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FLOOD EARLY WARNING SYSTEM: SENSORS AND INTERNET

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ABSTRACT: The *UrbanFlood* early warning system (EWS) is designed to monitor data from very large sensor networks in flood defences such as embankments, dikes, levees, and dams. The EWS, based on the Internet, uses real-time sensor information and Artificial Intelligence (AI) to immediately calculate the probability of dike failure, the ensuing scenarios of dike breaching, predicted flood spreading and escape routes for people from the affected areas. Results are presented on interactive decision support systems that assist flood defence managers and public authorities during flood events. It can also be applied for policy development and for everyday dike condition assessment. The separate *Virtual Dike* module can be used for advanced research into failure mechanisms and dike stability. By consulting international stakeholders the designers ensured that the EWS is well aligned with user requirements.

Key Words: flood, early warning system, ICT, climate change, sensor networks.

1. INTRODUCTION

A large number of European cities have to deal with flood risk management issues on a regular basis; as climate change effects result in more extreme conditions, this will worsen. Early Warning Systems (EWSs) can play a key role in mitigating flood risk by detecting abnormalities and indicators of flood defence failure before it actually happens, and by providing real time information during a flood event. EWSs thus fulfil multiple roles as general information systems, decision support systems and alarm systems for multiple stakeholders including government, companies and the general public.

We present the *UrbanFlood* project [www.UrbanFlood.eu] that creates an EWS framework linking sensors to predictive models and emergency warning systems; the general framework is validated for dikes. The data from sensors are interpreted to assess the condition and likelihood of failure of dikes [Pengel *et al.*, 2011]. Established and extensively tested models are used to predict the failure mode and potential inundation. The models have been adjusted to use additional 'Cloud' computer resources available on demand via the Internet, running on 'virtual machines' [Melnikova *et al.*, 2011a]. In this way *UrbanFlood* combines known and tested technologies in a novel way, using ICT and flood management, building the dike monitoring and EWS system of the future [Krzhizhanovskaya *et al.*, 2011].

2. RELATED WORK

In the last few years a large number of projects aimed at the development of stronger and "smarter" flood protection systems have been initiated around the world. All of them aim to solve flood control problems, and several by developing Flood Early Warning Systems (FEWS). Existing EWSs are mostly localized, custom-designed and using local computer resources [Akhtar 2008, Artan 2002, Delft-FEWS 2009, Samadi 2004, Zhou 2006], hampering exchange of experiences, data and results and duplicating efforts. Standardization in data, systems and flood risk assessment procedures is slowly taking place at national scale in many countries [Keys 2009, USAID 2011, Bea 2007, Farber 2007, WIRADA 2008]. The full potential of the Internet for setting up the actual EWSs is hardly used. Likewise, the use of electronic sensors to monitor infrastructure is just taking off.

State-of-the-art flood early warning systems use meteorological data, water levels and remote satellite monitoring data (optionally) as input sources [Flash, 2010; Bandon, 2011; FEWS NET, 2008]. The FLOODsite project [www.floodsite.net] has developed a set of efficient models essential for flood risk analysis as well as the management methodologies [Morris *et al.*, 2009; van Gelder *et al.*, 2008; Asselman *et al.*, 2009]. Sensor data was not used in these models; the main input parameter for the simulations was the water elevation data. EWS design was not the main goal of the project.

Delft-FEWS software by Deltares [Delft-FEWS 2009] provides a hydrological forecast and warning system [Gijsbers, 2010]. It is described as a collection of modules designed for building a hydrological forecasting system customised to the specific requirements. Delft-FEWS is a flexible system and Deltares has only begun to use real-time sensor information in addition to the water levels, precipitation, meteorological and radar data that are presently used. The *UrbanFlood* EWS provides additional functionality as requested by dike owners and emergency response organisations (see Section 3.1), such as an advanced decision support system, models that work with the data from the sensors installed inside the dikes, a city evacuation module and several simulation modules for expert users.

One of the more interesting ongoing projects is FloodControl 2015 [www.floodcontrol2015.com]. Like *UrbanFlood*, it is developing an advanced forecasting and decision support system. FloodControl 2015 uses the same experimental data from the IJkDijk, which was built for research purposes [www.ijkdijk.nl]. FloodControl 2015 also uses real-time sensor data as a stream input. *UrbanFlood* has some significant advantages: the *UrbanFlood* EWS has a truly interactive decision support system with a capability to overlay different types of data (weather, ships passing by, video from the dike, and model simulation results) and the multi-touch functionality to support team work in decision making. *UrbanFlood* also offers a *Virtual Dike* module which is an advanced multi-scale multi-model simulation lab for expert users and model developers [Melnikova *et al.*, 2011b]. This virtual lab is used for validation of the fast-response models involved in the real-time modelling cascade, and serves as a research tool for experiment planning and understanding the underlying physical processes influencing dike stability and failure.

