (SMS) provides the Division of Water Resources, other State and Federal entities, and the water user community with access to real-time and historic stream-flow data from gauging stations across the State of Colorado. These data and software systems provide for more effective water rights administration, improved water resource management, computerized hydrologic records development, flood warning and other types of flow alert notifications.

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