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CLIMDB/HYDRODB: A WEB HARVESTER AND DATA WAREHOUSE APPROACH TO BUILDING A CROSS-SITE CLIMATE AND HYDROLOGY DATABASE

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ABSTRACT

Emerging environmental grand challenges demand new scientific approaches that require collaboration and integration of long-term, multi-site data across broad spatial and temporal scales. The Long-Term Ecological Research (LTER) Network and the U.S. Forest Service (USFS) Experimental Forest Network sites collect extensive long-term ecological, climatological, and hydrological data. While many of the LTER and USFS databases are available on-line with adequate metadata, researchers find it problematic to locate, access, and assemble data from multiple sites. LTER and USFS Information Managers developed ClimDB/HydroDB as one approach to improving access to cross-site data (http://www.fsl.orst.edu/climhy/). As information systems at LTER and USFS are geographically decentralized and autonomous, this approach relied upon scientific interest, organizational and personal commitment, and participation incentives to build this integrated, cross-site information product.

ClimDB/HydroDB is a web harvester and data warehouse that provides uniform access to common daily streamflow and meteorological data through a single portal. Participating sites manage and control original source data within their local information systems, but routinely contribute data to the warehouse. This approach establishes service development at the central node, permitting rapid adaptation to changing needs, while maintaining low-overhead and technological neutrality for data providers. The ClimDB/HydroDB approach is an effective bridge technology between older, more rigid data distribution models and modern service-oriented architectures.

1. INTRODUCTION

Emerging environmental grand challenges demand new scientific approaches that require cross-site data integration, modeling and analysis to investigate global change at multiple spatial and temporal scales. For example, streamflow and meteorological data are critical for assessing long-term environmental change, so integrated climatologic and hydrologic databases are increasingly used in

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integrative research involving cross-site comparisons, modeling studies, and land management-related studies. To address this need, the National Science Foundation's (NSF) Long-Term Ecological Research (LTER) program collects and maintains extensive, long-term ecological databases within a network of 26 research sites and supports the integration of research data across sites and disciplines (Baker et al. 2000). Similarly, U.S. Forest Service Research (USFS) has a long history of research studies on a network of experimental forests including many small, experimental watersheds with a rich collection of long-term data as described in Lugo et al. (2006) and Adams et al. (2004).

Current LTER and USFS planning activities emphasize new network science approaches that demand collaboration and integration across broader spatial and temporal scales and require improvements in the flow of data and the synthesis of information. The 20-year NSF (2002) review of LTER challenges the network to enhance its inter-site research activities by adopting a strategy for network-based research. This review recommends that the LTER program "forge a bold decade of synthesis science, one that will lead to a better understanding of complex environmental problems and result in knowledge that serves science and society" and recommends the LTER program's informatics infrastructure provide "a virtual portal to LTER legacy data for investigators worldwide". Lugo et al. (2006) note that USFS Research intends to increase collaboration and contribution of resources to inter-site science, and understands that to tackle national and global issues at the proper scale will require the whole network to function as an integrated research platform.

The LTER Network broadly supports information management at all sites and is developing a Network Information System (NIS) to enhance the discovery, access and integration of information and facilitate synthetic science as described in a strategic plan by the NIS Advisory Committee (2005). While many of the LTER databases are available on-line with adequate metadata, researchers find it problematic to locate, access, and assemble data from multiple sites due to differences in web page structures, access requirements, and other factors. Data retrieved from individual LTER sites also differ in data format, scale, and semantics. Collections of long-term data from the USFS experimental forests and ranges are typically not accessible and not well documented. Integrating these distributed LTER and USFS data sources into a single, unified source is needed to overcome these limitations. As part of the LTER NIS effort and in response to an increasing demand for synthetic data products, LTER and USFS Information Managers developed ClimDB/HydroDB (http://www.fsl.orst.edu/climhy/), a data warehouse that provides uniform access to common daily streamflow and meteorological measurement data through a single portal.

