New Observational Tools and Datasources for Hydrology

Hydrological data Unlocked by Tinkering

Rolf Hut

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Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K. C. A. M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op dinsdag 1 oktober 2013 om 10:00 uur

door

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geboren te Amsterdam, Nederland.

Dit proefschrift is goedgekeurd door de promotor:

Prof. dr. ir. N. C. van de Giesen

Samenstelling promotiecommissie:

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Printed by: Scan Laser

Front & Back: Out of focus photo of a Delft-disdrometer, see chapter 4 for more information. Cover design by Peter Hut.

ISBN 978-94-6186-212-9

An electronic version of this dissertation is available at
http://repository.tudelft.nl/.

The Information Age offers much to mankind
and I would like to think that we will rise to
the challenges it presents. But it is vital to remember
that information, in the sense of raw data, is not knowledge
that knowledge is not wisdom,
and that wisdom is not foresight.
But information is the first essential step to all of these.

Arthur C Clarke

Contents

1

Introduction

Science is made up of so many things that appear obvious after they are explained.

Pardot Kynes[1]

[1]Imperial planetologist in the novel Dune, written by Frank Herbert

In a review paper covering millennia of scientific progress in astronomy, the astronomer Harwit argues that advances in astrophysical understanding alternate between advances through new observations and advances in theoretical understanding [1] . The advances in observations are largely driven by technological advances. The new astronomical spyglass, now known as the telescope, allowed Galileo to observe the planets and the moon in much greater detail than before. Advances in theoretical understanding, however, are driven by new theoretical tools: Kepler and Galileo could describe the orbits of astronomical objects, but the newly developed differential calculus was needed for Newton to formalise the observations into the general laws of motion.

The process of advances in hydrological understanding are no different than those in astronomy. For example: determining the isotopic composition of samples taken in the field became both technologically and economically feasible in the late 1980's and start of the 1990's. Quickly, hydrologists realised the potential of this novel technique and started to use isotope analysis in their work. This new source of information on catchment response to rainfall showed that the old paradigm that the main process in peak discharge is overland, or Hortonian, flow no longer held. The isotopic measurement results were discussed at large in the hydrology community in the so-called "old-water" discussions [2] leading to a host of new hypotheses on the dominant process in peak discharge such as preferential flow paths [3] and the "fill and spill" hypothesis [4]. New mathematical tools were needed to properly understand the new isotopic data. The advance of Bayesian analysis and related tools such as Markov Chain Monte Carlo methods [5] [6] helped to interpret and understand isotopic and other new data sources. The new analysis tools also pointed to the next problem with observational data. Fundamentally, there is not enough information in most hydrologic datasets to uniquely infer model-parameters and thus to accept or reject hypotheses on dominant processes [7] [8]. Adding more of the same data-source, i.e. longer time series from (spatially sparse) rainfall and discharge measurements will not yield the required gain in information: novel sources of information are needed.

One such novel source of information is satellite data. Satellite data are used, among others, for detailed elevation models [9], measurements of soil moisture [10] and depletion of groundwater aquifers [11]. Since biases in hydrological variables show spatial patterns, local calibration of satellite data is often needed [12]. Paradoxically, given the low number of ground observations worldwide, the rise of remotely sensed (satellite) data has increased rather than decreased the need for additional ground measurements.

The two facts:

1. hydrological models need more information
2. satellite data can provide part of that information, but need ground calibration,

both coincide with a set of technological revolutions that could potentially be valuable to hydrology:

- The occurrence of sensors in nearly every (consumer) device and the associated drop in cost of those sensors. Low-cost measurement devices allow for either measurements of variables previously thought unmeasurable, or for measurement campaigns with networks of sensors in denser grids than previously assumed feasible.

- Open source hardware. Especially the Arduino platform has opened up low-level electronics to scientists without a background in electronics. For hydrologists, the threshold to prototype one's owns sensors has been significantly lowered by the introduction of the Arduino.

- The open data mentality. The online sharing of research results and large datasets in searchable repositories, both in and outside of hydrology, allow easy, searchable, downloadable access to a host of data that used to be outside the grasp of most hydrologists. With data portals becoming more easily accessible, new sources of data previously outside both the attention and the logistic reach of hydrologists are now available to include in hydrology research.

Open source hardware (and software) and open data are both movements that strive toward the public sharing of designs and data. The idea behind these movements is twofold: ideas are generated by association, so being exposed to other peoples' ideas leads to new ideas and it is easy to innovate using freely available tools. The work presented in chapter 2 was inspired by videos that were shared on YouTube, and the work would have been impossible to do without free software libraries made by people much more skilled in low-level machine interactions than I am. Open source hardware, software and data has generated numerous shared re-usable building blocks that anyone can use and be inspired by. These movements are enabled by the rise of the internet. Worldwide online communities on obscure topics are able to connect to each other and share their work and ideas in real time. A full exploration of the cultural and technological impact of these movements is beyond the scope of this thesis, but the influence they have had and continue to have on hydrology will be made clear throughout the remainder of this thesis.

The scientific community (and hydrologists as part of it) has always had members who liked to build their own sensors and design their own experiments. For example: Darcy built his now famous sand column apparatus [13]. Building your own sensor used to be a costly business. The abundance of cheap sensors and open source hardware has empowered individual scientists with the inclination to build their own sensing equipment. However, getting cheap sensors out of consumer electronics and connecting them to open source hardware loggers or communication devices and finally publishing or sharing their measurements as open data requires a tinkering mindset not unlike that of MacGyver[2]. Just as sensors are not specifically made to connect to Arduinos, but can be attached with some MacGyvering, open datasets are not made to connect to each other. Although tinkering with software to connect different datasources to each other is often called

[2]the main character in an 1980s tv show of the same name. MacGyver is a special agent known for using his knowledge of science, his Swiss army knife, duct tape and everyday objects around him to solve the problems he encounters during his adventures.[14]

hacking, I would argue that it involves the same MacGyvering mindset. Figure 6.1 shows graphically that a lot of MacGyvering is needed before the three technological revolutions of low cost sensors, open source hardware and open data can lead to advances in hydrological understanding.

A special issue of Water Resources Research published 2009 focussed on recent advances in hydrologic measurement. The editors Selker and Ferre pointed out the importance of novel measurement equipment for the progress of science [15]. The introduction chapter of this thesis aims to expand and update the overview of that special issue with the most recent developments in the field. Sections 1.1 till 1.4 will detail the current state of measurement methods that are currently being developed by hydrologists using open source hardware, using a pragmatic MacGyver attitude towards measurements, using consumer electronics, or using inputs from sources outside of hydrology. For each section in the introduction, chapters 2 till 5 contain an example peer-reviewed article from my own involvement in this field. Finally, chapter 6 sums up the major conclusions from the previous chapters and offers my view of the near future for hydrological measurements.

1.1. Open Source Hardware: the Arduino

The Arduino platform was originally developed for educational purposes: to give design students an affordable and easy toolset to add interactive components to their work [16]. From the Arduino website:

> Arduino is an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. It's intended for artists, designers, hobbyists, and anyone interested in creating interactive objects or environments.[17]

Arduino works with an open source mentality: all hardware and software designs are available and anyone is allowed to make copies, variants or extensions of the Arduino. This has led to an ecosystem of third-party suppliers jumping on the bandwagon and producing Arduino-compatible hardware such as extensions for data logging on SD cards, for communication over Wifi or GPRS, etc. Some companies aim for a broad public of tinkerers [18][19] while others market specifically to (environmental) scientists [20].

Another open source hardware product that was originally developed for educational purposes, but has the potential to disrupt the sensing equipment business simply by virtue of its existence, is the Raspberry Pi - a credit card sized computer [21]. The Raspberry Pi has not made it into hydrological literature yet, but a quick search on the Raspberry Pi forum reveals a host of valuable applications that could benefit hydrologists [22]. The advent of open source hardware would have been impossible without open source software as an example to follow and a tool to use. The Raspberry Pi runs the free, open source operating system Linux. The open source Arduino Integrated Development Environment (IDE) in which users write the software that will run on their Arduino's is based on the open source programming language Processing [23].

