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Integration of Wireless Sensor Networks into Cyberinfrastructure for Monitoring Hawaiian "Mountain-to-Sea" Environments

Michael H. Kido · Carsten W. Mundt · Kevin N. Montgomery · Adam Asquith · David W. Goodale · Kenneth Y. Kaneshiro

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Abstract Monitoring the complex environmental relationships and feedbacks of ecosystems on catchment (or mountain)-to-sea scales is essential for social systems to effectively deal with the escalating impacts of expanding human populations globally on watersheds. However, synthesis of emerging technologies into a robust observing platform for the monitoring of coupled human-natural environments on extended spatial scales has been slow to develop. For this purpose, the authors produced a new cyberinfrastructure for environmental monitoring which successfully merged the use of wireless sensor technologies, grid computing with three-dimensional (3D) geospatial data visualization/exploration, and a secured internet portal user interface, into a working prototype for monitoring mountain-to-sea environments in the high Hawaiian Islands. A use-case example is described in which native Hawaiian residents of Waipa Valley (Kauai) utilized the technology to monitor the effects of regional weather variation on surface water quality/quantity response, to better understand their local hydrologic cycle, monitor agricultural water use, and mitigate the effects of lowland flooding.

Keywords Grid computing · Sensing platforms · Internet portal · Ad hoc networks · Social-ecological systems · Radio telemetry · 3D geospatial visualization

M. H. Kido (✉) · K. Y. Kaneshiro
Center for Conservation Research and Training, University of Hawaii, 3050, Maile Way, Gilmore 406, Honolulu, HI 96822, USA
e-mail: mkido@hawaii.edu

C. W. Mundt
InteleSense Technologies, Inc., 575 Cooke Street, Suite A-PMB2908, Honolulu, HI 96713, USA

K. N. Montgomery
National Biocomputation Center, Stanford University, 701A Welch Road, Suite 1128, Palo Alto, CA 94304, USA

A. Asquith
Sea Grant College Program, University of Hawaii, 7370A Kuamoo Road, Kapaa, HI 96746, USA

D. W. Goodale
The National Tropical Botanical Garden, 3530 Papalina Road, Kalaheo, HI 96741, USA

Introduction

Catchment-scale studies integrated into a landscape perspective have increasingly become the focus of river ecologists who recognize the hierarchical nature of river systems from microhabitat to basin-level scales which are viewed as "riverscapes" (e.g., Fausch and others 2002). Within these systems, characterized by high connectivity and spatial complexity, hydrological response is influenced by interacting catchment and stream characteristics (Walsh and others 2001). Human actions throughout watershed catchments, however, disrupt geomorphic processes and degrade natural conditions by causing increased sedimentation, nutrient enrichment, contaminant pollution, and greater intensities/frequencies of flooding (e.g., Allan 2004). Failure to incorporate the coupled nature of human-natural environments into riverine and coastal management policies can result in dire consequences as witnessed during Hurricane Katrina in August 2005 along the Mississippi River Delta, the effects of which were intensified by land management policies that overlooked the important role of coastal wetlands in mitigating floods (Postel 2005). These and other valuable freshwater ecosystem services (e.g., providing for biological habitat, groundwater recharge, renewing soil fertility, etc.). Postel (2005) suggests, function within a connected "headwaters-to-sea" environment that should be monitored in order to protect its integrity. However, monitoring ecosystems effectively on catchment (or mountain)-to-sea scales present major technological challenges which have yet to be fully addressed. Nevertheless, developing such capability is of significant national and global importance as the impacts of expanding human populations on watershed catchments intensifies.

The technological components required to develop this capability are maturing rapidly, albeit somewhat independently. Significant research effort, for example, has been focused on the use of wireless sensor networks to monitor environmental variables coupled to ecological habitat (e.g., Szewczyk and others 2004). The standardized template developed involves the use of untethered, battery operated sensor nodes distributed into a mesh network which collect an integrated view of the area being monitored (Santi 2005). Data is transmitted through neighboring nodes to gateways that interface with networking infrastructures (e.g., Ethernet or 802.11). Research applied to practical applications of this standard template, albeit at relatively small spatial scales, have focused on resolving challenges in areas such as power consumption (e.g., Hempstead and others 2005), scalable coordination (e.g., Estrin and others 1999), medium access control (e.g., Yee and others 2003), data stream management (Golab and Ozsu 2003), topology control (Santi 2005), and software architecture (e.g., Heidemann and others 2003).

