Best Practices for EWS Design and Implementation

1. **Remember that an effective EWS is not simply a collection of instruments.**

It is useful to approach early warning from a programmatic perspective, where the EWS includes not only instrumentation, but a user-friendly data viewing platform, emergency management documents, collaboration with emergency managers, a notification system, and ongoing maintenance and training activities.

Considerable effort should be expended to plan and document an EWS installation, through either a feasibility or design process that answers key questions related to project scope. Identification of key stakeholders early in development of the EWS program is a critical step to ensure that program goals and objectives are clearly understood in the development of the project scope. In addition to understanding of the technical requirements of the EWS equipment, development of a successful EWS program requires a realistic understanding of both initial capital costs, and just as importantly, the operational life-cycle costs of the equipment and program administration. An EWS will require periodic onsite maintenance, calibration, cleaning, and repair or replacement of equipment as needed, verification of data quality and reference datums, and quality control of the notification and alarming functions. Also, annual program maintenance activities should be identified and planned. Appropriate resources must be allocated for these activities.

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An effective EWS program requires an adequately funded and staffed maintenance program with well-defined responsibilities and testing procedures. Dedicated staff and regular training are necessary to maintain an effective program. If a program monitors multiple dams or sites as part of the EWS, equipment and procedures should be consistent across sites, so that parts and repair procedures are interchangeable and training can be effective no matter the location. Building local capabilities through training of local staff saves time, money, and makes the systems more robust, while promoting ownership and awareness of the system. Inclusion of operating personnel in the design process can return large dividends.

In order for EWS equipment to perform when needed, it must be continually tested and maintained. Sensors, computer hardware, and communication equipment are exposed to the natural environment and will eventually malfunction, requiring maintenance, repairs, and sometimes replacement. Careful review of and familiarity with historic sensor performance is helpful to identify when an instrument records unreliable or inaccurate measurements. When a piece of equipment consistently malfunctions or reaches the end of design life, or if product support is no longer available, it should be replaced with equipment that meets the current state of practice.

EWS equipment can be subject to external influences such as extreme temperature fluctuations, construction activity, vandalism, lightning strikes, fire, and water damage, rodent damage, etc. An inventory of spare parts should be maintained by the program to ensure no delays in procurement, and minimal breaks in monitoring occur. Over the longer term, hardware and software updates may be needed. EWS testing and maintenance procedures should be documented and can be a standalone document or can be included in a dam's Operations and Maintenance (O&M) plan, Standard Operating Procedures (SOP), Routine Maintenance Checklist (RMC), etc.

2. Decide what needs to be measured.

Every site to be monitored is unique, so no simple rules can determine the proper amount or location of instrumentation to provide adequate early warning. The complexity of the facility, known issues or concerns, and identified potential failure modes (PFMs) should all be considered in deciding what parameters should be measured and how this should be accomplished. Some key factors to consider when designing an EWS include:

- Size of the structure;
- Location (remoteness and availability of power);
- Accessibility; and
- Site security.

In general, an EWS will produce the best results if it's simple, robust, and easy to access: Simple for clear and understandable warnings of potential issues; Robust in not only having optimal instrumentation methods to monitor PMFs, but also the implementation of complimentary instrumentation and instrumentation redundancy as to not rely on a single instrument for safe project operations; Easy access to maintain a robust maintenance program or for visual confirmation of abnormal readings.

A list of all available instrumentation components is beyond the scope of this article and technology is constantly evolving, however there are many resources available that provide in-depth sensor listings [1, 17, 18]. Most available resources are related to traditional geotechnical dam performance monitoring, but as long as a sensor is able to automatically collect and disseminate information reliably in near real-time, it can likely be incorporated into an EWS. Each sensor is manufactured to operate within a specified range, resolution, accuracy, precision, and repeatability. Selection of instruments should be matched to program needs and weighed against reliability, availability, standardization priorities, and cost. Some of the most common parameters to measure at dams are water level and weather information.

Water Level

Water level is the most obvious parameter to measure at both large and smaller sized dams and there are several effective means for measurement. Typical observations include measuring inflows into a reservoir, the reservoir level elevation, and downstream or tailwater conditions whether through channel flows, flumes, or weirs to calculate discharge. Unanticipated rapid increases in tailwater and/or rapid changes in reservoir level are key components of an EWS and are often linked to activation triggers in the EAP.