2. HISTORICAL CONTEXT

The original concept paper for the establishment of the LTER, TIE (1979), included preliminary statements on requirements of sites to make standard meteorological measurements. Swift and Ragsdale (1985) describe a standard set of core baseline meteorological measurements necessary to document long-term changes in the physical environment and to correlate with measurements of ecological phenomena. An LTER Climate Committee was established in 1986 and developed a flexible standards document, last modified by LTER Climate Committee (1997), outlining levels of site compliance with the baseline measurements and obligating sites to provide detailed climatic histories to enable intersite comparisons. Greenland et al. (1997) describe and compare site climatic information, but difficulties experienced in accessing and assembling individual site data sets indicated the need for better access to current and comparable site data, leading to a series of workshops and the eventual establishment of ClimDB/HydroDB.

The LTER Information Managers proposed a mechanism for web harvesting of site climate data into a central database using emerging Internet capabilities at a meeting at the Archbold

Biological Station, IMC (1996). Subsequently a prototype was developed at the North Temperate Lakes LTER site, as described in Henshaw et al. (1998). This system featured limited harvesting of site data and demonstrated web access to multiple site data for download and graphical display. A workshop hosted by the LTER Climate Committee (1997) at the Sevilleta National Wildlife Refuge was attended by climatologists, data managers, modelers, and field technicians and resulted in defining climate domain-specific metadata necessary for cross-site comparisons. A more extensible database design and graphical display enhancements were also developed. A demonstration of the ClimDB prototype at the LTER All-Scientist Meeting at Snowbird in 2000 led to discussions with the USFS about extending ClimDB content to include streamflow data and the inclusion of USFS experimental forests and watershed sites.

A production version of ClimDB/HydroDB was ultimately established at the Andrews Experimental Forest LTER site in 2002 and presented in Henshaw et al. (2003). NSF and USFS funding both for software development and seed money distributed to participating sites for the preparation of data was key in moving the prototype into production mode. At Kellogg Biological Station in 2003 the LTER Coordinating Committee approved a motion that commits individual sites to populate and update existing basic network databases including ClimDB/HydroDB, and this support has been essential for securing complete participation from all LTER sites and many USFS sites (see attached file image_1).

3. CLIMDB/HYDRODB METHODOLOGY

The key components of ClimDB/HydroDB are the data providers, centralized architecture including the web harvester, data parser, and data warehouse, and query interfaces to allow both web and programmatic access to the data as shown in Figure 1.