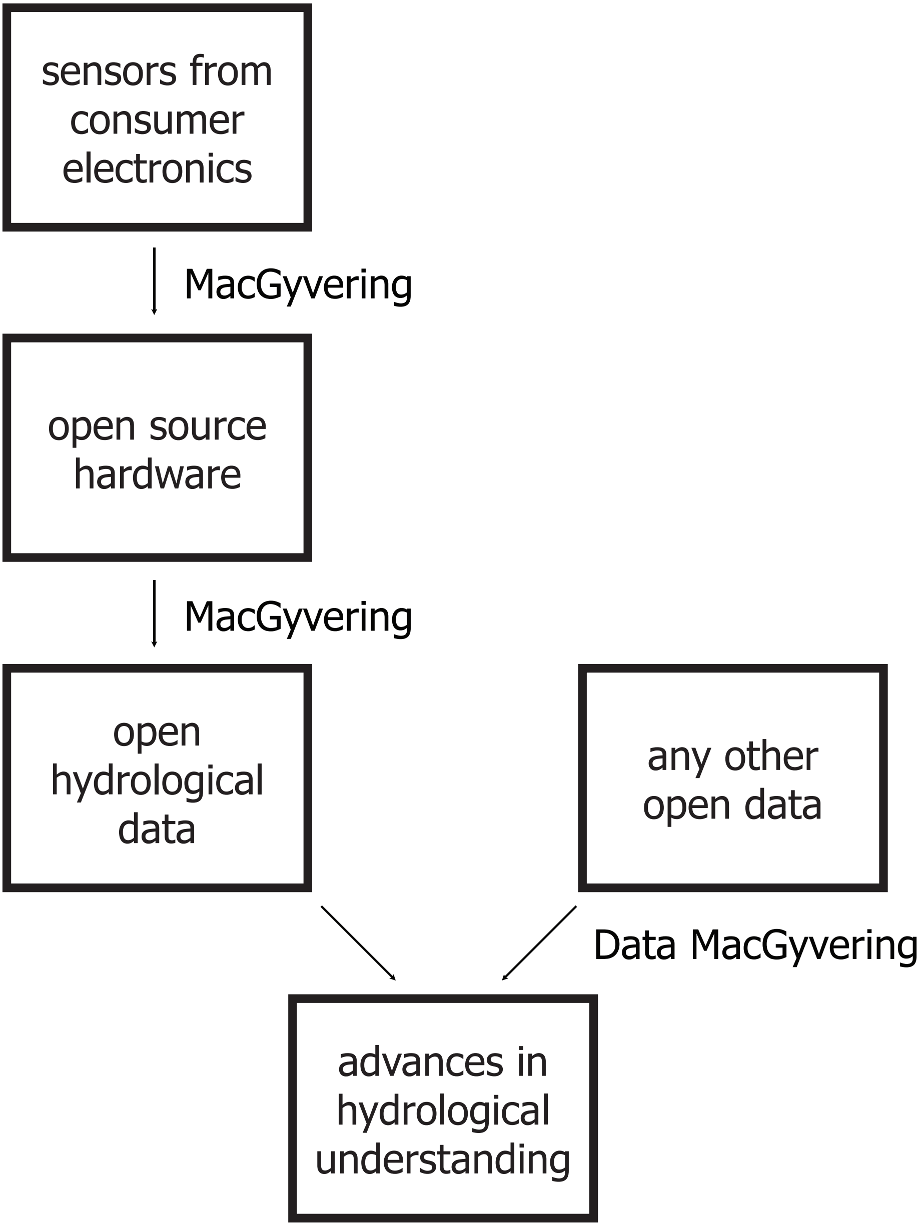

Figure 1.1: **Overview of how sensors from consumer electronics, through some MacGyvering, can be connected to open source hardware.** Further MacGyvering allows the (online) publishing of the data collected in open repositories. Finally some data-MacGyvering is needed to connect different data sources that will ultimately lead to new advances in hydrological understanding.

Hydrologists quickly realised the potential for hydrology: using off-the-shelf sensors connected to Arduino units, custom-made sensing units are now within the reach of everyone. Steve Hicks built a solar-powered Arduino data-logger node with self-meshing wireless communication for less than $150 [24] of which dozens were deployed in the Christina River Basin Critical Zone Observatory. Jay Ham connected an ammonia sensor to the Arduino to measure emissions from a livestock farm [25]. Queloz *et al.* used an Arduino to activate an automatic water sampler, allowing for event-driven sampling [26]. The advent of open source electronics has spurred some researchers to go beyond the Arduino and fully custom-build their measurement setups. John Ong automated the double-ring infiltrometer setup [27]. It might be argued that this type of work fits better in the MacGyver section below, within which an overview is given of research in which people custom-build measurement setups from scratch.

1.2. MacGyver

This section gives an overview of research in which a down-to-earth pragmatic so-called "MacGyver"[14] attitude was used to develop measurement devices. The term "MacGyver-science" was jokingly introduced by colleagues when the work presented in chapter 2 was published [28]. The definition of "To MacGyver" as given by wiktionary.org is:

> To assemble, or cause to be repaired or completed, an object, device, machine, or project from duct tape as the preferred repair tool, but in its absence, other items, (normally common, ordinary and mundane such as a rubber band or paper clip), not normally used for that purpose, where others would assume one needs a manufactured part, as per the design. Especially: if the items are used in ways significantly different than their intended use. [29]

Of course, other hydrologists also employ this attitude in their research. Rupp *et al.* showed that a simple bucket with carefully placed holes can measure plot scale run-off [30]. Lundquist *et al.* used trees instead of expensive radiation shields to shield off the shelf temperature sensors from radiation [31] [32]. The drifters designed by Kruger *et al.* [33] that float down rivers and measure water and air temperature while logging their GPS positions might have been mentioned in the "Arduino" section as well, if they had not been designed from scratch. A similar idea was used by Herma *et al.* who built a sensor and logging device that was attached to a cable car in an alpine valley to measure fluctuations of temperature, humidity and pressure with altitude in the valley [34]. Kean *et al.* placed pressure sensors designed for measuring groundwater levels (i.e. divers) in river banks to measure the timing of the peak of a debris flow in post forest fire catchments [35]. Stewart *et al.* filled soil cracks with watertight bags with a single outlet and measured soil movement by measuring volume change in those bags, the so-called "crack-o-meter" [36]. Friesen *et al.* realized that changes in canopy water content (including interception) can be indirectly measured via stem compression. Stem compression was measured by connecting linear displacement gauges to tree stems [37]. Campbell realised that an LED can be used reciprocally as a sensor and used this to build a single-pixel Normalized Difference Vegetation Index (NDVI) sensor [38]. Using the fact that most digital cameras are good at detecting near-infrared radiation, the infragram kickstarter project aims to build a consumer-price camera that can make NDVI photographs [39]. By using an off-the-shelf accelerometer connected to a small boat, van de Giesen *et al.* measured the wave spectrum on a lake [40]. In chapter 3 the same accelerometer is used to measure, via its eigenfrequency, the changes in mass of a bucket on a stick, turning it into a rainfall and evaporation recorder.

Using "MacGyver-science" as badge of honor[3], together with Theresa Blume, John Selker and Wim Luxemburg, I organised the first "MacGyver-session" at the AGU fall meeting of 2009. We felt that pragmatic work on developing measurement devices was not shared adequately with other scientists, but rather was hidden in the "Methods and materials" sections of papers, if mentioned at all. By giving scientists a place to share and demonstrate their home-build devices we created the opportunity for scientists to learn from each other. The AGU session has been repeated annually ever since and now goes by the name "Transformative Measurements to Understand the Geosphere: Zip-Ties, Arduinos, Novel Sensors, and Twitter". A "sister-session" was organised at the EGU General Assembly called "Innovative Techniques and Unintended Use of Measurement Equipment" starting in 2011. Unsurprisingly, all of the work referred to in this section was presented in those sessions.

1.3. Consumer Electronics

With the automation of everyday objects, the number of sensors in households has dramatically increased during the last few decades. The production cost for the sensors in consumer electronics is generally lower than for sensors intended for scientific research. This is due mainly to the economies of scale that are achieved in producing consumer electronics. Many scientists are now seeing sensors in their home that they are using, or would like to use, in their lab or field. This has spurred a movement of scientists who use the generally low-cost sensors in consumer electronics in their research. Below, I will first highlight two examples in some detail and end with a brief overview of other consumer-designed sensors used in hydrology.

1.3.1. Nintendo Wii™

The Wii game console that Nintendo introduced in November 2006 was a breakthrough in electronic gaming as it was the first (major) system to incorporate motion-sensing in the controller: users (gamers) have a wireless (bluetooth) controller called a Wiimote. The location of this controller relative to a sensor bar is measured by the Wiimote. The Wiimote incorporates an infrared camera that tracks the location of four infrared LEDs in the sensor bar. In addition, the Wiimote has an onboard accelerometer that measures its displacement in time. Before the intro-

[3] in Dutch best translated as "Geuzenaam", not "ere-teken"

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duction of the Wii, game consoles all used a classic controller interface that relied on buttons and analog sticks for user input. The Wiimote was sold as part of the Wii system, but could also be bought separately at around $40.

In November 2007, Johnny Lee, then a graduate student at Carnegie Mellon University, published an instruction on his website on how to connect the Wiimote to a regular computer, using the bluetooth connection [41]. The video [42] associated with this went viral. Based on this viral video, Lee gave a highly influential TED talk [43]. Lee now works at Microsoft Research, where he worked on the Kinect project, see section 1.3.2, below. Lee inspired a lot of people to find their own uses for the sensor. Most of these were focussed on using the sensor as an input device for computers [44] or robotics [45]. Ultimately, the Wiimote found its way into the peer-reviewed literature: Lee published his work [46] and many papers followed that focussed on applications in man-machine interaction and robotics (among others, [47], [48]).

It is not self-evident that a sensor like the Wiimote can be used for research in the geosciences. However its low cost and high sampling frequency make it interesting for research where motion is tracked. In chapter 2, it is shown that the Wiimote can be used to measure evaporation from a class A pan that is floating in an open-water body.

1.3.2. Microsoft Kinect®

In response to the commercial success of Nintendo's Wii motion sensor, Microsoft developed and released the Kinect-sensor for the Xbox game console. The Kinect combines a 3D depth scanner and a "regular" camera to reconstruct a 3D image of a user's living room. The Kinect allows for touch-free communication with the Xbox system, such as waving to browse through media, or dancing in front of the console in games such as "Dance Central"[4]. As with the Wii, the introduction of the Kinect first led enthusiasts working in the computer sciences to try to connect it to their computers and access its data-stream. Within weeks of its release, Daniel Shiffman released a library on his blog to capture the Kinect data using the Processing integrated development environment [23] [49]. Shiffman's work was quickly picked up by the hacking and making communities that started to use the Kinect in their projects. Overviews of what was achieved can be read in books such as "Kinect Hacks" [50].

Building on this early work, peer-reviewed papers were published that focussed on the characteristics of the device itself. Khoshelham *et al.* determined optical parameters for the Kinect system, allowing experiments to be done with greater accuracy [51]. Cui *et al.* built an algorithm that uses the depth camera and rgb camera of the Kinect to reconstruct 3D models of scanned objects [52]. This is based on Cui *et al.*'s similar earlier work that uses time-of-flight cameras [53]. Microsoft's Zhang, the producer of the Kinect [54], chipped in with a paper on the technology and idea behind the sensor. Many computer science labs started using the Kinect in their classes and research, especially in robotics [55].

3D scanning techniques like Lidar have been widely used in the geosciences [56].

[4]mentioning a game is not intended as an endorsement, certainly not in the case of "Dance Central"

The usefulness in the geosciences of a low-cost 3D scanner like the Kinect, even with a limited range of around 5m, is more likely than for a hand-held motion sensor like the Wiimote. Mankoff [57] illustrates three applications: scanning the surface of glaciers to detect heterogeneous ablation rates, collecting stream bathymetry using a special ”through-water” calibration, and defining the characteristic length-scale of sand ripples on a beach. Azzari [58] scanned the 3D structure of plant canopies. All these papers take care to point out the advantages and disadvantages of using the Kinect for geoscientific research. The main advantages mentioned are low cost, relative high resolution and ease of implementation. The main disadvantages are the inability to measure in full daylight, the relative short range and the need to connect the Kinect to additional logging equipment such as laptops.