Water level monitoring devices are normally housed within a conduit running along the upstream face of the dam to measure headwater, or in the stream channel to measure tailwater, or a stilling well is used to house a measuring device to measure the phreatic surface within the dam. Level-monitoring instruments should be located away from spillways and intake or outlet structures to avoid nappe effects. Common devices used include submerged pressure transducers, bubblers, ultrasonic, radar, or float switch systems. In climates where temperatures drop below freezing, it is important to submerge pressure transducers and bubblers deep enough below potential frozen water surfaces to avoid damage to the sensors and erroneous data caused by ice forming around the sensor.

Weather parameters

Weather sensors can be used to measure precipitation, relative humidity, wind speed and direction, air temperature, and water temperature. Precipitation is often measured with a tipping bucket rain gauge, which consists of a funnel and a small container affixed to a tipping lever. When the rain gauge collects a set amount of precipitation, the collection container tips, dumping out any collected water and sending an electrical signal to a data transmitter. Total amounts of precipitation and precipitation intensity (i.e. hourly rate of precipitation) are important hydrological parameters to consider, and are useful when evaluating instrumentation data from piezometers and weirs, reservoir level data, and watershed response as rainfall affects spikes and trends. It is important to note that point precipitation measurements taken at the dam site may not adequately reflect the basin precipitation for a large watershed.

Wind speed and direction monitoring can be important to understand wave run-up affecting dams. Particularly windy days can also cause large waves that may cause erroneous data records within the lake level monitoring equipment.

Other sensors types

Many conditions at dams can be monitored through instrumentation. For example, sensors that measure turbidity, a measure of the degree to which light traveling through a water column is scattered by suspended particles, can detect material being eroded from an embankment dam. Increases in turbidity measurements in seepage flow can indicate internal erosion, and can be installed at toe drains and near outlet works. Soil moisture content can be also be measured using sensors. A change in embankment or foundation soil water content may indicate a change in the phreatic surface and rising pore pressures. A more direct method to monitor the phreatic surface is by installing piezometers within a dam embankment. Site security can also be monitored using intrusion type sensors that send an alert when a gatehouse or EWS enclosure is opened.

3. **Keep it as simple as possible, but not simpler.**

One key to a successful EWS program is simplicity in planning, coordination, site design, installation, data collection and display, and communication. An uncomplicated program is more likely to produce reliable measurements with fewer errors and lower costs. Simplicity is achieved through the use of simple, robust instruments and sensors that are easy to install, calibrate, maintain, and replace when necessary. When EWS sites are consistent across a program, maintenance procedures and training opportunities can be standardized and more effective.

There are cases when sophisticated instrumentation may be necessary; however, even the best instruments do not enhance early warning if they are not working as anticipated, recording irrelevant information, installed in the wrong location, or not transmitting with appropriate frequency. An EWS and the types and number of sensors can be scaled and expanded to the particular needs of the dam.

Proper understanding of the purpose and intent of a monitoring tool maximizes its benefit [1], and more data collection requires more database management and data storage.

4. **Hire a professional.**

During procurement, installation, and testing of the system, it is recommended that a qualified engineer with dam safety experience and familiarity of the instrumentation be involved, especially for a dam rated with significant consequences. A successful EWS installation requires the harmonization of diverse areas of expertise, such as civil engineering, electronics, communications, programming, instrumentation, data management and website design. This type of expertise, guidance or oversight may be available from engineering consultants, instrumentation vendors, or regulatory agencies, who can provide training to local operators of the system. There are also professional organizations that promote education, training, and standards within the flood warning and dam safety community, such as the National Hydrologic Warning Council (NHWC). Lowest price procurements generally lead to disappointment [1].

There are many instrumentation vendors available who may offer various types of equipment that could provide data at a dam. During the planning and design phase, it is important to consider dam-specific conditions that can impact monitoring needs, such as inflow hydrology, dam design and construction features, appurtenant structures, and general conditions of the dam. Prior to this phase, a detailed potential failure mode analysis (PFMA) should be conducted to assess where instrumentation would be most beneficial to monitor for changes in behavior in relation to PFMs. The qualified engineer, as noted as recommended in the following paragraph should participate in the PFMA if possible.

5. **Design with telemetry and power supply in mind.**

Telemetry

Telemetry is the wireless collection and automatic transmission of data records through forms such as radio, satellite, internet protocol (IP), cellular, meteor burst communications, etc. to a server or central computer where the data can be displayed, verified, and acted on. It’s not enough for an EWS to simply detect an issue; that near real-time data must be disseminated as quickly as possible to decision makers.