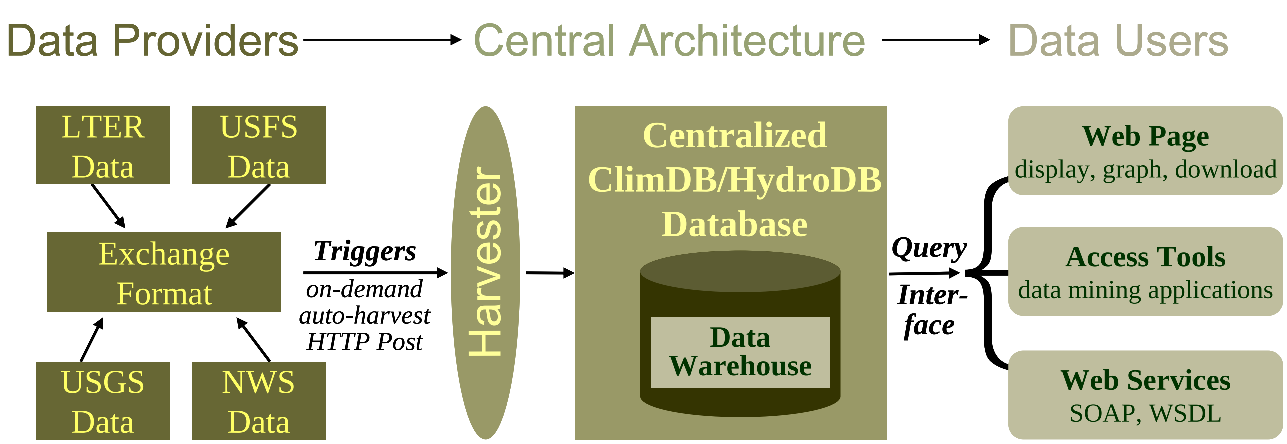

Figure 1 ClimDB/HydroDB data harvester and warehouse architecture

3.1 Data Providers

Participating sites manage and control original source data within their local information systems and contribute data to the warehouse in a standardized, comma-delimited **exchange format**. Typically, data providers must restructure or resample local site data into daily resolution exchange format files for web harvest (currently only daily resolution data is supported). These harvest files are exposed to the web harvester at user-specified URLs and can be static text or can be generated dynamically upon harvester request. The flexible exchange format allows contributors to add or remove parameters from harvest files at any time, and simple header lines can be modified to specify the measurement data and can vary in the number and order of attributes. Data contributors must adhere to standardized attribute names and units defined in a controlled vocabulary and provide a data qualifier flag for every value. This architecture allows local information systems and data management protocols to be revised transparently to the data consumer without affecting site participation in the data warehouse.

The data providers are responsible for assuring harvested data are accurate and frequently updated, but the web harvester provides feedback mechanisms and features to assist site providers in this task. A participant web page provides overview information, a simple mechanism to trigger the harvest of site data and access to password-protected metadata entry forms. Participants agree to use online forms to provide extended meteorological and hydrological domain metadata for the overall research area, for every gauging and weather station and for every measurement parameter. An online user guide is available describing the data harvest process and the required steps for site participation.

3.2 Web harvester

Various **triggers** can initiate data harvests into the central data warehouse. The simplest mechanism is an *on-demand* harvest that is initiated using a form on the participant web page. A complete summary of run-time diagnostics is reported to the user's web browser indicating a successful harvest or providing quality assurance warnings or fatal execution errors. An *auto-harvest* feature allows data to be harvested on a regular schedule, which is beneficial for sites that dynamically produce exchange data through queries within their local information system. Harvests can also be