1.3.3. Other Consumer Electronics

Of all the devices consumers own, modern cars are arguably the ones fitted with the most sensors. Haberlandt [59] and Rabiei [60] realised that the optical sensors used to automatically operate the windshield wipers can be used as mobile rain-gauges. Ultrasonic rangefinders are nowadays mostly known as “parking-aid” sensors. They have been on the market for a long time, but their use in the automotive industry has brought the cost per unit down. In geosciences they are, for example, used to measure snow depth [61]. The temperature sensors that Lundquist *et al.* used were already mentioned in the MacGyver section above. Those off-the-shelf sensors were originally designed for the food industry[32]. Also used in the food industry are “temperature guns” that measure the temperature of a shipment by looking at the IR radiation from a single point. Van de Giesen *et al.* used the sensor in these guns to measure the surface temperature of an alpine valley [62]. Creutin used an off-the-shelf video camera to calculate stream flow by tracking natural foam on a river [63], showing that the original work by Fujita [64] could be done using low-cost equipment. This approach was later expanded into the field-operational mobile large-scale particle image velocimetry (MLSPIV) device that can measure streamflow by standing on the bank and “looking” at the river [65]. Off-the-shelf GPS loggers are normally used by scientists during fieldwork to measure the exact location of a measurement point. Lievens *et al.* attached GPS loggers to buoys in an estuary to measure the timing of tidal slack [66]. Mansheim *et al.* used gunnplexer to measure the Doppler shift that falling rain drops induce in a microwave beam. A quote from their article:

> Gunnplexers and DRO modules find application in radar speed guns, vehicle parking radars, aircraft landing gear, and motion sensing. They also find application in speedometers in agricultural applications where the low speeds make it difficult to make accurate measurements using conventional methods. In fact, the Gunnplexer-based module that we used for this study is marketed as the sensing head of a tractor or is combined with a speedometer. [67]

Unmanned aerial vehicles (UAVs) have long been military equipment [68]. Recently, small UAVs have become more economic and thus more easily accessible for researchers. Smoorenburg *et al.* used a UAV equipped with an IR camera to measure surface-temperature at field scale [69], similar to the work of Freer *et al.* using a small unmanned helicopter [70]. Development in this field is fast: unmanned helicopters equipped with infra-red cameras are currently being offered at prices affordable to researchers, although producers still focus on the security and safety market [71]. Koh *et al.* used a small model plane for the hobby market and equipped it with video and still cameras and a pre-programmable flight unit to be able to monitor both wildlife movement and land-use change in Sumatra [72]. The firmware of the still camera was replaced using the Canon Hack Development Kit, giving researchers greater flexibility in the use of the cameras. The same kit was used by Weijs *et al.* who added an external power-saving circuit, in order to autonomously measure snow cover for several months [73]. Also measuring snow cover, Garvelmann *et al.* added battery life to simple cameras by soldering on an additional battery pack. They placed their cameras in bird houses to protect them from the elements and to avoid vandalism [74]. A final ”trick” with off-the-shelf cameras was employed by Stewart *et al.*: by placing a soil sample on a pivot and using freely available software, they created 3D models of their samples, which allowed them to study soil shrinkage [75].

Figure 1.2: **Examples mentioned in this chapter** Upper left: the Arduino Uno development board that allows quick prototyping. Upper right: the motion sensing remote of the Nintendo Wii™. Lower left: the Kinect 3D scanner. Lower right: Angus MacGyver, namesake of the verb “to MacGyver”

1.4. Looking Beyond Hydrology

Hydrological understanding has recently been improved using measurement techniques and data sources developed outside hydrology. Compared to the era of paper journals and publications, online access to both journals and data sources outside one's own field has made both cross-disciplinary research and learning from other fields of science a lot easier. Distributed Temperature Sensing (DTS) was originally developed as a measurement technique in the oil and gas industry. Since its introduction in hydrology by John Selker *et al.* [76], it has found numerous applications. For example Westhof, *et al.* [77] studied hyporheic exchange in details previously impossible. DNA profiling, a well-known technique developed in medical research[5], was used by Sharma *et al.* [79] who used little plastic spheres injected with known DNA sequences as conservative tracers. Another use of small plastic spheres in hydrology was pioneered by Tauro *et al.* [80]. The spheres were coated with low doses of fluorescent paint to allow detection by normal cameras mounted over small streams, in order to measure stream velocity. Using data outside of hydrology allows for novel insights. Satellite data is the prime example of data that may not have been originally collected for purposes in hydrologic research. The ASCAT instrument on the ERS-1 and ERS-2 satellites was designed to measure wind fields over the ocean. The scattered signal over land turned out to contain valuable information on soil moisture [81]. A complaints-database operated by municipalities was analysed by ten Veldhuis *et al.* [82] for use in flood-risk modelling. This shows that not all relevant data for hydrology needs to come from (scientific) measurements. In chapter 5 research is presented in which demographic data is combined with water quality samples to link pharmaceutical pollutions to different population groups.

Harwit [1] reasoned that observational and theoretical breakthroughs follow each other. Hydrology is currently at a stage where it needs new data from observations or from new data sources before a new breakthrough in hydrological system understanding can be achieved. The following chapters will highlight my work in unlocking this hydrological data. My approach to unlocking this is by tinkering with existing hardware from consumer electronics (chapters 2 and 4), by using a MacGyver attitude (chapter 3) and by looking beyond hydrology (chapter 5).

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2

Using the Wiimote as a sensor in water research

Anything that is in the world when you're born is normal and ordinary and is just a natural part of the way the world works. Anything that's invented between when you're fifteen and thirty-five is new and exciting and revolutionary and you can probably get a career in it. Anything invented after you're thirty-five is against the natural order of things.

Douglas Adams

The $40 "Wiimote" (an input device belonging with the Nintendo® Wii™game system) can be used by hydrologists as a sensor. The device contains three accelerometers and an infrared camera with built-in source tracking. It communicates by Bluetooth®. Because of the efforts of the hacking community it is now easy to let the Wiimote communicate with a standard personal computer. Using a floating evaporation pan as an example, we show that the Wiimote, although it may have potential drawbacks when used in field campaigns, is a good addition to the hydrologist's bag of tools, especially for proof of concept testing.

This chapter has been published as "Using the Wiimote as a sensor in water research" by R.W.Hut, S.V. Weijs and W.M.J. Luxemburg in Water Resources Research **46**, 12 [1].

2.1. Introduction

A large collection of sensors is available for hydrological experimentation (see Fraden [2] for an overview). A limiting factor in employing these sensors is often the number of sensors available in a lab and thus, directly or indirectly, their cost. Scientific sensors are often very expensive, partly due to the inclusion of digital data storage of measurement data or digital interfaces. Because of the high cost of those sensors, they are usually not available for simple proof of concept experiments, or for educational purposes.

With this paper, we wish to draw the attention of the hydrological community to a new low-cost piece of equipment that can be used to conduct measurements: the Nintendo® Wii™remote (commonly known as Wiimote). This game console controller contains motion sensors, an infrared camera with position tracking and a wireless connection to a computer by Bluetooth®. In recent years, the (online) hacking community has reverse engineered most of the functionality of this device. The knowledge gained in these efforts has largely been made available online through wikis and Web sites such as http://wiiyourself.gl.tter.org. A large body of software aimed at communicating with the Wiimote is (freely) distributed. Anything presented in this paper benefits greatly from the work of the anonymous individuals who publish on those wikis. The work presented here was sparked by the video (YouTube) tutorials and free software downloads from Johnny Lee, whose work on the Wiimote was recently also published in a scientific journal [3]. Using the software available online (we added logging capabilities to software available at http://wiiyourself.gl.tter.org/), it is easy to read the observations from the sensors on the Wiimote and store them on a computer. Because of this, the Wiimote offers an opportunity for hydrologists to conduct proof of concept experiments at low cost.

2.2. Specifications

The Wiimote is a remarkable game controller in that it contains, along with the regular buttons, a three-axis linear accelerometer and a infrared camera. Lee [3] gives an overview of the technical specifications of the device. In this section, those relevant for measuring will be repeated.

The accelerometer has a range of ± 3 g and communicates at 100 Hz in 8 bits per axis. Since gravity is not canceled out in the sensor, this sensor can also be used to retrieve the orientation of the Wiimote relative to the earth gravitational field.

The infrared camera has a resolution of 1024 x 768 pixels and a 45 degree angle of vision (horizontal). The output of the Wiimote is not its recorded image, but the location (measured in pixels) of the 4 brightest infrared sources in its view. Tracking of these infrared sources is done by hardware on the Wiimote.

Communication between the Wiimote and the computer is done by Bluetooth®. Connecting a Wiimote to a computer is as straightforward as connecting any other Bluetooth® device. The software mentioned above, although usually designed for a specific purpose, provides easy-to-use interfaces to read out the data that the Wiimote's sensors detect.

2.3. Example: Floating Evaporation Pan

As an example of the capabilities of the Wiimotes as a hydrological sensor, we will present some results on water level measurements in a floating evaporation pan. To measure the evaporation from open water bodies, usually an evaporation pan is placed in a contraption that lets it float, while making sure that the water in the pan is at the same temperature as the water in the open water body [4]. A problem with real-time measurements in this setup is that wave motion (both of the pan on the water and of the water in the pan) prohibits good measurements of the volume of water in the pan with high enough accuracy. To test whether the water level in an evaporation pan can be measured at high sample frequencies, and whether small changes in water level can be retrieved from the recorded signal, we decided to do a proof of concept experiment.

2.3.1. Experimental Setup

The experiment was carried out under controlled circumstances in the wave generator basin at the hydraulics lab of Delft University of Technology. A class-A evaporation pan was strapped to some sheets of styrofoam. In the center of the pan, a steel vertical rod was mounted, along which a little styrofoam float was placed. On the float, 4 infrared LEDs were installed. See Figure 2.1 for a picture of the float. On the side of the pan, the Wiimote was mounted in a PVC holder, aimed at the float with the LEDs. In this way, the Wiimote ”sees” the LEDs and communicates their coordinates with respect to its own field of vision to the laptop. A small hose, connected to a low-flow pump, also fed into the pan. This pump can produce low flows that would result in water level changes of a few millimeters per hour in the pan (mimicking the order of magnitude of the evaporation flux, with opposite sign). See Figure 2.2 for a schematic overview of the experimental setup.

In the wave generator, waves were generated with an amplitude of about 5–10 cm and frequencies between 0.5 and 2 Hz. The generator was switched on and off repeatedly to see the effect of increasing and decreasing wave activity. The low-flow pump was set to a flow of 6 L/h, resulting in a water level rise of 6 mm/h. The pump was also intermittently activated.