Radio frequency telemetry is a common method of transmitting EWS data due to the low-power requirements and the low cost of radios. Radios make it possible to transmit under a common standard of communications criteria and may work for large networks of sites in close proximity, however transmission distance is short, so repeater towers or networks are necessary to communicate over long distances.

Satellite telemetry can be a reliable option that does not require repeaters to communicate between sites, which is desirable for remote sites, or individual monitoring stations. A data subscription from a private satellite provider is needed for transmitting real-time data, but the latency (the time it takes for the data record to be sent from the instrument, to the satellite, and back to the database for further analysis) is short. Geostationary Operational Environmental Satellite (GOES) transmitters, operated through the National Weather Service (NOAA/NESDIS) are available at no cost. The latency of GOES transmitters, ranging up to 60 minutes, can be an issue for stations that require near real-time data, which includes many dam safety applications. The latency becomes more of an issue for small basins that have a quick response to storm events, and for small to medium-sized dams.

Wireless internet protocol (IP) routers allow for seamless communication of instrument data but is not always available at dams. As cellular networks expand, data records and larger files such as camera images and live video can be transmitted via cellular signal, however, these networks should not be used for mission critical needs. During incidents these options may not be reliable due to high demand. Inclusion of backup means of telemetry are worth consideration when the primary telemetry option is not completely reliable at all times.

Power supply

An uninterruptible power source is a critical consideration when implementing an EWS to avoid missed data. Alternating Current (AC) power is good option if a reliable source is available. However, this option may not be attainable due to the remote location of many dams. Even when AC power is available, a backup power source is recommended in case the AC power is lost.

EWS sites are designed for minimal power consumption, and are most often battery operated, with the battery recharged using solar panels. Solar panels are reliable, and can maintain the batteries at a fully charged condition. Non-interruptible power sources like rechargeable batteries allow for continued operations during intermittent charging interruptions. In some cases, an EWS powered solely from a battery can continue to transmit data for weeks or months even after the recharge source is lost.

Battery and solar panel power supply designs should be sized appropriately for a particular site. Items to consider include: the worst-case anticipated load, which is mostly driven by data transmission needs, and local site conditions including expected amount of sunshine and average ambient temperatures.

6. **Design with maintenance, safety, and accessibility in mind.**

EWS sites should be designed with accessibility, future maintenance, calibration and replacement of equipment, and safety in mind. Maintenance costs will increase for sites that are difficult or dangerous to reach, and can create dangerous working conditions for technicians. Potential falls from exposed heights and confined or enclosed spaces should be avoided when designing an EWS. Utilizing junction boxes installed for access at various points along a wire run make maintenance and sensor calibration much easier.

The system layout should allow for failed sensors to be easily replaced. Sedimentation can cause instruments to become buried or stuck in place, so locations where deposits are likely to occur should be avoided when possible. A staff gauge installed near an EWS site provides a reference so that reservoir level or stage measurements can be calibrated. Instrumentation should be calibrated regularly as part of a SOP.

7. **Design for robustness and redundancy to make the system highly reliable.**

Ideally an EWS is fully operationally 24 hours a day, 7 days a week, but conditions at dams can be harsh. EWS infrastructure, such as cables, conduits, connections, power sources, and equipment enclosures must be hardened to handle a wide variety of environmental circumstances and remain operational through dark, cold, hot, wet, dry or corrosive conditions. Installing electronics and batteries in weathersealed enclosures helps to prevent moisture and water damage. Cables can be protected by PVC or metal casings, and buried if needed. Unprotected electronic components are likely to be damaged by high-voltage pulses, so EWS equipment must include an effective earth ground connection to protect against lightning discharges and direct strikes. Equipment should be secured to deter vandalism or theft. Initial investments to increase robustness will promote long-term reliability of an EWS.

Redundancy can be designed into an EWS for data quality and emergency warning objectives. Confidence in a measurement is improved if verified by multiple sensors. For example, as the reservoir level begins rising during a large inflow event, float switch sensors installed at critical levels would lift, providing level verification. A redundant system also allows for more reliable alarming capabilities. For example, certain emergency notification scripts could be written to include two sensors instead of one, providing better assurance of actual conditions (see notification alarms section below).