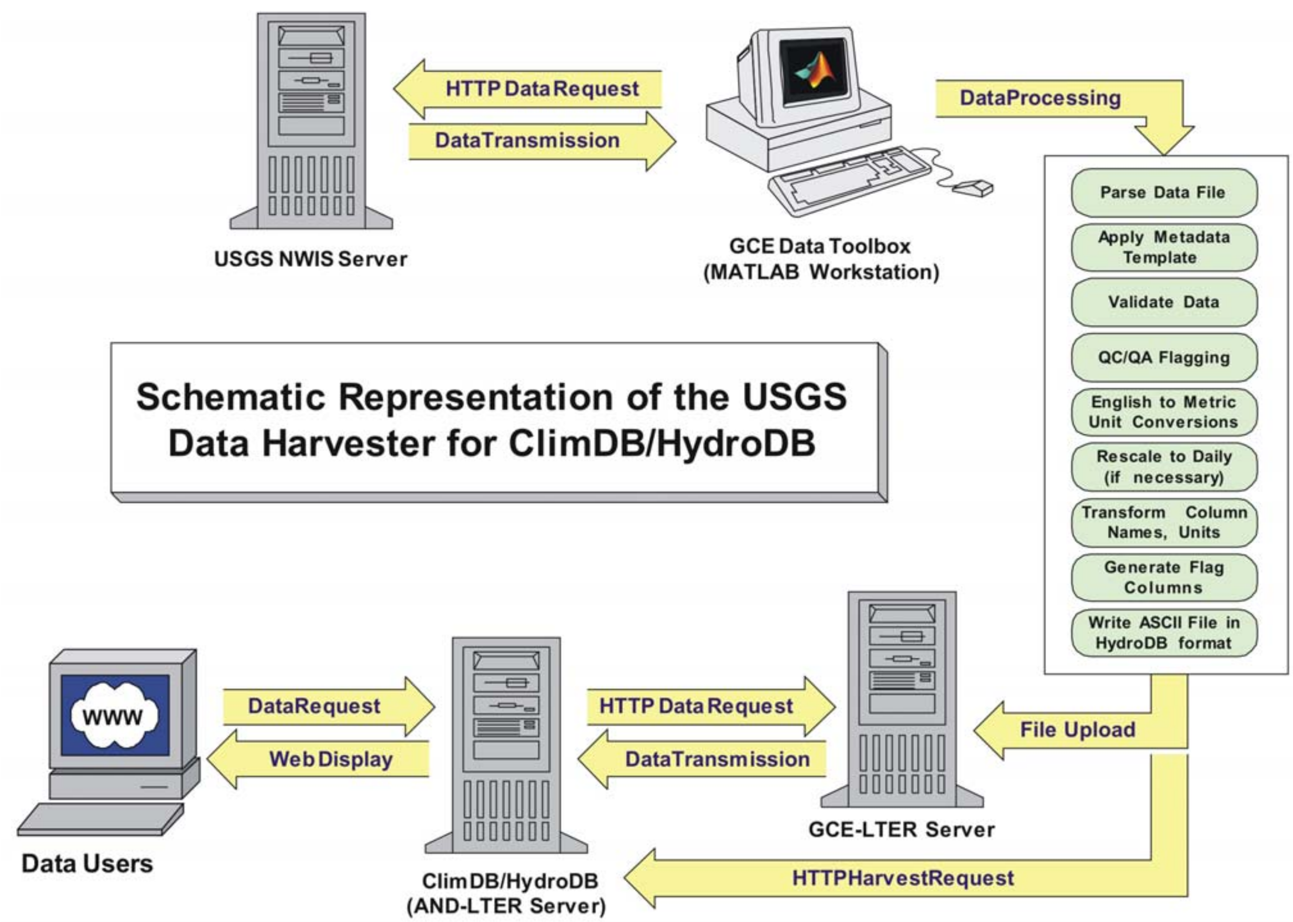

Figure 2 Schematic representation of the USGS data harvester for ClimDB/HydroDB

triggered programmatically using *HTTP Post* methods, allowing sites to invoke the data harvester directly using custom programs. This method can also be used to develop middleware services to harvest other agency data (e.g., USGS, NWS, NOAA) into the database as described below.

An automated data harvesting service was also developed by the GCE LTER site to incorporate near-real-time and historic data from the USGS National Water Information System (NWIS) into HydroDB (http://gce-lter.marsci.uga.edu/lter/research/tools/usgs_harvester.htm) as illustrated in Figure 2. Streamflow and precipitation data are automatically downloaded from the USGS NWIS web site on a weekly basis for 55 monitoring stations in close proximity to 12 LTER and USFS sites. The data are converted to metric units, quality checked, transformed, and exported in ClimDB/HydroDB exchange format. Harvests are then triggered programmatically to incorporate the aggregated data into the central warehouse from this single node, with finalized data automatically overwriting provisional values as they are released by USGS. This "concentrator node" implementation demonstrates how middleware services can be deployed very easily and rapidly within this model to improve efficiency and build bridges to other federated databases.

Additionally, prototype web service architecture was developed in cooperation with the San Diego Supercomputer Center and described in Vanderbilt (2002) as an alternative to the conventional web harvester program. This “federated database” or virtual data warehouse demonstration includes “live” site data and is dynamically built through distributed site queries to relational databases. While this technology holds great promise for future data integration as noted by Haas et al. (2002), it is not implemented in the current production mode primarily due to the lack of relational database technology and persistent archives at many participating sites.