Recent improvements in the use of digital computing, information technologies, and communications as cyberinfrastructure (e.g., Kaur and others 2005), promises to deliver the end-to-end digital capability required to handle the massive quantities of sensor data generated by automated systems, integrate environmental data sources across scientific disciplines, and interface researchers with geographically distributed user communities desiring access to data and analytical capability (e.g., Karasti and others 2006). Recent advances in grid infrastructure technologies, in particular, will enable the processing and management of large datasets, distributed resource sharing/collaboration, and data intensive computation in a wide range of scientific domains where large data collections are widely distributed (e.g., Chervenak and others 2000). In addition, advances in the use of portal technologies, which coordinate internet and grid infrastructures to deliver authenticated access to a diverse range of information resources, will create secure user access to data integrated across physical and intellectual domains (e.g., Jaeger-Frank and others 2006). Extended three-dimensional (3D) tools for global-scale exploration, visualization, and animation of environmental data, have also become readily available in the public domain with the releases of NASA World Wind and Google Earth (Verbree and Zlatanova 2007). However, despite significant technological advancements in the components necessary for creating a regional-scale platform for environmental monitoring, synthesis of these technologies into a working prototype system has been slow to occur.

The Hawaiian Islands represent a unique opportunity of both benefits and challenges for the development of this new capability. Its geographical topology (mountains, steep valleys, oceans), ecology (native biodiversity in terrestrial, freshwater, and marine ecosystems) and human development (natural, managed, and urban) all within limited island areas make it a unique microcosm of continental systems. Because of the compact size of watersheds, it is also feasible to study ecosystems on mountain-to-sea scales not practical on continents (Kaneshiro and others 2005). As is the case globally, Hawaii is facing serious environmental challenges from urbanization and intensifying human activity. Catastrophic flooding occurring historically in lowland areas around the state, for example, exacerbated by extensive habitat alteration in watershed catchments, poorly designed flood control projects, and increases in impervious surfaces in urban areas, have resulted in human deaths, major property damage, and enhanced conditions for the spread of zoonotic and vectorborne emerging infectious diseases. In this article, our intention is to provide readers with an overview of a prototype observing platform which integrates the use of wireless sensor networks into cyberinfrastructure for monitoring Hawaiian mountain-to-sea environments on the island of Kauai. Subsequent publications will follow which will focus on specific details of the engineering aspects and software/hardware solutions to the technological challenges encountered.

Methods

Study Area on North Kauai Island

The primary study area was located in an extremely rugged and biologically rich region of North Kauai (an area of about 10360 hectares [40 sq miles]) which includes the four ancient *ahupua'a* of Waipa, Lumahai, Wainiha, and Haena (Limahuli Valley) (Fig. 1). In ancient Hawaii, *ahupua'a* were social-ecological land units within which an attempt was made to temper human resource use with a holistic understanding of the interconnectedness between terrestrial, freshwater, and marine ecosystems (Kaneshiro and others 2005). Ancient Hawaiian land management units, therefore, encompassed a mountain-to-sea perspective, including both the biophysical