2.3.2. Experimental Results

In this section, selected pieces from the experiment are highlighted to illustrate the opportunities and difficulties when measuring water levels in a floating evaporation pan at high sample frequencies.

In Figure 2.3 the water levels in the evaporation pan are shown when the wave generator makes 10 cm (amplitude) waves with a frequency of 1 Hz. In the first part of the experiment the low-flow pump pumps 6 L/h into the evaporation pan. The pump and the wave generator are switched off at the same time. The different colors represent the different LEDs. A low-pass, first-order filter with a cutoff frequency of 0.1 Hz is applied to those signals. The result is shown by the black lines. The output of the first-order filters shows the long-term average, from which the pumping rate of the low-flow pump (simulating evaporation) can be inferred.

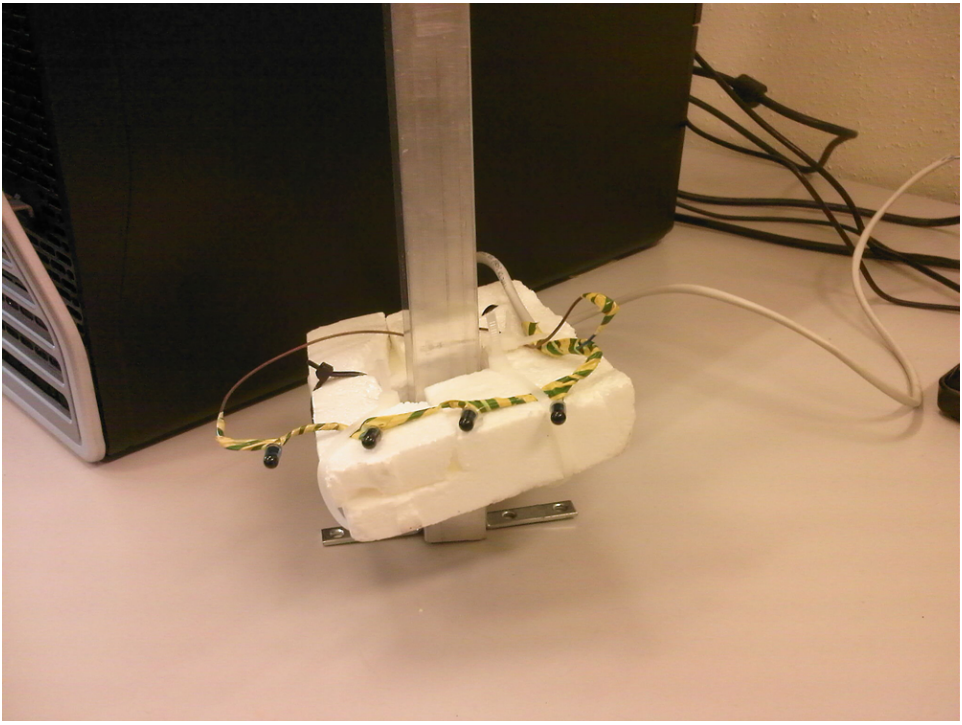

Figure 2.1: Picture of the float used in the experiment, with the four infrared LEDs clearly visible. The LEDs are bolted to the float with small bolts to make sure they do not move around with respect to the float during heavy wave motion.

In Figure 2.4 the water levels are shown for a period where the water was initially at rest, and then the wave generator was switched on. Remarkably, the average water level decreases when the wave generator is switched on and it returns to its original level when the generator is switched off. This is attributed to an unknown (nonlinear) effect. Possible explanations include the size of the float compared to the wavelength of the waves in the pan, a nonlinear interference effect, or the (difference in) resistance that the float experiences as it moves along its guiding rod. If a floating evaporation setup was to be part of a field campaign, this effect has to be taken into account. The experiment with the Wiimote showed this in a first test.

2.4. Discussion

In this paper, we have shown that the Wiimote is a useful low-cost addition to the existing set of sensors available to hydrologists, especially for proof of concept testing. Its usefulness is limited by a few shortcomings. First, it needs batteries. A Wiimote can work continuously only for up to around 24 h on two standard AA batteries. Secondly, it needs a connection to a recording station (usually a regular

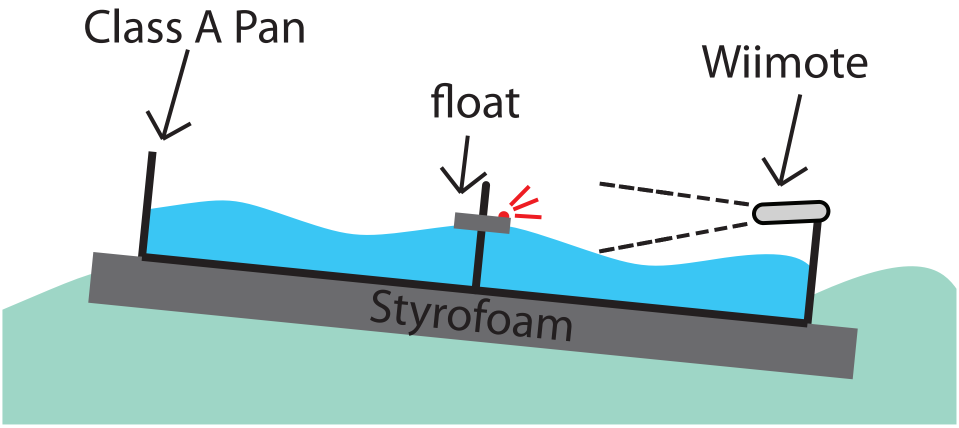

Figure 2.2: Schematic overview of the experimental setup, showing the class A evaporation pan floating on the waves of the wave generator. The styrofoam float is placed around a rod in the center of the pan. The Wiimote is attached to the side of the pan. The Wiimote "sees" the infrared LEDs on the float and sends their coordinates to a logging laptop using Bluetooth®.

computer/laptop) with Bluetooth® capabilities. Leaving such a device in the field is not always a viable option and power supply can be a problem. Finally, currently, it is unknown what the temperature and humidity range is in which the Wiimote functions. Because of its design, it functions correctly in ambient indoor environmental ranges, but further work is needed to test its limits. These shortcomings limit the usability of the Wiimote in prolonged field campaigns. In the example of the floating evaporation pan, the Wiimote was used to illustrate that it is possible to record water levels at high frequencies and retrieve the evaporation from a moving pan by filtering. For an extended field experiment, another sensor such as a capacitance probe might be used. The experiment with the Wiimote did show proof of concept in a single day, at very low cost. Furthermore, the experiment immediately revealed the effect of the time-averaged water level dropping in the presence of wave movement in the pan. This led to new research questions and more hypothesis to be tested in experiments. All in all, the versatility, low cost and ease of implementation of experiments using the new tool shortened the experimental cycle of experiment-result-conclusions-hypothesis-experiment, which makes it suitable for students' projects and first proofs of concept. Although the Wiimote itself

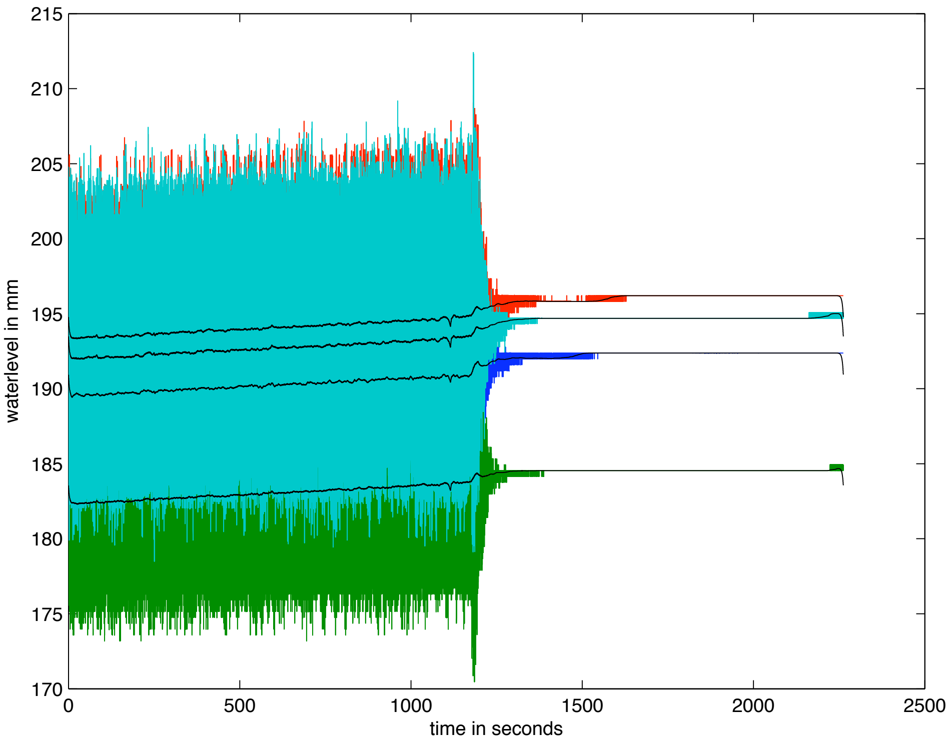

Figure 2.3: Water level fluctuations in the evaporation pan, as recorded with the Wiimote. In the first part of the measurement both the wave generator and the low-flow pump are active. The wave generator makes waves with a frequency of 1 Hz and an amplitude of 10 cm. The different colors represent the four different LEDs, and the black lines are the signals, filtered with a first-order low-pass filter with a cutoff frequency of 0.1 Hz.

is mainly of interest for such proofs of concept, the technology it uses might have wider use in larger sensor networks. Applications like the one presented in this paper are part of a larger possible shift toward technology transfer from gaming and consumer electronics (e.g., the use of graphic cards for computations). For example, at present many oceanographic sensors have origins in the medical industry, with associated high cost. Technology developed for mass-manufactured consumer electronics, with low cost if acquired in bulk, may offer valuable applications for geosciences, where the spatial density and extent of sensors is often an important constraint on the amount of information that can be obtained from a natural system.