The International Levee Handbook is another large and promising project uniting 6 nations [www.leveehandbook.net]. It started in 2010 and will run until 2013. The goal of the project is to offer comprehensive guidance on the design, construction, maintenance and improvement of levees/dikes and to describe the international state of the art on these matters. They are also promising to offer a decision support framework for competent engineers.

3. THE URBANFLOOD EARLY WARNING SYSTEM

The *UrbanFlood* flood early warning system is designed to monitor data from extremely large sensor networks in flood defences like embankments, dikes, levees and dams, using Internet resources, Artificial Intelligence and special computational models.

The EWS uses real-time sensor information to rapidly calculate the probability of dike failure and the possible scenarios of dike breaching, hydrographs and flood spreading. Computed information is presented using the internet on interactive decision support systems, like the *UrbanFlood* multi-touch table (Figure 1), which is optimized to assist the decision making process of collaborating, multidisciplinary, medium-sized emergency teams and decision makers. This interactive user interface also allows intuitive map-based access to libraries of detailed pre-calculated flood scenarios, as well as initiating multiple computer simulations as part of "what-if" scenario analysis. Web-based interactions and smart phone apps using intuitive map-based user interfaces are also supported.

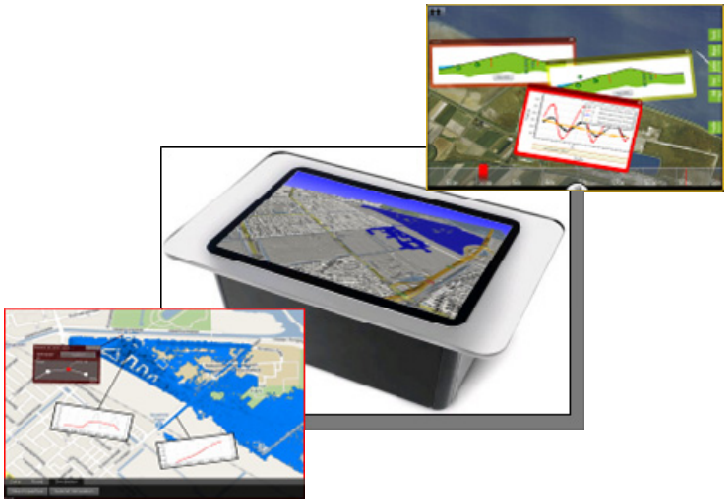


Figure 1. Accessing EWS results

3.1 Stakeholder Requirements and Wishes

One of the first activities of the *UrbanFlood* project was to conduct a stakeholder survey, in order to match the initial concept and design with the requirements of the intended users. The stakeholder analysis started with a synopsis of known issues in a discussion document. Based on this document a series of interviews was held in the Netherlands, verifying the document and adding detail. Then questionnaires were sent in a targeted manner to international key resource persons, resulting in responses from 8 countries. The stakeholder requirement report [Pengel *et al.*, 2010] provides background on relevant policies, programs and projects; it also mentions a number of example "smart dike" implementations and a list of stakeholder requirements for EWS and smart dikes in three classes:

1) Technical requirements. These have to be met to ensure that the system actually works and a working prototype can be build: robust sensors, reliable communication during emergencies, standardized formats and protocols, reliable computing, trusted models, easy, intuitive and interactive visualization and compatibility.
2) Non-technical requirements. These mostly focus on the security, reliability and economics of the system: Security and access, legal standards, financial aspects.
3) Institutional issues – a system that is proven as a working prototype which is secure, reliable and economical still has to be accepted by the organizations that are going to implement it, and by the people who need to work with it.

Based on the stakeholder requirements several adjustments have been made in the original design, and are still being made. For example: the *UrbanFlood* EWS can now also be deployed for flood management policy development in non-emergency situations, and is able to support dike managers in day to day dike condition assessment. In this way it becomes an integral part of the professional toolkit providing information on the actual conditions of the embankments and fact-based computations of their strength, which ensures that staff members of the involved organizations will have the necessary routine and practice to use the EWS effectively and with confidence if a flood emergency occurs.