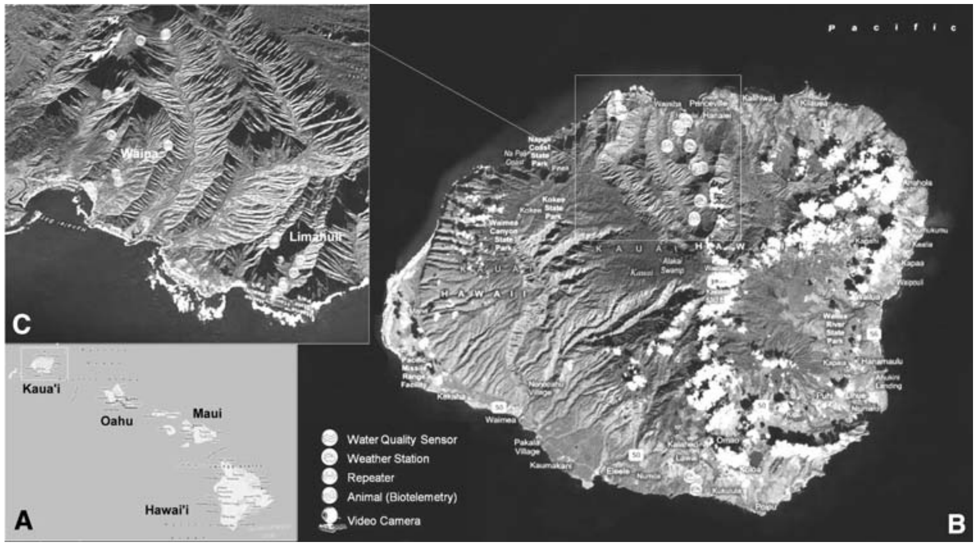

Fig. 1 *InteleView-Landsat 7* imagery showing locations of (**a**) Kauai Island, (**b**) North Kauai Test Bed, (**c**) Waipa and Limahuli Valleys. *Circles* indicate locations of sensor/repeater nodes transmitting data wirelessly to the Base Station in lower Limahuli Valley

and social resources contained within, which provided a convenient geographical, traditional, and holistic conceptual framework for our study. The boundaries of these four *ahupua'a* in the North Kauai study region generally aligned geographically with steep-walled valleys within which drainage streams flow to the ocean from high rainfall zones located above 1219 m (4000 ft) elevation in the interior of Kauai's central extinct volcano, Mt. Waialeale (Fig. 1). This region of Kauai is often referred to as one of the "wettest spots on earth" with recorded rainfall of over 15.2 m (600 inches) per year (Stearns 1985).

Technology Development

Extending the radio telemetry-based, wireless sensor network template (e.g., Hill and others 2004) into a platform able to accommodate environmental monitoring needs on Kauai, presented a worst case scenario because of extremely rugged terrain, high rainfall/humidity, and line-of-sight restricted by steep canyon walls and dense valley vegetation. The initial phase of the study, therefore, was focused on technology development and establishing a radio telemetry-based backbone able to transmit sensor data collected within Waipa, Lumahai, and Limahuli Valleys (Fig. 1) reliably across the North Kauai region (a straight line distance of about 8.1 km [5 miles]). The solution developed was a tiered architecture common to most wireless sensor networks (e.g., Hill and others 2004), but scaled-up to accommodate the regional study area. The platform consisted of dedicated data acquisition devices (*InteleCells*) able to interface generically with individual or groups of sensors (Fig. 2). Units were deployed to form a distributed mesh sensor network (*InteleNet*) capable of intelligently relaying data packets across long distances to a remote base station with units functioning as repeaters and/or gateways depending upon location in the network (Fig. 2). A base station module for the *InteleCell* was developed to interface generically as a plug-and-play device with standard Ethernet connections to upload sensor data over the Internet to a computer server. At the server-level, other data sources were integrated and clients given access to sensor data through a secure, internet portal-based, grid infrastructure (*InteleSense* Grid) displaying data through a 3D geospatial visualizer called *InteleView* (Fig. 2).

InteleCell for Wireless Data Acquisition from Sensor Arrays

The *InteleCell* (Fig. 2) was designed as a compact, remotely deployable, rugged, smart data acquisition device able to accommodate unattended wireless sensor-based monitoring across regional-scale landscapes. The device readily interfaces with generic sensor types, provides for local processing through a small, low-power microcontroller, and is GPS-enabled to allow for precise localization and mobile operation. These features make feasible robust, long-range, secure wireless data transmission across regional landscapes with potential *InteleCell*-to-*InteleCell* connection of up to 40 miles (with directional antennas and robust line-of-sight). The *InteleCell* interfaces generically with sensor devices via serial (RS232/485), analog (0–3.3 V, 4–20 mA), and SPI to accommodate most sensor hardware currently available, and thus provides a flexible framework for adaptation to future sensor devices. In addition to communication, the *InteleCell* is able to control external devices to power them up as needed or take readings and/or control actuators (e.g., pumps, video cameras, etc.). Internally, the low-power microcontroller can sample sensors at regular user-defined intervals, detect