2.4.1. Outlook

The example experiment presented in section 3 only made use of the infrared motion tracking capabilities of the Wiimote. For future applications in water research, the 3D accelerometers could provide interesting extra data. The floating evapora-

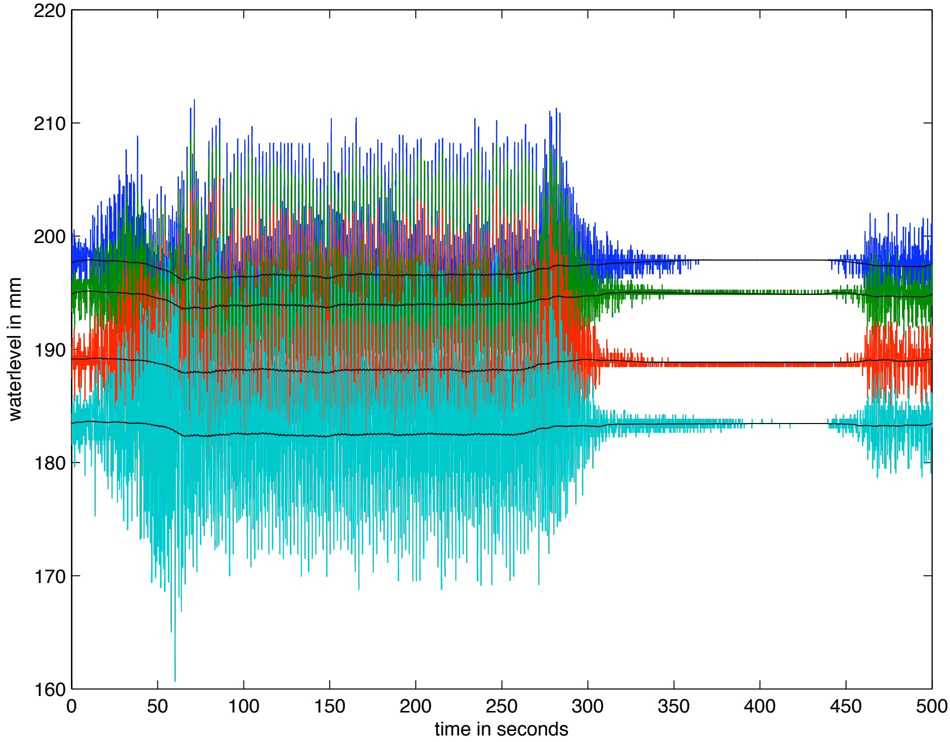

Figure 2.4: Water level fluctuations in the evaporation pan, as recorded with the Wiimote. In this experiment the low-flow pump was never on and the wave generator was switched on and off. The wave generator makes waves with a frequency of 1 Hz and an amplitude of 10 cm.

tion pan could for example record the acceleration of the Wiimote to get information about the waves on the lake. Other possible applications could be streamline tracking with infrared reflective floating balls or other motion tracking applications involving up to 4 points in a 2D plane. Use of multiple Wiimotes opens up the possibilities for inexpensive 3D tracking applications.

acknowledgments

We would like to thank to technicians at the Waterlab of the Delft University of Technology. Since this paper is on doing experiments at low cost, it might seem counterintuitive to use a large wave generator. However, large measurement setups such as wave generators, once built, are never used full time. The technicians were more than happy to switch the generator on for a while, in between large “official” experiments. If without this experiment, the wave generator would have been idle, it means that the marginal cost for conducting our simple experiment are very small. We like to encourage this way of looking at costs in research institutes, opposed to the “pay per minute” attitude normally used for using large

experimental equipment, because it acknowledges the economics of sunk costs and compares marginal costs versus marginal benefits.

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3

A resonating rainfall and evaporation recorder

I'm picking up good vibrations.

The Beach Boys

We propose a novel, accurate quantification of precipitation and evaporation, as needed to understand fundamental hydrologic processes. Our system uses a collection vessel placed on top of a slender rod that is securely fixed at its base. As the vessel is deflected, either by manual perturbation or ambient forcing (for example, wind), its oscillatory response is measured, here by a miniature accelerometer. This response can be modeled as a damped mass-spring system. As the mass of water within the collection vessel changes, through either the addition of precipitation or by evaporative loss, the resonant frequency experiences an inverse shift. This shift can be measured and used to estimate the change in mass of water. We tested this concept by creating a simple prototype which was used in field conditions for a period of one month. The instrument was able to detect changes in mass due to precipitation with an accuracy of approximately 1 mm.

This chapter has been published as "A resonating rainfall and evaporation recorder" by R.D. Stewart, R.W. Hut, D.E. Rup, H.V. Gupta and J.S. Selker in Water Resources Research **48**, 8 (2012) [1].

3.1. Introduction

Accurate measurement of precipitation and evaporation is crucial to the understanding of fundamental hydrologic processes, but achieving reliable estimates often involves a tradeoff between accuracy, dependability and cost.

Instruments that measure precipitation rates directly (i.e., non-remotely) include tipping buckets, weighing gauges, optical sensors, capacitance sensors, acoustical sensors, and disdrometers (sensors that measure individual drop sizes), with tipping buckets and weighing gauges being the most common [2][3]. Weighing gauges use a scale to calculate the weight of water in a collection vessel; types of scales used include counterbalance weights, springs, and strain gauges. In the case of a spring-based weighing platform, the deflection can be sensed using potentiometers or Linear Variable Differential Transformers [4], or a chart recorder, such as traditionally used by the United States National Weather Service (NWS) [5]. More recently, the "GeoNor" gauge scale was developed that suspends a collection vessel from one or more wires and calculates the weight of water from the tension of one wire, determined by vibrating the wire and measuring its resonant frequency [6][7]. Another meteorological sensor based on vibration frequency is the icing sensor used by the NWS in its Automated Surface Observing System (ASOS). Freezing rain and ice accumulations are inferred by measuring the vibration frequency of a small cylindrical probe; the frequency changes as mass accumulates on the probe [8].

Each system is subject to different limitations. Many disdrometers (such as impact disdrometers) tend to underestimate the rainfall rate, and are insensitive to small droplets, while acoustic methods tend to have higher variability and greater bias than other methods [2]. Optical rain gauges only measure rainfall rate, not total accumulation, and therefore have inherent uncertainty due to the need to estimate drop size distributions [2]. Capacitance gauges have been seen to give good results, but have relatively high noise when the rainfall rate is low (less than $2\mathrm{mm/h}$ of rainfall), and have increased scatter in windy conditions [2]. Tipping buckets can have significant error at small and large rainfall rates, can fail to tip due to blockage or friction, will have different tipping volumes at different rainfall intensities, and can lose water to evaporation between tips [9][10][2][11]. Weighing buckets may underreport data due to friction in the bearings and potentiometer linkage [3], and can be affected by temperature- and wind-induced noise [12]. In addition, weighing buckets must be periodically emptied, either manually or through an auto-siphon, leading to error whenever the bucket overtops or drains during a rainfall event [12] or when the drainage system fails completely [2]. Cable-based weighing gauges have higher noise as wind and/or collected mass increase [7]. The ASOS icing sensors only measure accumulated frozen precipitation, and thus are not useful for measuring liquid or solid precipitation. Finally, all of these methods, with the exceptions of optical sensors, acoustic sensors and disdrometers, are generally unusable for monitoring rainfall on ocean-placed buoys or floating platforms [9]. Instruments that directly measure evaporation are relatively rare compared to those used to measure precipitation. Often, reference evaporation is estimated from predictive equations based on meteorological parameters, with a large variation in results between models [13], or else estimated from indirect measurements such as infrared surface temperatures [14] or water vapor and nitrogen gas concentrations [15]. Less commonly, evaporation is determined using a water balance approach, such as pan evaporation [13] or weighing and/or small-scale lysimeters [16]. All of these methods require extensive effort and/or expense to implement, and are therefore not practical for small-scale farmers and other irrigators. ETGage Company (Loveland, CO) sells an evapotranspiration simulator that allows water to evaporate through a clay-ceramic plate. However, to be automated, this instrument requires the purchase of an external datalogger; further, the instrument needs to be regularly refilled with water, and the ceramic disc can become fouled by minerals if it is contacted by irrigation water or precipitation.

In this note, we propose a simple method that uses the natural frequency of the gauge itself to measure the mass of the system (thereby allowing inference of cumulative precipitation and evaporation amounts), and show preliminary results from a prototype configuration. While resonance has long been used to measure the accumulation of certain types of precipitation, including snowfall (with the GeoNor system) and freezing rain (with the ASOS icing instrument), our method can be configured to measure both precipitation (in liquid or solid form) and evaporation. Furthermore, the instrumentation needed is relatively inexpensive, contains no moving parts, uses low-power solid state micro-electronics, can be easily calibrated, and can theoretically be designed to be insensitive to wind or buffeting. Unlike other precipitation-measurement sensors, our configuration has the potential to take advantage of ambient driving forces such as winds or waves, and can therefore be placed in remote or challenging environments. Altogether, simplicity of this method's design, components and calibration should enable wide use by researchers as well as irrigation and urban-planning managers.