3.3 Central Architecture

The centralized architecture consists of the web harvester and data loader middleware in conjunction with a relational database management system. The data loader middleware transforms, performs quality assurance (QA) checking, and loads the harvested source data into a global schema in the **central relational database**. Data are aggregated at monthly and annual resolution upon data loading and stored for quick access. Date ranges for all station measurement parameters are also calculated and maintained. The central **data warehouse** is persistent and participants can continually update and replace harvested data.

The global schema for the data warehouse is based on highly normalized tables using a general relational model as originally described by Codd (1990), allowing simple structures to house all site data and metadata (see attached file image_2). The schema design has proven to be extensible to new daily time series parameters and descriptive domain metadata content, requiring only minor changes to table structures at the central site since the original deployment. Source organizations and personnel contacts are also maintained for web display and email purposes.

Quality assurance and diagnostic reports are generated and emailed to the registered site contact and data warehouse administrator after every data harvest. These reports and feedback have proven very beneficial to the data providers as a means to quickly identify and resolve data problems. The data loader middleware checks for entity integrity (duplicate records, null values), domain integrity (site and station names, qualifier flag values, date values), exchange format integrity, and quality control limit checking (min-max checks). Valid ranges for every parameter can be user-specified and violations are reported as non-fatal warnings. All other errors result in harvest failure and require resolution and re-harvest. The data harvester quality assurance and feedback system is diagrammed in Figure 3.

Administrative controls include an administrative configuration file for editing platform specific information and file pathways to allow rapid migration to other database servers (currently, the middleware is written in Perl and Microsoft SQL Server® is the relational database). Several log files are created during data harvest for tracking and reporting purposes, and allow inspection of harvest data for tracing errors and debugging problems.

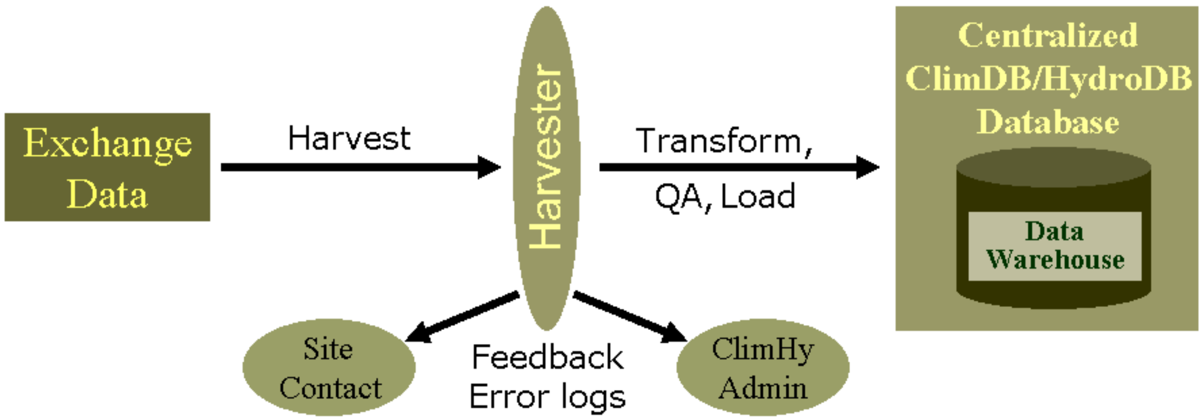

Figure 3 Data harvester quality assurance (QA) and feedback system

3.4 Data Access

A web application-based **query interface** provides public access to the data warehouse through the ClimDB/HydroDB web page (http://www.fsl.orst.edu/climhy/) and also supports access through custom *data mining applications*. A conventional *web-form interface* allows public access and exploration of comparable cross-site data and metadata. Daily measurement data and monthly or annual summary statistics for participating sites and stations can be selected for viewing, downloading or graphical display. Detailed metadata reports describing sites and stations can be viewed or downloaded in Adobe Acrobat© PDF format. Several *web services* implementing the SOAP protocol have also been developed to "wrap" the central database and provide programmatic access to daily and aggregated measurement data, allowing the ClimDB/HydroDB data warehouse to participate in broader cross-agency data federations. The web service descriptions and WSDL documents are described at http://lterweb.forestry.oregonstate.edu/climhy/climhy_ws_api.htm.