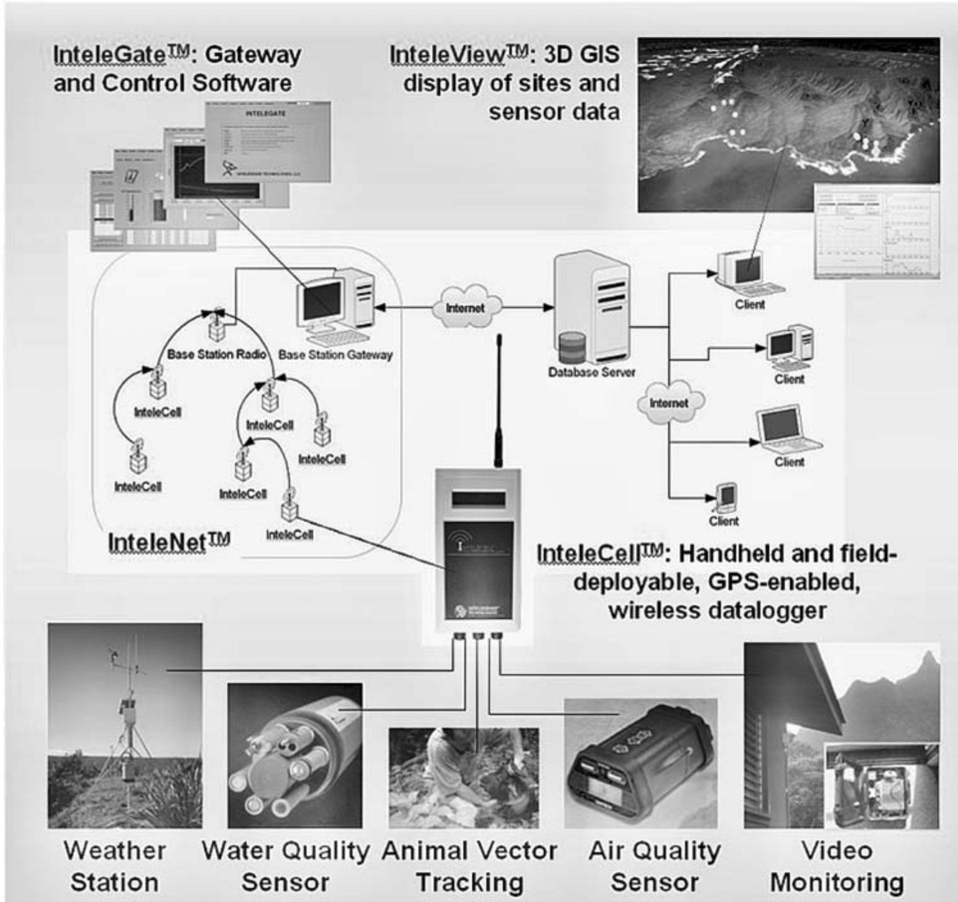

Fig. 2 Platform architecture, *InteleCell* hardware, and supported sensor types

user-defined trigger events for immediate processing and/or transmission, as well as transmit stored data on demand as needed. Each *InteleCell* is also able to log and store large amounts of data (including imagery and digitized audio) using inexpensive Secure Digital (SD) flash memory cards with capacities of up to four gigabytes.

To achieve the functionality required of a regional-scale platform for environmental monitoring, engineering effort was directed at addressing challenges identified by researchers working on relatively small scale deployments of wireless sensor networks (discussed previously). Stable, long-term power of almost indefinite longevity is provided by an internal solar-rechargeable battery and various sleep/low-power modes implemented to keep the size of the battery and solar panel to a minimum ($\sim 23.5 \times 9.5$ cm [9×4 in.]). To further conserve power, units power-off connected sensors individually or implement programmed startup time delays and/or adjust power levels through its firmware based upon signal strength readings. Self-description through built-in GPS modules and real-time clocks allow all sensor data to be time- or location-stamped. Metadata such as sensor status information are stored in the *InteleCell* itself and transmitted over the network along with the sensor data, so the condition of each deployed unit in the network is monitored. Data transmission is fully authenticated and encrypted (256-bit AES) to ensure complete security of data transmission. Any *InteleCell* that is added to an established network is automatically configured to use neighboring nodes to intelligently relay its data using a specifically designed localized algorithm programmed into the *InteleCell*'s firmware. Firmware can be upgraded remotely in all *InteleCell* units while field-deployed enabling flexible, future support for additional sensors or features. Components are housed in a rugged, sealed, waterproof case and a membrane keypad provides access to basic functions such as nearest-neighbor node searches, range testing, power displays, signal strength readings, and on-demand sampling of attached sensors.