An interesting development that needs close attention is the 'Multi-Level Flood Safety' concept. In this concept a distinction is made between the *probability* and the *consequences* of flooding. In Multi-Level Flood Safety different areas (or "levels") of activities are recognized: prevention, sustainable spatial development and emergency management. These are already being applied in everyday practice, but almost always considered separately when assessing flood risk. Approaching all aspects of flood safety as an overall encompassing concept based on flood *risk*, not *probability*, is new and relatively unknown, but might raise new opportunities to fight flood risks at lower costs. The next years are crucial; successful

application of multi-layer flood safety may be an excellent way to improve flood safety while optimizing budgets. This will also increase the importance of EWS's and digital, online monitoring, though both acceptance and the necessary legal framework (when is a flood defence safe?) need to be developed.

3.2 Design and Functionality

The *UrbanFlood* EWS is built on a generic Internet-based EWS framework. It can use virtually all types of digital (sensor) information. It is able to run computationally demanding applications such as almost instantaneous flood modelling in Internet-connected Cloud-based data centres that allocate computational resources according to priority and requirements. For dependable use during flood emergencies, several EWSs can run in parallel in different geographic locations, possibly operating different computational models. This enhances the reliability of the system and offers a second opinion for assessment of the current emergency situation. In addition, local mirroring, alternative communication means and even the ability to use a minimum set of functionality locally should be considered.

4. WORKFLOW AND COMPUTATIONAL MODULES

The *UrbanFlood* EWS is built in a modular way [Krzhizhanovskaya *et al.*, 2011]; the workflow is presented in Figure 2. The *Sensor Monitoring* component receives sensor data from the sensors in the dike. Raw sensor data is filtered by the *AI Anomaly Detector* that identifies abnormalities in dike behaviour or sensor malfunctions. The *Reliability Analysis* module calculates the probability of dike failure in case of unusually high water levels or a predicted storm and extreme rainfalls. If the failure probability is high then the *Breach Simulator* predicts the dynamics of a possible dike breach, calculates the water discharge through the breach and estimates the total time of the flood. After that, the *Flood Simulator* models the inundation dynamics (Figure 3) and the *Evacuation Simulator* calculates escape routes from the affected areas.

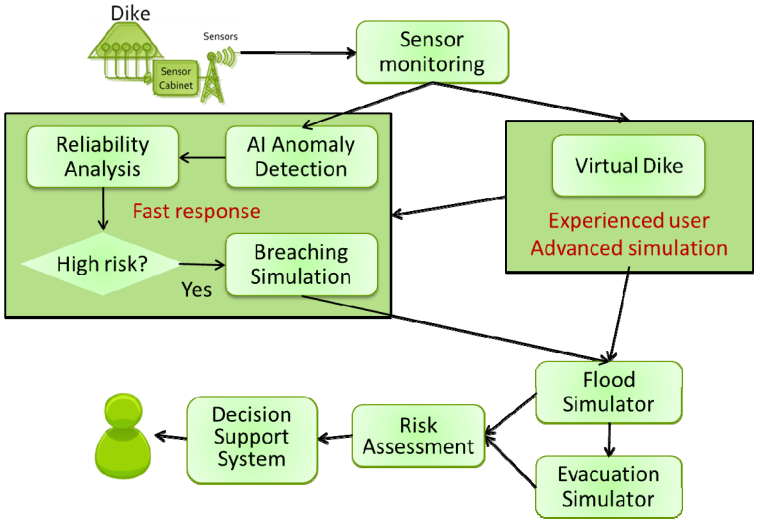


Figure 2. Early warning system (EWS) workflow.

Information from all the modules is visualized in the *Decision Support System*, which works as an intelligent interactive interface between the data and information and the users. For more advanced research into dike stability and failure mechanisms, the *Virtual Dike* component is available for experienced users and experts. All these modules are automatically invoked by the EWS on distributed Cloud computing resources [Melnikova *et al.*, 2011a]. Flood Simulator and *Virtual Dike* modules have been ported and successfully tested on the SARA BiG Grid HPC Cloud [http://www.sara.nl/].

A detailed description of the workflow and computational models has been published in [Krzhizhanovskaya *et al.*, 2011, Melnikova *et al.*, 2011a, 2011b, Gouldby *et al.*, 2011]. In Sections 4.1and 4.2 we briefly describe two modules: Artificial Intelligence and *Virtual Dike*.

Figure 3. Flood simulation results for Vasilievsky Island, St. Petersburg, Russia.