MATLAB-based data access client software is also available from the GCE LTER project (http://gce-lter.marsci.uga.edu/lter/research/tools/data_toolbox.htm). The software proxies HTTP communication with the server, allowing users to directly request daily measurements for specific time periods from any registered site and station. Retrieved data are automatically transformed for compatibility with the MATLAB environment, and parameter names can be aliased using customizable metadata templates. Both GUI forms and scriptable command line interfaces are available to support data access in both interactive and automated work-flow scenarios (see attached file image_3).

4. CLIMDB/HYDRODB CONTENT AND USE

The data warehouse currently accepts 14 measurement parameters represented by 22 attributes in a daily time step. Precipitation, stream discharge, and air temperature are the most common data values contributed by sites, accounting for more than 75% of the measurements in the database, with relative humidity, soil temperature, wind speed and direction, and global radiation accounting for 15%. Atmospheric pressure, dewpoint temperature, snow depth, soil moisture, water vapor pressure, and water temperature are less frequently contributed. The data warehouse currently includes over 7 million daily measurement values from approximately 280 stations at 40 sites.

Interactive summary tables are provided on the web site for viewing sortable lists of sites, stations, and attributes (variables) along with temporal coverage and last harvest date. The dynamically-generated reports are also available in eXtensible Markup Language (XML) format to facilitate programmatic use. Sites and stations can be displayed by source organization, currently LTER (including international LTER), USFS, and USGS.

Extended meteorological and hydrological metadata elements are grouped into categories for ease of entry and web form implementation. Metadata categories include 1) Research Area Information, 2) Watershed Spatial Characteristics, 3) Watershed Ecological Characteristics, 4) Watershed Descriptions, 5) Hydrologic Gauging Station, 6) Meteorological Station, and 7) Measurement Parameters (14 parameters). Extended metadata categories were established to provide critical information anticipated as necessary for conducting cross-site synthetic research.

Analysis of general web statistics indicates that use of the data warehouse is increasing, and currently averages 30 user sessions per day. Tracking of comments provided by users on the data access sign-on form (i.e., "purpose for this download" field) indicates that data are primarily used for research, education, general exploration, or participant testing Dividing responses by affiliation, general research, exploratory analysis, and modeling are frequently cited by researchers, and demonstrations or class projects are cited by both students and educators. Web monitoring reveals 50% of data access is viewing or downloading plots, 40% is downloading data, and 10% is web display of data only.

5. KEYS TO SUCCESSFUL IMPLEMENTATION

Information systems at LTER and USFS are geographically decentralized and autonomous, relying upon scientific interest, organizational and personal commitment, and participation incentives to build network-level, cross-site and cross-agency information products.

5.1 Scientific Interest

Paramount to success is a scientific requirement for the integrated data product. As new science approaches demand better research integration and synthetic products, science drivers and incentives for building data warehouses and adopting federated system approaches will grow. Early efforts to access and assemble LTER climate data across sites were extremely problematic even as data sets became available on the Internet. Data sets were still hard to locate and were highly variable in storage format.

The need for comparable LTER climatic summary data led to a meeting of science leaders, information managers, and data users. This meeting was critical in the development of the global schema, identifying key domain metadata elements and graphical user interface requirements. Science need for unified access to USFS experimental watershed streamflow data led to similar interactions of science leaders with information managers and resulted in the extension of the LTER ClimDB to the cross-agency ClimDB/HydroDB project. Current research use of this resource is documented and increasing. For example, Jones and Post (2004) used ClimDB/HydroDB in the development of their synthesis of climate and vegetation influences on streamflow in several experimental forests around the country.