The standard protocol adopted to establish the regional wireless sensor network (*InteleNet*) was to deploy an array of nodes consisting of weather stations (HOBO—Onset Computer Corporation) equipped with *InteleCell*s functioning as sensor data loggers, RF transmitters, and repeaters/receivers, all connected by line-of-sight to one or more nodes. On North Kauai, nodes were established on valley ridges using helicopters to create a wireless transmission backbone to an Internet-connected *InteleCell* base station located in lower Limahuli Valley (Fig. 1). To evaluate the ease-of-integration of new sensors into an *InteleCell* network to accommodate changing environmental conditions or monitoring needs, two different commercially available sensor types were used to monitor in mountain streams: (1) basic surface water quality parameters (pH, temperature, conductivity, dissolved oxygen, and turbidity) using *YSI Inc*. Model 6920 water quality sondes; and (2) correlated stream stage, testing both ultrasonic water level sensors (*Echotel* Ultrasonic 2-Wire Transmitters—*Magnetrol International Inc.*) and submersible pressure transducers (WL 400 Water Level Sensors—*Global Water Instrumentation, Inc.*). *InteleCell*-connected sensors were deployed in multiple locations along longitudinal stream gradients in Waipa, Lumahai, and Limahuli Valleys transmitting data to the base station via nearest nodes located on valley ridges (Fig. 1).

The *InteleNet* for Mesh Networking of Sensors

Groups of deployed *InteleCell* nodes form a self-configuring, self-organizing, self-repairing intelligent distributed mesh network, the *InteleNet* (Fig. 2). At regular intervals, the devices awaken, take readings from attached sensors, automatically organize into a minimum cost spanning tree mesh network, and route data intelligently through the network to one or more base stations. This method proved to be a robust, reliable, no-configuration necessary network which could potentially cover hundreds of miles and was simple, extendable, and reliable. Once data arrives at one of the base station nodes, they are transmitted to the server over the Internet using a traditional connection (Ethernet or 802.11) or via cellular (e.g., GPRS or 1XRTT) or satellite (e.g., *Immarsat Global Area Network*) over an encrypted TCP/IP connection to a central server. These connection methods were tested and verified on Kauai as a "proof-of-concept" that the network could be deployed and operated in extremely remote locations and still provide for reliable, near real-time, bi-directional transmission of data.

The *InteleSense* Grid Cyberinfrastructure

The *InteleSense* Grid was developed in the study to add grid computing capability to the platform. The Grid can be generalized as a federated set of information resources managed through workflow/orchestration systems in such a way that allows for authenticated user access to tools/data existing outside their individual information systems (e.g., Jaeger-Frank and others 2006). The Kauai sensor data were treated as one such information resource. To house the *InteleSense* Grid, a ten terabyte capacity server was developed which utilizes a workflow system as middleware to access, coordinate, manage and process sensor (and other) data using emerging Grid-based technologies. In the workflow engine, a number of software agents obtain information from Internet-based sources using any protocol required (SQL query, HTTP, FTP, etc.), parses the information, and subsequently adds new data to the server's database (Table 1). Agents are generic, reusable, and easily configurable, adding significant capability to the system by being able to awaken at regular, programmable intervals (based upon data temporal dynamics) to automatically connect to external data sources.

User access to data resources linked to the *InteleSense* Grid is provided by an Internet-based portal designed to hide technical details of the systems functionality not required by the user. An initial prototype portal was developed in the study which consisted of a custom internet site packaged with a workflow engine to handle data source access, searching, conversion, and routing as an integral component of the grid environment. Authenticated user entry through the portal and access to resources is controlled by a registration/authorization process managed by the Grid which identifies users, assigns security level clearance to data resources based upon identity/sensitivity, and delivers appropriate tools/information to specific users as authorized by the owner of the resource. A single prototype portal was initially developed as a template to provide user access to raw data, graphing tools/displays, and analyses for sensor data from the Kauai deployment (Fig. 3); however, additional portals are currently under development which will integrate other user group applications and data resources into the Grid.