4.1 Artificial Intelligence

The Artificial Intelligence (AI) component of the EWS aims to detect abnormalities in the behaviour of monitored objects by analyzing sensor data with machine learning methods. The core of the component is a *Committee* of one-side classifiers [Lang *et al.*, 2008] (Figure 4). It is trained on historical data of "normal" (reference) conditions and on extracted known "features" of dike behaviour. The *Committee* is created and configured taking into account the domain knowledge and specific data. For instance in Figure 4, separate classifiers are created for every cross section of the dike.

After the training stage, the *Committee* of classifiers calculates the *Confidence values* indicating the current state of the system in order to detect deviations from the reference state. If previously unknown combinations of particular parameters are detected, it flags exceptions and alerts flood experts. A more detailed description of the AI module can be found in [Pyayt *et al.*, 2011].

Based on all available information, the experts or the EWS make a decision if the exception indicates a potentially dangerous situation or if further analysis should be carried out, which could be done by using the *Virtual Dike* module for identification of potential failure mechanisms.

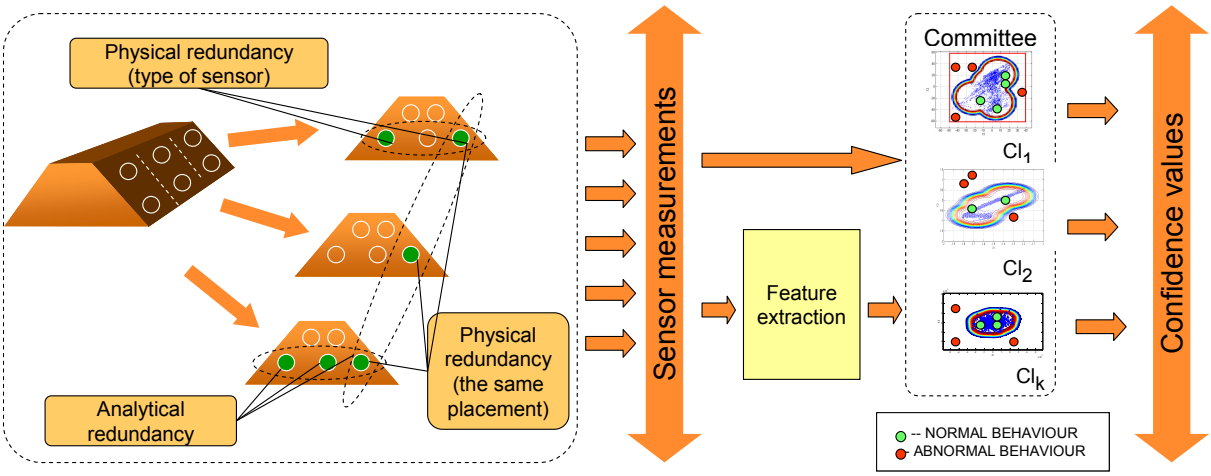
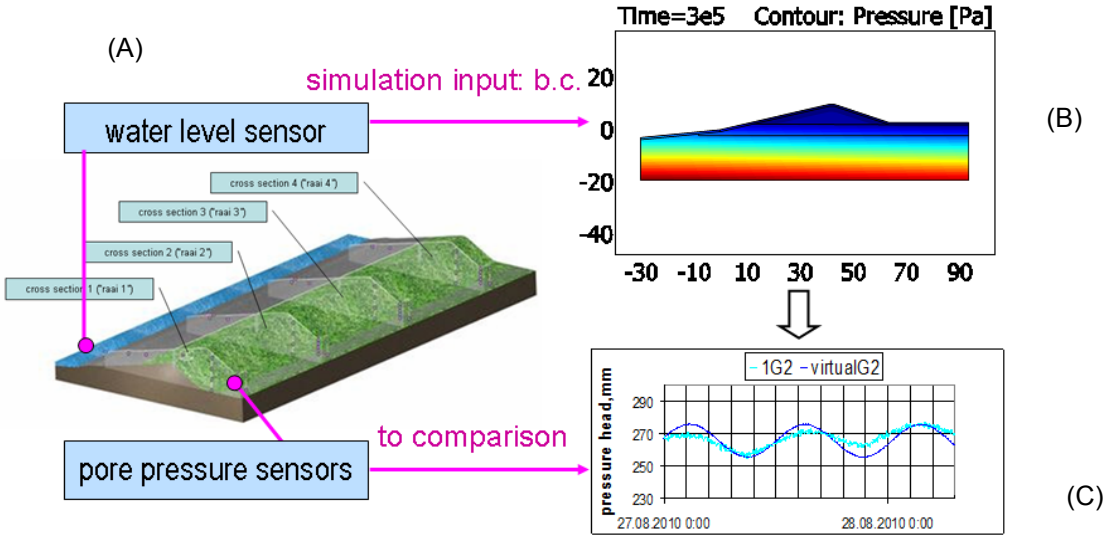