3.2. Materials and Methods

At its most basic configuration our rain gauge system is a damped mass-spring system, where the collection bucket is the mass and a flexible pole acts as the spring. If the bucket is displaced, through either manual/mechanical or natural forcing, the natural frequency of its response will be a function of the mass of the bucket. When a damped mass-spring system is displaced, its position through time can be modelled as:

$$z\,(t) = Ae^{-\zeta\omega_0 t}\sin\left(\sqrt{1-\zeta^2}\omega t + \phi\right) \tag{3.1}$$

(1) where $z\,(t)$ is the deviation from resting position, A is the amplitude of the impulse, ϕ is an initial phase, ζ is the damping ratio, and ω_0 is the undamped natural frequency. The damping ratio, ζ, is given by:

$$\zeta = \frac{c}{2m\omega_0} \tag{3.2}$$

where c is the viscous damping coefficient and m is the mass. The undamped natural frequency (in rad/s) is given by:

$$\omega_0 = \sqrt{\frac{k}{m}} \tag{3.3}$$

where k is the spring stiffness. It should be noted that the observed frequency of oscillation (ω_1) is slightly lower than the undamped natural frequency, as shown by

$$\omega_1 = \omega_0\sqrt{1-\zeta^2} \tag{3.4}$$

Therefore, in the case of known, manual forcing (such as during calibration), Equation 3.1 can be fitted to the observed oscillation, using A, ζ, ω_0 and ϕ as parameters. This is called time-domain fitting. In the case of ambient forcing (such as in the case of wind), the measured signal is a convolution of Equation 3.1 with the (unknown) ambient force. The resulting time series cannot be fitted to a known form. However, the frequency spectrum of wind has been shown to be a power law function [17]. The total frequency spectrum of the measured signal is the multiplication of the frequency spectrum of the wind (forcing) with the frequency power spectrum of the impulse response (i.e. Equation 3.1) [18]. The amplitude of the frequency spectrum of the impulse response is derived by taking the Fourier transform of Equation 3.1:

$$|Z(\omega)| = \frac{1}{\sqrt{\omega_0^2 - 2\zeta^2 - \omega^2 + 4\zeta^2\left(\omega_0^2 - \zeta^2\right)}} \tag{3.5}$$

Leading to an expected amplitude of the power spectrum of the measured signal:

$$|H(\omega)| = \omega^\alpha \frac{1}{\sqrt{\omega_0^2 - 2\zeta^2 - \omega^2 + 4\zeta^2\left(\omega_0^2 - \zeta^2\right)}} \tag{3.6}$$

where ω^α is the frequency (power) spectrum of the driving wind force. This equation can be fitted to the frequency spectrum of measured data, again using ω_0, ζ and α as parameters. The fitting procedure must be designed in such a way that ω_0 is the most sensitive parameter. To achieve this, fitting is only done on a window of the frequency spectrum around $\omega = \omega_0$, making sure that a deviation in ω_0 is weighted more strongly than deviations in the other parameters. The choice of window is arbitrary, so long as the window is sufficiently large to include the expected minimum and maximum resonance frequencies. These minimum and maximum frequencies can be found by doing a controlled experiment, i.e. during calibration. The relation between the resonance frequency and the mass of the amount of water in the gauge, and thus the cumulative rainfall, is also obtained by doing a controlled experiment, resulting in a calibration curve.

A prototype system (Figure 3.1) was constructed using $0.013\mathrm{m} \times 0.0035\mathrm{m}$ steel strap for the system's spring. An asymmetrical spring was chosen to ensure distinct

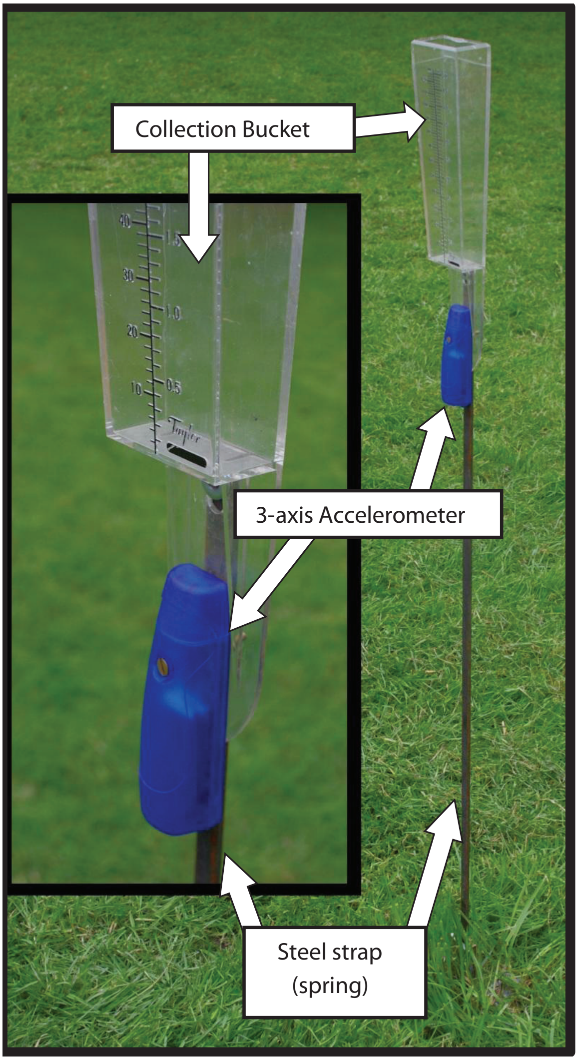

Figure 3.1: Major components of the precipitation and evaporation gauge prototype (inset picture is close-up of accelerometer and collection bucket). The collection bucket acts as the mass and the steel strap acts as a spring in a simple damped mass-spring system. Oscillations of the mass-spring system (after lateral deflection) are measured using the 3-axis accelerometer.

and separate resonant modes between the main and transverse directions. This strap was attached to a heavy four-legged steel base using two 0.001m (0.375 inch) bolts; this base had a $0.001\text{m} \times 0.0635\text{m}$ (0.375 x 2.5 inch) bolt at the end of each leg, which allowed the base to be securely set into the soil. The strap's effective length (measured from the uppermost fastening bolt to the base of the collection bucket) was 0.87m. A clear plastic rain gauge (Taylor Precision model 2702N) was used as the collection bucket, as this allowed for visual confirmation of the amount of water in the gauge. This gauge was attached to the strap using two #8 ($0.0033\mathrm{m}$) bolts, the lower bolt also served to attach a 3-axis accelerometer (Model X6-2 Gulf Coast Data Concepts, LLC.). The accelerations of the gauge were measured at a sampling frequency of $80\mathrm{Hz}$. For the outdoor testing, the accelerometer was placed within a sealed $0.5\mathrm{L}$ Ziploc bag before being secured to the system.

On 10 March 2012, the prototype was installed in an open outdoor location in Corvallis, Oregon, United States. Data collection began the following day, in which acceleration was recorded at a frequency of $80\mathrm{Hz}$. The data collection was continuous except for periods where the accelerometer was temporarily removed to allow for the battery to be recharged (this typically took four to eight hours of time). No data were collected between 18 March 2012 and 27 March 2012. To verify the instrument's accuracy, visual readings of the amount of water within the rain gauge collection's bucket were performed between 1 and 4 times per day. When the amount of water within the gauge exceeded $90\mathrm{mm}$, the gauge would be unfastened and pivoted to empty. This data collection period included two major storm systems. Wind speeds, monitored by an adjacent Memsic Inc. (formerly Crossbow) ES2000 Weather Station Sensor Suite weather station, reached a maximum of $18.6\mathrm{km/h}$, with a mean maximum speed of $5.9\mathrm{km/h}$.

On 13 April 2012, the prototype was calibrated in-situ by adding known depths of water to the collection bucket. The following depths (in millimeters) of water were tested: 0, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100. For each measurement, the bucket was manually displaced by approximately $0.10\mathrm{m}$ and released, and the resulting oscillation was recorded by the accelerometer. After being manually displaced, the gauge was then allowed to collect data for at least an additional ten minutes, to allow for the ambient forcing to occur. This combination of manual displacement and natural forcing allowed for calibration in both the time and frequency domains.

To interpret the manual displaced (oscillatory) data, the relationship between natural frequency and mass was derived by fitting Equation 3.1. Time-domain fitting was performed by manually identifying the beginning (just after the instrument was displaced and released) and then performing the analysis over the next 25 seconds. The resultant oscillatory data were modeled by optimizing for A, ζ, ω_0 and ϕ, using the Matlab function nlinfit [19]. Because optimization using nlinfit minimizes RMSE residuals, only the portion of the spectrum immediately around ω_0 was used. This ensured that no weight was placed on the very low frequency portion of the spectra, which (due to wind influences) can at times have a relatively high amplitude. An example dataset and model in the time domain are presented in Figure 3.2a, which shows the model is correctly capturing the system's frequency and damping.

The ambient forcing calibration data were modeled in the frequency domain using Equation 3.6. To fit data in the frequency domain, one must decide on the duration of signal to be used to represent one time-step. A larger interval of data collection will contain more data points, thereby allowing for higher accuracy in the determination of the resonance frequency, whereas a smaller window allows for better time resolution. If the chosen data window is too long, the resonance

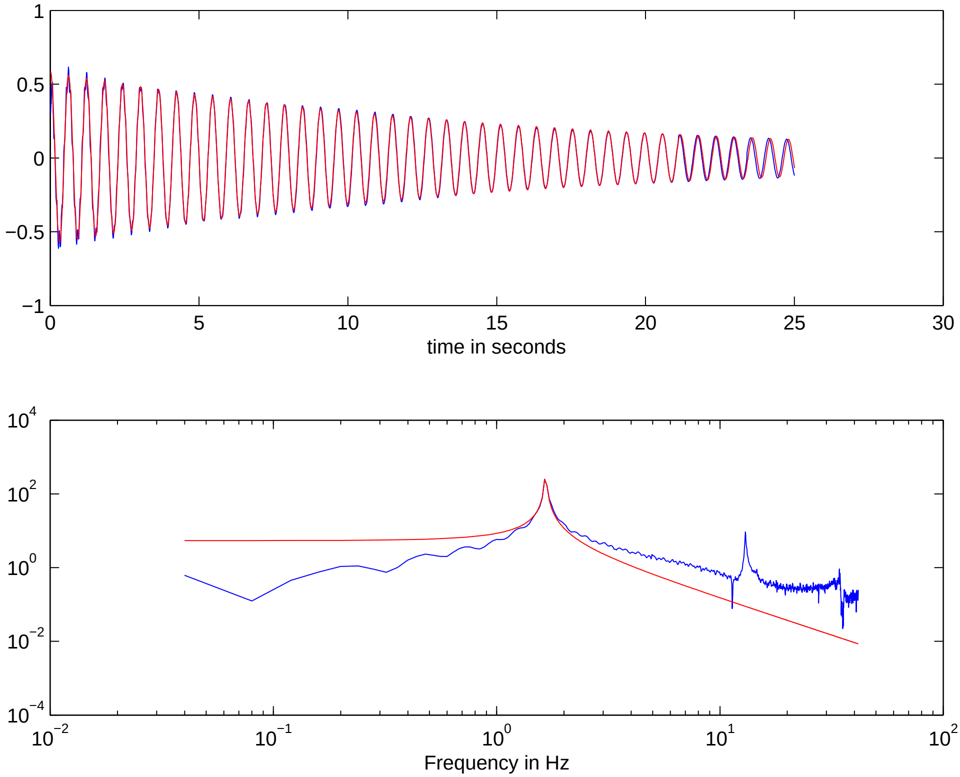

Figure 3.2: Acceleration response of the system after being manually deflected and released. Data is shown in both the time (2a) and frequency (2b) domains. Measured data is shown in blue, while modeled fit is shown in red. There is a clear resonant peak near 1.7Hz, due to the main oscillatory axis, whereas the secondary peak at 12Hz corresponds to vibrations in the transverse axis. For this reason, it is important to focus the fitting algorithm around the expected frequency range. Also note that ambient forcing data can only be modeled in the frequency domain.

frequency could shift during the interval (due to rain or evaporation); however, the window should be selected to be long enough for the resonance frequency to be observable within each windowed dataset. The decision was made to use a 10 minute window (containing 48,000 data points); this length of window provided ample data to allow accurate estimation of the resonance frequency, while being short enough that changes in mass due to precipitation or evaporation would not cause a significant shift in resonant frequency. An example of data fit in the frequency domain is shown in Figure 3.2b. The highest peak, around 1.7Hz, is the resonant frequency of the main axis, whereas the secondary peak around 12Hz is due to vibrations in the transverse axis. Theoretically with proper calibration either mode could be used for the analysis, but the decision was made to focus on the lower resonant peak, which corresponds to the resonance of the main axis.