Visualization, interaction, and collaboration capability for the *InteleSense* Grid was built upon *World Wind*, an open source software package developed by NASA Ames Research Center (e.g., Leslie 2005). In NASA *World Wind*, users are able to "zoom in" to any location on the planet and "fly around" 3D adjustable terrain constructed by draping online satellite imagery (e.g., Landsat 7, Quickbird, IKONOS, etc.) over a georeferenced wire mesh grid of NASA Shuttle Radar Topography Mission (SRTM) data. A growing body of free plug-in products developed by an extensive *World Wind* user-community and integrated into the *InteleSense* Grid continually expands upon its base of external data sources for viewing and animating earth systems in 3D. The enhanced visualizer, called *InteleView*, expands upon *World Wind's* already extensive capability through its authenticated encryption framework and ability to integrate near real-time sensor data from deployed wireless sensor arrays. In *InteleView*, sensor node locations appear automatically to users as icons on 3D maps as *InteleCell*-based sensors are field-deployed and their positions fixed by internal GPSs (Fig. 1). Sensor icons are

Table 1 Data source examples integrated into the *InteleSense* Grid Cyberinfrastructure

Category	Data integrated
Sensors	Real-time weather, water quality, air parameters, imagery, video, biotelemetry, tracking, specific biosensors, soil properties, GPS
Surface imagery	Landsat visible & vegetation, USGS maps and urban area imagery, Quickbird, daily worldwide MODIS, high-res Landsat, Ikonos
Atmospheric	Worldwide CO_2 sensor networks, IR/suspended water vapor, heat flux, aerosols, suspended sediments, atmospheric carbon
Weather	Real-time cloud cover, cloud chemistry/composition, worldwide meteorological station data, satellite and aerial imagery, aviation pireps, NWS weather warnings
Marine	NOAA ocean depth data OGS WMS, bathymetry, buoy data, chemical composition & temp, reefs, ice field maps, sea level, shipping routes and vessels
Human	Placenames, political boundaries, military bases, population density, languages, aviation routes/bases/beacons and aircraft tracking, demographics, travel medicine, land use patterns, census data, news media, contributed media
Disease	Argus media reports, promed, WHO, CDC reports, syndromic surveillance data, medical informatics/hospital admissions data
Seismic	USGS real-time earthquakes, seismic hazard zones, volcanoes, magnetometer, magnetic flux
Solar	Solar irradiance and flux, spectroradiometer, eclipse predicted path
Event	Quickbird imagery, tsunami imagery, NOAA hurricane imagery

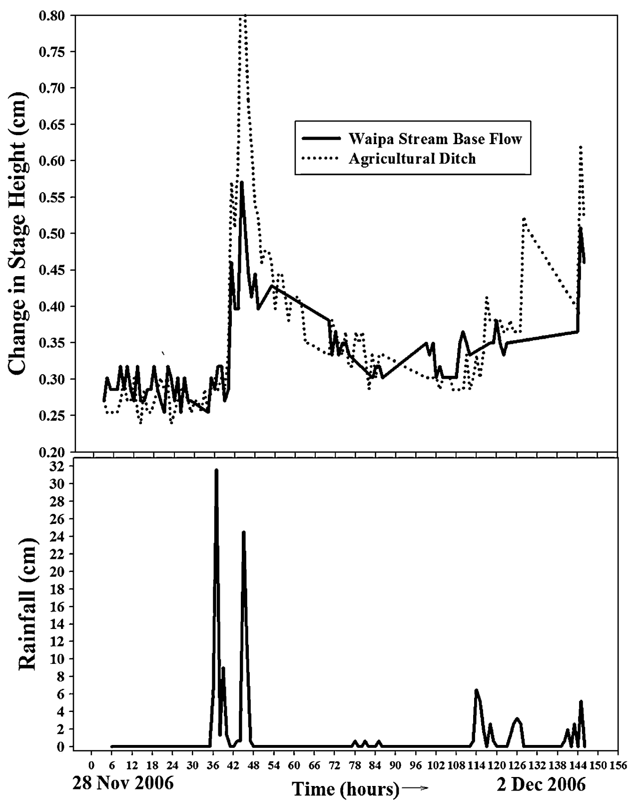

Fig. 3 Example of near-real time data downloaded from *Inteleview*, used to evaluate flood response in Waipa Stream and taro agricultural ditch, to torrential rainfall occurring in lower Waipa Valley over a five-day period from November to December 2006

clickable to provide an additional user entry point into the portal for access to sensor data, analyses and graphing tools.