Figure 4. Abnormality detection scheme using Artificial Intelligence

4.2 Virtual Dike

The *Virtual Dike* computational module uses the finite element method to analyze dike stability and investigate failure mechanisms. The module solves the linked problem of flow through porous media and structural stability analysis, using an elastic-perfectly plastic material model with Mohr-Coulomb slip criterion [Melnikova *et al.*, 2011b]. The *Virtual Dike* can compute the same observables that sensors are registering, including pore pressure, strain and stress fields. In this way the model can explain the physical mechanism that may cause observed behaviour. The module is also used to train the AI component to detect anomalous combinations of sensor measurements.

The first test case performed to validate the *Virtual Dike* module is slope stability analysis of the *LiveDike Eemshaven* (a sea dike in Groningen, the Netherlands, see Section 5), under tidal load. The dike is equipped with a water level sensor and pore pressure sensors installed inside the dike in four cross-sections shown in Figure 5A.



(A) – a dike and its cross-sections with sensors installed; (B) – pore pressure field at one moment of time (simulation results); (C) – comparison of pore pressure dynamics obtained from sensor and from simulation, at sensor location.

Figure 5. *Virtual Dike* module: workflow of the dike stability analysis under tidal load.

The water level sensor signal is streamed in real-time to the *Virtual Dike* application. The pore pressure sensor data was used to calibrate soil parameters, so that sensor data and simulation results agree (see Figure 5B, C). The dynamics of stability parameter distribution under tidal load have been published in [Melnikova *et al.*, 2011b]. The results confirm that the *LiveDike Eemshaven* is stable under tidal load.

4.3 Integration and Visualization

In order to organize individual components into a working Early Warning System, *UrbanFlood* provides the *Common Information Space* (CIS) [Balis *et al.*, 2011], a generic framework for creating and hosting any EWS which works according to a four-step cycle: Monitoring, Analysis, Value Judgment, Advice/Act. The CIS takes care of the organization of the resource management processes 'under the hood', like virtual machine control, provenance, data management etc.

Visualization can be used by one or more client applications. The applications allow users to create new simulations by first defining simulation parameters and then submitting the simulation to the CIS for execution. Several client applications have been created: a prototype of a Decision Support System (DSS) for a multi-touch device, a web-based interface that visualizes pre-executed simulation results and an application for visualization of sensor data. Despite the complexity of the system architecture, simulations are computed and visualized within a timeframe of less than one minute. This allows the system to be used for interactive testing of different flooding scenarios.

5. PILOT SENSOR NETWORKS

For the *UrbanFlood* project, several sensor networks have been installed in various types of dikes and levees in the Netherlands and the United Kingdom, demonstrating the usefulness of a EWS based on sensor networks. In addition, data of other pilot sensor networks are also used within the *UrbanFlood* project. Although the currently available networks are rather limited in size, a significant variety of useful parameters is measured. The current short dike lengths which are instrumented can easily be extended to hundreds or thousands of kilometres, the system is completely scalable.

Most of the installed instruments are 'Geobeads'. These compact instruments measure pore pressure, temperature (to detect flow) and local tilt. In Boston, UK, in close collaboration with USA partners, comparable 'SAA' (ShapeAccelArray) were installed, which measures global tilt and temperature, and 'SAPP' instruments, like the SAA, plus pore pressure measurement, as well as a vibrating wire piezometer and a GPS. Fibre optic cables which measures deformation and groundwater flow are installed at LiveDijk Eemshaven and in Boston, UK. Existing pilot sensor networks of which the data is available to the *UrbanFlood* project are:

LiveDijk Eemshaven, Groningen, the Netherlands: a large sea dike mainly composed of sand with a clay cover and an asphalt revetment. Over 50 sensors for water level, pore pressure, temperature and local tilt, and 800 meter fibre optic cable. Probable failure mechanisms: slope or revetment failure (Figure 5A);

Stammerdijk, near Amsterdam, the Netherlands: a small river dike with a nearly constant river water level, composed of clay on top of soft layers with a deep sand base, 16 instruments in 2 cross sections measuring pore pressure, temperature, local tilt. Probable failure mechanisms: landward slope stability and piping;