3.3. Results and Discussion

Our experiments with the prototype show that an inverse relationship exists between undamped frequency and depth of water in the collection bucket (Figure 3). While this relationship is not truly linear, for the expected frequency range a linear approximation (shown as the linear fit line) will achieve $\pm 1\mathrm{mm}$ accuracy. This was deemed acceptable for a proof of concept, though certainly a higher-order curve fit could be utilized, with likely corresponding improvement to the accuracy. Figure 3.3 shows that the time- and frequency-domain models give nearly-identical results, and thus either is a feasible method of determining system resonant frequency.

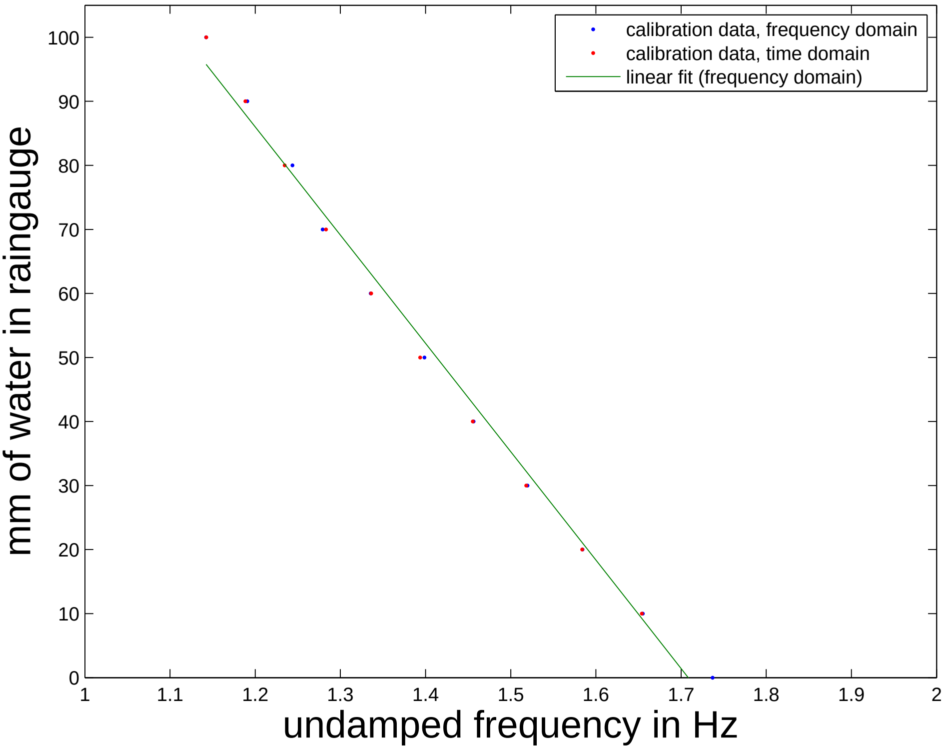

Figure 3.3: Undamped frequency of the prototype rainfall measurement system, against depth of water in the rain gauge, in millimeters. The plot indicates a non-linear inverse relationship between undamped frequency and depth of water. The linear fit represents the calibration curve used to convert frequency into equivalent water depth within the raingauge.

When left outside during periods of intense rainfall and moderate winds, the instrument was able to accurately capture changes in mass of the system (through additions of precipitation and losses due to emptying or adjusting the gauge) (Figures 3.4 and 3.5). The measured data correspond well to the data obtained through visual checks of the water level within the gauge (shown in red in Figures 3.4 and

3.5), with an accuracy of approximately ± 1 mm (the exact accuracy is difficult to quantify due to the low resolution of the gauge's visual markings). The variability of adjacent data points during non-rainy periods gives an indication of the instrument's precision: maximum variability was observed to be $\pm 1\text{mm}$. Though this

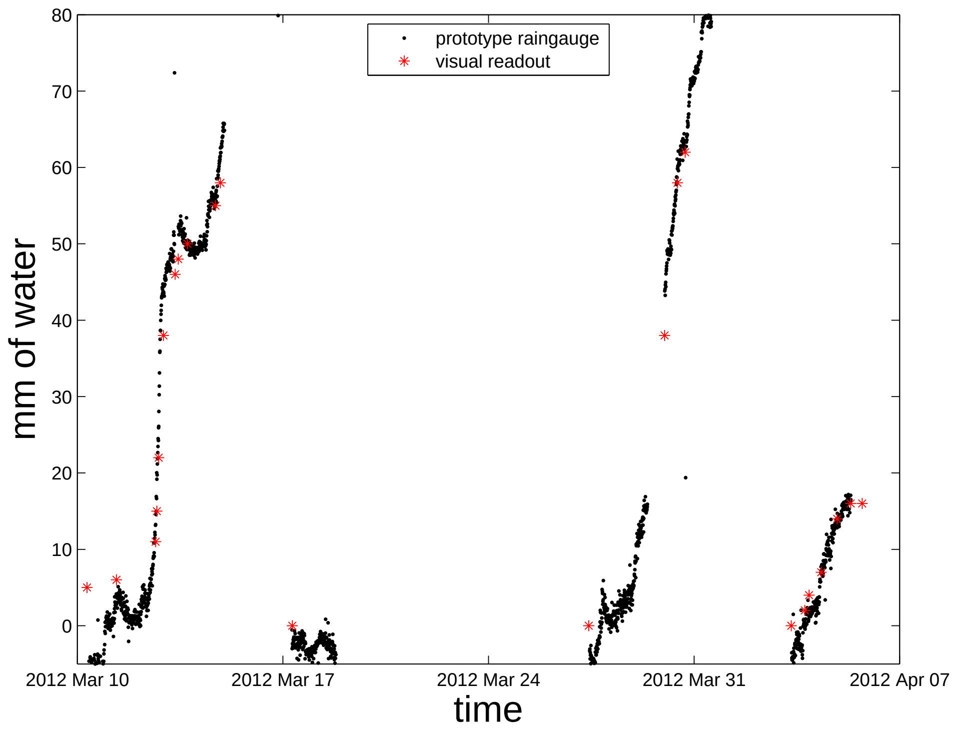

Figure 3.4: Measured precipitation accumulation within the prototype gauge, along with visual checks of the amount of water within the rain gauge. The amount of water within the gauge was inferred by determining the system's undamped frequency by frequency-domain fitting of the acceleration data over 10-minute windows. Gaps in the data correspond to times when the accelerometer battery became discharged and required recharging.

prototype was configured for precipitation collection, since the instrument is measuring the mass of the system, evaporation measurements can be obtained with the same gauge (evaporation data from a separate prototype are presented in the electronic supplement). While this is theoretically possible in any weighing gauge system, there have been few or no raingauges that have been configured to allow and measure evaporation.

In addition, these data show that wind can be a satisfactory forcing mechanism for the system; the gauge had sufficient sensitivity to provide data even in periods where the cups of the adjacent anemometer were not moving due to such low wind. The only observed gaps in the dataset came from times when the accelerometer was removed for recharging the battery (for this reason future implementations will

3

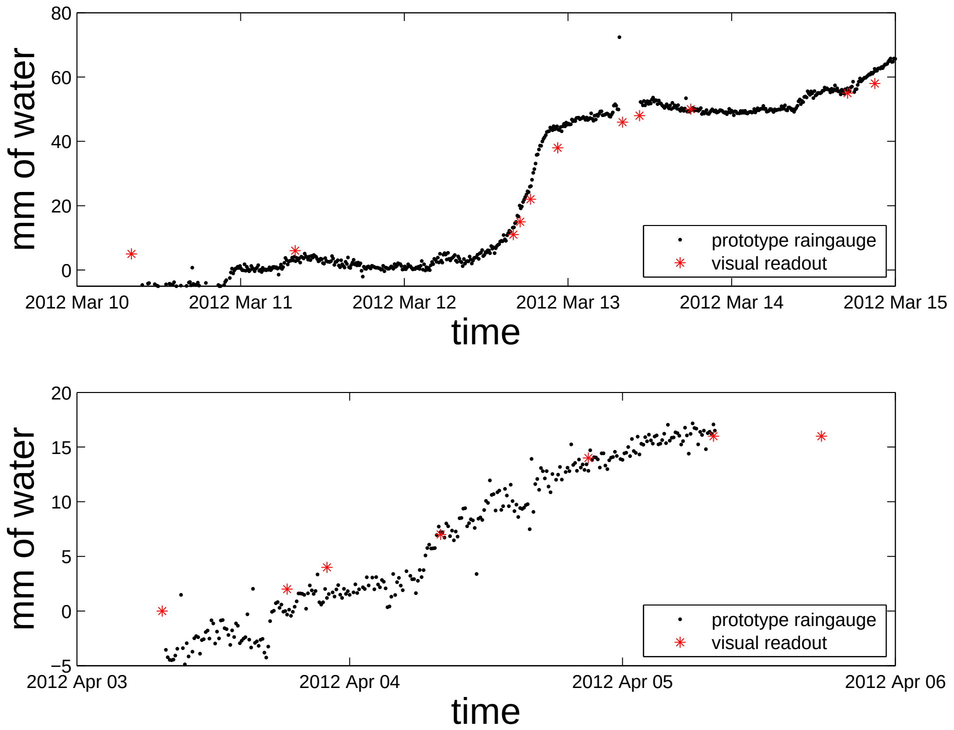

Figure 3.5: Close focus on the first (5a) and third (5b) rainfall events. These plots shows that the prototype configuration, when subjected only to natural forcing from the wind, has accuracy of approximately ± 1 mm (based on the comparison to visually-measured amounts of water in the gauge) and precision of approximately $\pm 1\mathrm{mm}$ (based on the variability of consecutive measurements under no rain conditions).

therefore need to have a continuous source of power, such as a solar panel).