Results

Waipa (Kauai) Mountain-to-Sea Use-Case Example

As discussed previously, the original intent of the study was to develop an environmental observing platform capable of monitoring coupled human-natural systems in real-world settings on mountain-to-sea scales. An initial test application implemented was designed to address local community concerns in Waipa, Kauai, about stream water use/availability for traditional agriculture and chronic flooding occurring in lowland areas. Waipa Valley is a small Hawaiian mountain-to-sea system of about 5000 acres (2024 hectares) located on North Kauai (Fig. 1) which has been drastically altered by human uses including taro cultivation by native Hawaiians (prior to European contact) followed by extensive periods of rice cultivation and cattle ranching. Except for remnant patches near the headwaters of Waipa Stream, human activities have decimated nearly all of the native forest in the valley replacing it with alien pasture grasses. About thirty years ago, the Waipa Foundation (a nonprofit organization) was started by native Hawaiian residents to restore the biophysical resources of Waipa and to perpetuate Hawaiian culture by revitalizing the traditional growing of wetland (i.e., flooded pond field) taro (*Colocasia esculenta*) as a food staple. Today, about 20 acres (8.1 hectares) of taro are cultivated in Waipa with an estimated 75% of the base flow of Waipa Stream used for their irrigation.

The single most important issue in the traditional understanding and management of Hawaiian *ahupua'a* (i.e., traditional mountain-to-sea systems) was the localized hydrologic cycle. As an example, there is an ancient chant from the island of Kauai, *Ka Wai a Kane*, that is an inquiry-based technique used to teach the hydrologic cycle to children. Even the Hawaiian term and concept of wealth (*waiwai*) is, literally, "abundant water." Still, traditional *ahupua'a* had their surface water resources fully developed, from sequential irrigation systems along stream courses to constructed fish ponds enclosing shoreline springs and reef flats; however, these systems were managed within strict societal rules that enforced sustainable use of water resources. Today, there appear to be limitations in the surface water supply needed to support the expansion of wetland taro agriculture in the region. To complicate matters, historic changes to forest structure and composition in Waipa's upper watershed have altered the natural dynamics of surface water capture, retention, and release in the system, as well as made the stream environment more vulnerable to flooding. Flooding during storm events is a common occurrence in flashy Hawaiian stream environments; therefore, there is great uncertainty today for Waipa residents as to the quantity, quality, and movement of surface water in their *ahupua'a*.

To assist the Waipa community in obtaining the information needed to address these concerns, two *InteleCell*-based weather stations, a water quality sonde, and two stream stage sensors were initially deployed in Waipa Valley (Fig. 1). The prototype stream monitoring network was designed to relate localized climate variation occurring in the valley along mountain-to-sea gradients to surface water quality/quantity responses in the stream and ditch system used for taro irrigation. Local residents were provided with authenticated access to *InteleView* to monitor in near real-time, data on weather parameters and surface water conditions in the valley so as to better understand their hydrologic system. Although, sensor networks are currently under development and the data preliminary, weather parameters in Waipa Valley (December 2005 to June 2006), were found to differ markedly over a relatively compact spatial gradient (Table 2). Coastal areas around Waipa, for example, were found to have higher and more variable temperature, solar radiation, and rainfall as compared to an upper valley area less than ~1.1 km (~0.67 mi) inland (Table 2). As a proof-of-concept of the systems utility for monitoring floods, data from Waipa's wireless sensor network were used to track in near real-time level increases in Waipa Stream and in the agricultural ditch during a storm-driven rainfall event occurring in the valley between November 29, 2006 and December 3, 2006 (Fig. 3). No comparable data has been previously available for monitoring environmental conditions in a Hawaiian hydrologic system in near real-time on a mountain-to-sea scale. As the sensor networks and associated cyberinfrastructure are further improved in Waipa Valley, predictive models able to forecast hydrologic trends/trajectories will be possible and new prototype wireless sensor applications such as an "early flood warning" system developed. This would be an invaluable tool, which would help Waipa and other communities around the state prepare for and mitigate the effects of catastrophic flooding which can occur unpredictably in Hawaii during any season.

Discussion

The cyberinfrastructure developed in this study successfully synthesized the use of wireless sensor technologies, grid computing with 3D geospatial visualization, and an internet-based portal interface, into a robust observing platform for regional scale environmental monitoring. The *InteleCell* wireless data acquisition devices resolved various technological issues (e.g., Estrin and others 1999; Hill and others 2004; Ravi and others 2004; Golab and Ozsu 2003) that previously constrained the application of wireless sensors to relatively small areas. The generic communications interface of *InteleCells* enables the creation of heterogenous networks to monitor environmental parameters at macro- or micro-scales and leverage new innovations arising in the capabilities of existing sensing platforms as well as commonly used commercial sensor products. The wireless networking capabilities of meshed *InteleCells* use an innovative frequency-hopping, spread spectrum technique to move data (including images) intelligently between nodes at rates of up to 115 kbps to an