5.2 Organizational and Personal Commitment

Early adoption of standard methods by the LTER and USFS in the collection of climate and streamflow data provides the basis for inter-site comparison. The commitment to data release and access policies in making data publicly available is another important aspect in the success of implementing integrated data products.

Karasti and Baker (2004) noted that Information Management plays a critical role within the LTER program in terms of support for science, and that LTER requires an IM component in each site's science plan. Information Managers from every site are supported to meet annually and strategize on cross-site and network-level database development and other collaborative projects. This Information Management Committee, working in association with LTER science leadership, has been a key factor in initiating development of the NIS (including ClimDB/HydroDB) and in adopting strategies and standard approaches to facilitate synthetic science. Support of the science leadership for network-level databases and the establishment of requirements for individual site participation are essential. Individual leadership and the devotion of site personnel time and resources in both software development and preparation of data sets are also vital components to success.

5.3 Participation Incentives

Providing financial or other incentives to the sites is essential for growing participation in the data warehouse, and a certain level of participation and database population is required before the resource becomes useful. The complementary distribution of NSF and USFS funds to support individual site participation provided critical seed funding in the preparation of site data and in supporting development of critical information system components at the sites. ClimDB/HydroDB also offers positive benefits to the sites as enticement. For example, the public web page offers an alternative to local site systems for accessing daily, monthly and annual aggregated data, and also provides the capability to download data and plots; descriptive metadata can also be packaged in well-organized PDF files; and USGS data can be harvested on behalf of sites with no additional effort as a value-added service. The prospect that participation will result in access to integrative and value-added products useful to site research further enhances site participation.

6. CONCLUSIONS

The LTER Network and USFS Experimental Forest Network sites collect extensive long-term ecological, climatological, and hydrological data. Long-term environmental data are important for understanding the impacts of global change, including land use. The value of these data collections will continue to grow as temporal and spatial coverages and resolutions increase over time, allowing new research questions to be addressed. Planned integrated research approaches demand the development of information systems that improve accessibility and facilitate integration of long-term, multi-site data.

The ClimDB/HydroDB data warehouse is a key component to the LTER Network Information System and an important step in "confederating" individual site data repositories, providing a single portal for multi-site and multi-agency climate and hydrology data. The data warehouse represents a successful ongoing integration of cross-site data and the approach is an effective bridge technology between older, more rigid data distribution models and modern service-oriented architectures. This approach establishes software and service development at the central node, permitting rapid adaptation to changing needs, while maintaining low-overhead, flexibility and technological neutrality for data providers. Development of these network-based data products provides network identity to participating LTER and USFS sites, and helps prepare site information systems for participation in more advanced data integration architectures of the future.

The ClimDB/HydroDB project was initiated as a grassroots effort among information managers, climatologists, and modelers to establish better methods for the assembly, access, and display of cross-site data. The project builds upon established standardized methods for data collection and a shared responsibility of sites within the networks to make these data publicly available. Ultimately, financial incentives were offered and official network requirements for network-level databases were established, resulting in the more reliable and complete version currently deployed. Data use has also increased dramatically as the content surpassed a threshold level of completeness, which greatly increased its overall value for research.

This data warehouse approach is extensible to other time-series data sets and will accommodate higher temporal resolution data. A WatershedDB database component is in development to provide spatial GIS layers for participating sites, including site and watershed boundaries and other landscape features. Extensions to other data types such as precipitation (and dry fall) chemistry, stream chemistry and vegetation surveys will be more problematic because there is less agreement on standard collection methodology. This extension will require careful consideration of global schema requirements and may require manual mapping of local system attributes to the global schema. Overall, this data warehousing approach constitutes an important technological bridge from existing site and network cyberinfrastructure to planned development of modern service-oriented architectures that will enable generic federated system approaches to integration.

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