Ringdijk, in an Amsterdam city polder area: a secondary dike with a nearly constant outside water level, with a deep construction pit and trees causing damage on the landside, composed of clay and peat layers, 18 instruments in 3 cross sections measuring pore pressure, temperature and local tilt. Probable failure mechanisms: landward slope stability, possibly influenced by dry conditions;

Grand Sluice embankment in the centre of Boston, United Kingdom: an embankment under significant tidal influence composed of clay, sand and till, with three instrumented cross-sections where inclination over depth, pore pressures, temperature and local tilt are measured, and two lines of fiber optics at two

levels over a length of 300 meters measuring deformation and temperature (Figure 6). Probable failure mechanisms are outward slope stability after rapid drawdown, followed by erosion and breaching.

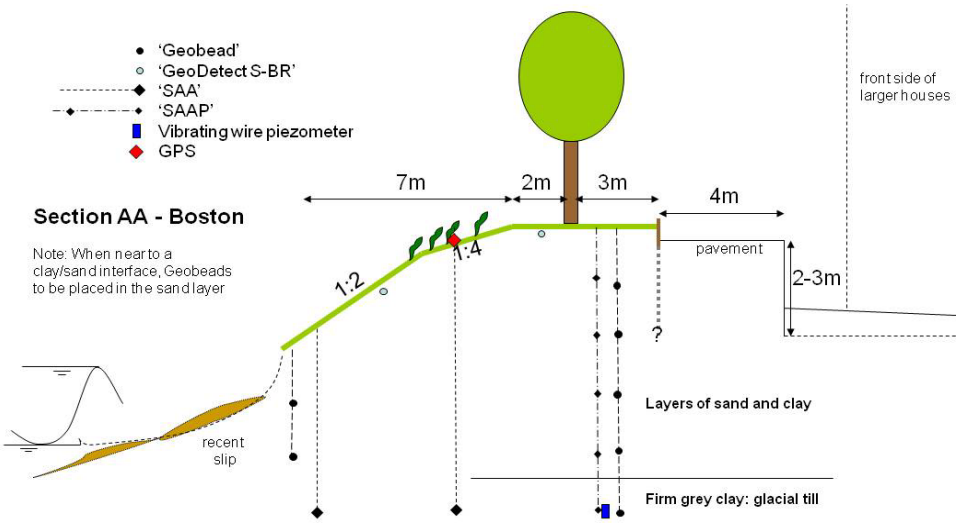


Figure 6. Cross-section showing instrumentation at Grand Sluice embankment, Boston, UK.

By September 2011 other locations may be instrumented: the Rhine dike near Emmerich, Germany, prone to piping (backward seepage erosion) and landward slope stability, and the St. Petersburg Flood Protection Barrier, where sensors control the sluices and dam gates, to ensure that they do not fail to close in flood emergency.

6. CONCLUSION

In this paper a technology for building early warning systems based on real-time signals from sensors and its application for monitoring dikes is described. Sensors are becoming ubiquitous in our modern society, and have evolved into ever smaller, cheaper and easier to read instruments. The *UrbanFlood* project and its partners show that combining such sensor networks, modern communication technology and Cloud computer technology can be used to build the monitoring and early warning systems of tomorrow.

For operational implementation the methodology will have to be tested and proven in mission-critical circumstances. As technology improves further and the need for better and cost-efficient real-time monitoring of large infrastructure works becomes increasingly clear, we are confident that this is only a matter of time, not least because the system is built using proven technologies combined in an innovative way, and allows much needed increases in flood safety while conserving presently limited budgets. The *UrbanFlood* project is looking forward to work with all water managers who install sensor networks to monitor dikes or other large infrastructure.

7. ACKNOWLEDGMENTS

Special thanks are due to the organizations that made the installation of sensors in 'their' dikes possible. The first clearly is the IJkdijk Foundation [www.ijkdijk.eu], for creating a testing facility for sensors in dikes in Groningen, the Netherlands; this has given the research a huge boost. Thanks also go to the organizations and individuals who made the brave step to install sensors in their flood defences: Waternet of Amsterdam, the Netherlands, and the Environmental Agency in the UK. These organizations and individuals ensured that we have data to show how useful this technique is. And of course we wish to thank all stakeholders who shared their insights with us, and continue to share them, to make the *UrbanFlood* EWS a system that is made *for* the users and *by* the users.

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