Table 2 Comparison of weather station data from lower versus upper Waipa Valley (Kauai) based upon averaged hourly *InteleCell* measurements downloaded from *InteleView* from December 2005 to June 2006

	Air temperature, °C		Solar radiation, W/m2		Wind speed, m/s		Wind direction, °		Rainfall, cm	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Mean	21.988	20.824	163.485	137.158	0.799	1.286	128.534	315.966	0.042	0.034
Median	21.930	20.410	7.500	4.000	0.750	1.209	88.900	313.100	0.000	0.000
SD	3.092	2.182	238.114	212.156	0.581	0.638	88.769	14.674	0.187	0.130
Min pos	10.320	15.580	1.000	0.001	0.001	0.065	0.031	299.800	0.025	0.025
Max	30.610	30.500	1057.000	1064.000	4.551	5.052	359.400	351.000	4.242	3.632

Internet gateway without interference over distances of up to 40 miles. Stable, long-term power to the backbone network provided by efficient, solar-powered *InteleCells* able to store up to four gigabytes of data per unit, reduce power consumption in linked embedded sensor arrays which no longer need to store or process data. *InteleCells* also handle other low-level communications tasks such as localization (with built-in GPS), triggering sensors on-off, system monitoring, clock synchronization, and data routing/caching (using secure 256-bit AES encryption), all of which minimize communication costs to the overall network to further conserve power, bandwidth, and resources. Firmware in field-deployed *InteleCells* may also be upgraded remotely to provide flexible support for new sensors or to adapt to topological changes in the sensor network making previously deployed systems essentially future proof to evolving research needs.

Grid computing capability is integrated organically into the observing platform so that data from deployed wireless sensor arrays are linked into a federated set of information resources and middleware. This facilitates information resource sharing, coordination, management and processing using the latest in emerging Grid-based technologies. The Grid infrastructure handles the metadata, system catalogs, and data store, providing authenticated user access to information and tools through powerful internet-based portals. *InteleView*, constructed upon NASA World Wind, serves as the 3D data display/exploration engine which is seamlessly integrated into the platform. With further development, this initial framework will be better able to facilitate extended information use/sharing among researchers, educators, and citizen users. While this new cyberinfrastructure initially focused on needs specific to regional-scale environmental monitoring, it was designed from the outset to be open-sourced and expandable by user communities with its base set of features left highly pliable for further exploration of advanced concepts and potential application to use-case scenarios that address environmental research questions.

Future Work

The cyberinfrastructure implemented on Kauai through several iterations produced a robust starting framework to leverage upon and identified a number of additional hardware/software issues to address. For example, developing automated methods to maintain calibration of deployed wireless sensor arrays through comparisons with per-sensor baselines (for sensor drift compensation, sensor-specific calibration, etc.), or normalizing data within the statistical dynamics of previous readings to reduce false positives or comparing these data across sensor types (intermodal) to identify trends, is important to maintain data quality, particularly in harsh environments. Grid-based middleware topics related to data management/integration identified for future work, include improving the system's ability to handle differences in data spatiality (location and coverage region), temporality (frequency of transmission), and confidence values across different data types, as well as increasing data security while accommodating easy data sharing among user-groups. Additional work is also needed to improve portal architectures to reduce barriers to users for adding new data to the server database or customizing portal features/functionality, as well as to improve the speed of data delivery to users, automate data extraction/input by researchers directly from the field and enable this improved functionality while maintaining data security for individuals and organizations.

Conclusion

In Hawaii, as is the case globally, intensifying human impacts to watershed catchments seriously threaten the health and integrity of coupled human-natural systems. We believe that the new cyberinfrastructure for environmental monitoring developed in this study with its sophisticated but flexible, open-sourced, portal-based Grid infrastructure and ability to leverage innovations in sensor technologies on regional scales, has the potential to meet the scientific and engineering challenges created by humanity's expanding global environmental impact. Its underlying strength lies in its ability to cross-connect among technologies/scientific disciplines and thus initiate the new forms of multidisciplinary collaboration within academia, industry, and government needed to effectively deal with the next decade of challenges from emerging infectious diseases (e.g., Wilcox and Colwell 2005), the effects of global warming (e.g., Malcolm and others 2002), loss of biocomplexity (e.g., Colwell 1998), and over-demand for natural resources, such as water (e.g., Vreke 1994).

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