8. Make the data useful and intuitive.

EWS data need to be stored safely, evaluated, communicated to the appropriate decision makers, and displayed in an understandable manner that relates it to the dam. Data presentation (such as a dashboard) should allow for an engineer, dam tender, or decision maker, even those not intimately familiar with the dam, to understand and observe developing conditions, behavior summaries, and weather trends, without referring to a lot of other documentation. Structural and appurtenance elevations should be plotted along with reported water levels. Programming can reduce data transmissions until specific changes are detected, or thresholds are met. Data viewing platforms should be mobile-friendly, ensuring viewing capabilities while away from a computer.

In addition to data gathered from instrumentation, there are voluminous amounts of publicly available data sources that can supplement on-site sensors, providing additional data that can corroborate observations, expand alarming capabilities, and provide useful information that may be outside the scope of a typical dam instrumentation. Data can be organized and displayed online through dashboards. Some examples of trusted data sources include, but are not limited to: USGS streamflow gauge network, USGS earthquake shakemaps and automated alerts, NWS weather data (precipitation, temperature, etc.) and forecasts, NOAA Hydrometeorological Automated Data System (HADS) weather sites, and NRCS SNOTEL and snow course sites (snow depth and water content). These and many other data sources can be used in combination with EWS stations to provide a complete picture of conditions at and around a dam.

9. Ensure proper notifications and alarms.

A formalized set of triggers or thresholds should be used to differentiate between threat levels at a dam. FERC guidelines use the terms ‘Thresholds’ and ‘Action levels’ as values to take action [19]. Regardless of the name, the intent is to provide a basis to support a decision, and these levels should correspond to a dam’s EAP. Thresholds should be agreed upon in advance of an incident to help ensure prompt responses, leading to less delay in implementing the plan. Exercising the EWS on a periodic basis will improve the effectiveness of the decision process and verify that the proper people are receiving alarms. False alarms do not necessarily hinder future response, but care should be taken to verify conditions before EAP actions or evacuations are initiated.

Alarms can be written such that defined recipients receive particular alarms tailored to their informational needs. For example, leaders within an organization may only be interested in emergency alarms, however dam tenders and field staff may be expected to respond to more routine notifications such as maintenance alarms that need addressed, or when sensors are reporting readings outside an expected range.

Precipitation alarm thresholds can relate to magnitude and duration of storm events and the storm's probability of occurrence. NOAA Atlas 14 rainfall duration estimates and other similar datasets (e.g. REPS MetPortal tools in Colorado and New Mexico) help provide more detailed, site specific information for most locations within the United States. If flood hydrology studies are available for the watershed above a dam, smarter alarms can be created by predicting inflows and expected reservoir levels based on real-time rainfall data. Forecasted rainfall grids are also often available as model inputs to generate anticipated flood estimates.

An EWS is only effective if instrumentation data is accurate, appropriate thresholds are set, and the correct people receive the information they need to make the best decision. Multiple methods of communication are often more effective than one. Examples of methods of communicating alarms include text messages, email messages, voice information from a call center or automated telephone calls, road crossing flashers, and sirens. How communications may be impacted during an emergency should be considered. For example, thinking through how important EWS messages can still be transmitted should cell towers and phone lines become inoperable creates a more robust system for emergencies. Each communication channel has strengths and weaknesses such as speed of dissemination and susceptibility to failure.

10. Take advantage of the latest technology.

Camera and Video Monitoring

EWS can include digital cameras to allow for continuous visual surveillance from remote locations. Inclusion of a camera can provide emergency response staff with important visual confirmation of a major event at a dam. High-quality cameras with tilt-pan-zoom and infrared night vision capabilities combined with the low cost of high-speed communications, make it affordable to supplement instrumentation with remote visual camera surveillance for monitoring remote dams or potential areas of concern. Cameras can be used to take readings from a staff gauge, identify signs of distress, verify current or developing conditions, and aid in deciding what actions are necessary. In the near future, artificial intelligence (AI) for video surveillance will continue to develop, and will be able to provide measurements and recognize situations much like an instrument would. Remote sensing techniques are likely to add even more capabilities for advanced monitoring of dams.

Future Technologies

As technology continues to advance, more options for faster, more reliable and affordable data transmission methods will likely become available. Instrumentation and power sources are becoming more efficient and agile. There will be more tools available to measure and monitor conditions in ways we currently cannot, and when it makes sense, could be included in EWS. The future of EWS is bright, but despite advances in data acquisition and techniques, the factors affecting dam performance will remain unchanged. It is important for the reader to keep up with the latest industry technology and methods and to seek out reference materials (including the ones provided here) for more guidance on EWS development.