Using wind as the driving force has several advantages compared to mechanical activation: it is simple to implement, and data is continuously collected. Moreover, with modern low-cost, high-sensitivity accelerometers, wind-forced gauges have the potential to be designed in a way to directly measure wind speed and direction, and thereby provide a highly-sensitive alternative to a classic anemometer. However, there are also several minor disadvantages to relying only on wind to drive the sensor. First, in most locations, wind is unpredictable and readings may not be obtainable during very calm periods, although with the 16-bit accelerometer we employed this was never experienced in practice. Second, the acceleration magnitudes are typically smaller and the signals are affected by both the energy spectrum of the natural forcing and the properties of the device, in contrast to a mechanically-vibrated system for which a simple impulse response is obtained. Third, the acceleration data from a naturally-forced system must be analyzed by averaging over specified time intervals (Figure 3.5 was created using 10-minute averages), whereas with a mechanically-forced system the analysis can focus only on the immediate response following the perturbation. Finally, data from a naturally-forced system can be analyzed only in the frequency domain, whereas data from a mechanically-displaced system can be analyzed in either the time or frequency domain, though it should be noted that both analyses give comparable results (as shown in Figure 3.3). Should mechanical perturbation of the gauge be desired, one efficient and reliable method for perturbing the system is to position an electromagnetic coil next to a ferrous part of the gauge, which can then allow for the coil to be briefly powered at set intervals (an example of this forcing mechanism is presented within the electronic supplement). Furthermore, by measuring the inductance of the coil itself, the relative position of the gauge can be measured through time, which negates the need for an accelerometer and simplifies the system even more.

Finally, it should be noted that like all precipitation gauges, this instrument can be subject to errors including rainfall undercatch, due to wind effects, and clogging and/or changing readings due to contamination [20]. To combat rainfall undercatch, the device could be placed into a pit and be mechanically perturbed at specified time intervals using simple piezoelectric motors, solenoids and/or electromagnets. This would have the additional advantage of limiting wind vortex-related resonance modes, though this phenomenon was not observed to be a major influence during field testing. With regard to contamination, since the device has no moving parts, clogging would only be of concern in a drainage system (such as an auto-siphon), a well-designed screen or filter could likely prevent most clogging occurrences. For changes in gauge mass due to biological fouling (such as moss or dust), the gauge could be configured to monitor relative changes in mass after each emptying event. Therefore, these errors should be kept in mind when implementing this system, so as to ensure that they are mitigated or controlled.

3.4. Conclusion

We developed a simple method for measuring both rainfall and evaporation via a single gauge, based on measurements of the natural frequency of the gauge itself, and demonstrated the feasibility of the concept using a prototype. Our configuration had an accuracy of approximately 1mm; with optimization of the design, installation, and data processing framework, this accuracy can be expected to markedly improve.

As currently configured, the system uses nominal power (it could be powered by a small solar panel in the field) and requires minimal maintenance. It addresses several disadvantages of other rainfall and evaporation measurement devices, provides the prospective ability to be used in windy environments or in ocean-based applications (though considerable challenges would need to be addressed in any marine installation), contains no moving parts (which can introduce friction-induced errors or malfunction altogether), and has the potential to be insensitive to wind-induced noise. To be placed into widespread use, the design will need to be optimized, and features such as an auto-siphon for precipitation or a filling system for evaporation measurements may need to be incorporated. Altogether, the proposed system has the potential to provide a low-cost, easy-to-use, and accurate way for research scientists, irrigation managers, and others to monitor cumulative rainfall and evaporation.

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4

Design, calibration and field evaluation of a prototype acoustic disdrometer designed for distributed rainfall measurements

Some people feel the rain. Others just get wet.

Bob Marley

The design, calibration and first field evaluation results of an acoustic disdrometer are presented. The "Delft-disdrometer" is specifically designed to be low maintenance, thus allowing the installation of dense networks without incurring large upkeep costs. In the field evaluation, the Delft-disdrometer was compared to existing rain gauges and disdrometers. Results show that the Delft-disdrometer is capable of measuring precipitation intensities with comparable uncertainties as those of the industry standards Thies LPM and Ott Parsivel. For drops bigger than 1.75mm*, the Delft-disdrometer measured drop size distributions similar to the drop size distributions measured by the Thies LPM and Ott Parsivel. The inability of the Delft-disdrometer to measure drops smaller than* 1mm *is an issue that should be addressed in future iterations of the design. The experiments with this first prototype show that*

This chapter is in preperation for submission to Sensors as "Design, calibration and field evaluation of a prototype acoustic disdrometer designed for distributed rainfall measurements" by R.W. Hut, S.A.P. de Jong, N.C. van de Giesen, H. Leijnse and M. de Haij

it is feasible to measure precipitation intensities with the low maintenance Delft-disdrometer.

4.1. Introduction

In hydrology, accurate rainfall data is of utmost importance [1]. In daily practice, the choice is often to use integrated rainfall data from weather radars or point measurements from ground based devices. Both radar and ground based devices have problems when distributed precipitation data is required. Rainfall radars have pixels that are usually too big to capture the dynamics of a rainstorm ([2], [3], [4]) and rainfall radars also need to calibrate the relation between radar backscatter and precipitation (the Z-R relation) on the basis of ground based drop size distribution measurements ([5], [6], [7], [8]). The accuracy of rainfall estimates from radars can be greatly improved by adding ground measurements ([9], [10], [11]). Furthermore, the use of radars in mountainous regions is challenging ([12], [13]). Ground based measurements come in many forms, including tipping buckets, weighing gauges, optical sensors, capacitance sensors, and disdrometers (acoustic, [14]; video, [15]; laser, [16]; microwave, [17]; or impact [18]). Tipping buckets and weighing gauges are the most common ([19], [20]). Because of their high maintenance cost [21], it is often not feasible to install such ground-based instruments in dense enough grids to capture the spatial variability of rainstorms. From an operational point of view, this is especially a problem in urban settings where high resolution rainfall data is needed to link rainfall to localised flooding events [22]. It would be of great value to both the scientific and the operational hydrological communities to have access to a ground based sensor capable of measuring rainfall intensities and drop size distributions at a fraction of the operational cost of currently available sensors. To our knowledge, the current price for professional tipping buckets ranges from €400 to €2000. Disdrometers are more useful because, in addition to rainfall intensities, they measure drop size distributions and requiring less maintenance but none are available for less than €2000. In this paper, we present the design, calibration and first field evaluation results of an acoustic disdrometer specifically designed to be cheaper than a professional tipping bucket rain gauge (ca. €500), but be low maintenance, thus allowing the installation of dense networks without incurring large upkeep costs. We show that this novel sensor can measure drop sizes and rain intensities with accuracies on par with current state of the art rain gauges.

4.2. Methods and Materials

In this paper, the newly developed acoustic disdrometer will be compared to existing rain gauges and disdrometers. To avoid confusion, the newly developed disdrometer will be called "Delft-disdrometer" throughout this paper. Below, first the design choices will be explained, followed by the electronics and algorithms used to derive precipitation information from the raw acoustic signal. Finally, the setup of the calibration and field evaluation experiment is elaborated upon.

4.2.1. Design

The Delft-disdrometer was first and foremost designed with an eye on robustness to keep upkeep and overall price down to make replacing a more feasible option than repairing, thereby keeping downtime to a minimum. The basic sensing principle of the Delft-disdrometer is that of a drum excited by raindrops. The main difference with the model proposed by Henson et al [23] is the lack of additional acoustic mass in the Delft-disdrometer. This greatly reduces the resonance time of the sensor [24], allowing for measuring higher precipitation intensities without missing individual drops. The main difference with a Joss-Waldvogel type disdrometer is that in a Joss-Waldvogel disdrometer, the entire upper part of the body moves rigidly and transfers the energy of the drop to a lower measuring coil or piezo [18]. In the Delft-disdrometer only the upper lid, or "drum-skin", vibrates when a drop impinges on it. See figure 4.1 for a schematic of the different parts and dimensions of the Delft-disdrometer.

The Delft-disdrometer is fabricated by glueing a piezo-electric disc under a PVC cap that covers the end of a PVC cylinder. Inside the PVC cylinder, a custom made printed circuit board (PCB, see electronics, below) is placed and connected to the piezo. The tube is filled with acoustic foam, for acoustic damping, and silica gel to protect the electronics from moisture. The tube is closed with a standard end-plug which has a cable-gland drilled through for power- and data-cables. PVC was chosen as material for its ready availability and ease of use in prototype fabrication. The amount of acoustical damping in the drum is a compromise between low damping to achieve long resonance, which makes it easier to detect drops, and high damping to achieve short response times, which reduces the probability of two drops hitting the instrument within one resonance time. The resonance time of the Delft-disdrometer is circa 2ms, compared to about 30ms for the device of Henson et al [23]. A large surface area is desired to reduce uncertainty by collecting as large a sample of drops as possible. Given the resonance time, a too large area increases the chance of two drops hitting simultaneously[25]. Given the small surface area and the short resonance time, the chance of two drops hitting simultaneously are neglectable [26]. With our focus on cost, we chose a standard off-the-shelf piezo disk of 40 mm diameter with a 25 mm effective piezo element. Because of this relatively small diameter, a significant number of drops will hit the edge-area. However, compared to Joss-Waldvogel type disdrometers, in the Delft-disdrometer, the "drum-skin" extends beyond the 25 mm effective piezo element. Drops hitting the edge of the piezo area will thus still excite the sensor, although at smaller amplitudes. Thorough investigation of this effect is beyond the scope of this proof of concept, but is the focus of ongoing and future research.

4.2.2. Sampling Fluctuations

The effect of sampling a limited area has been investigated by numerically simulating the arrival of individual drops at the disdrometer. The arrival of the drops was assumed to be represented by a Poisson process. The underlying drop size distribution was assumed to be the exponential distribution found by Marshall and

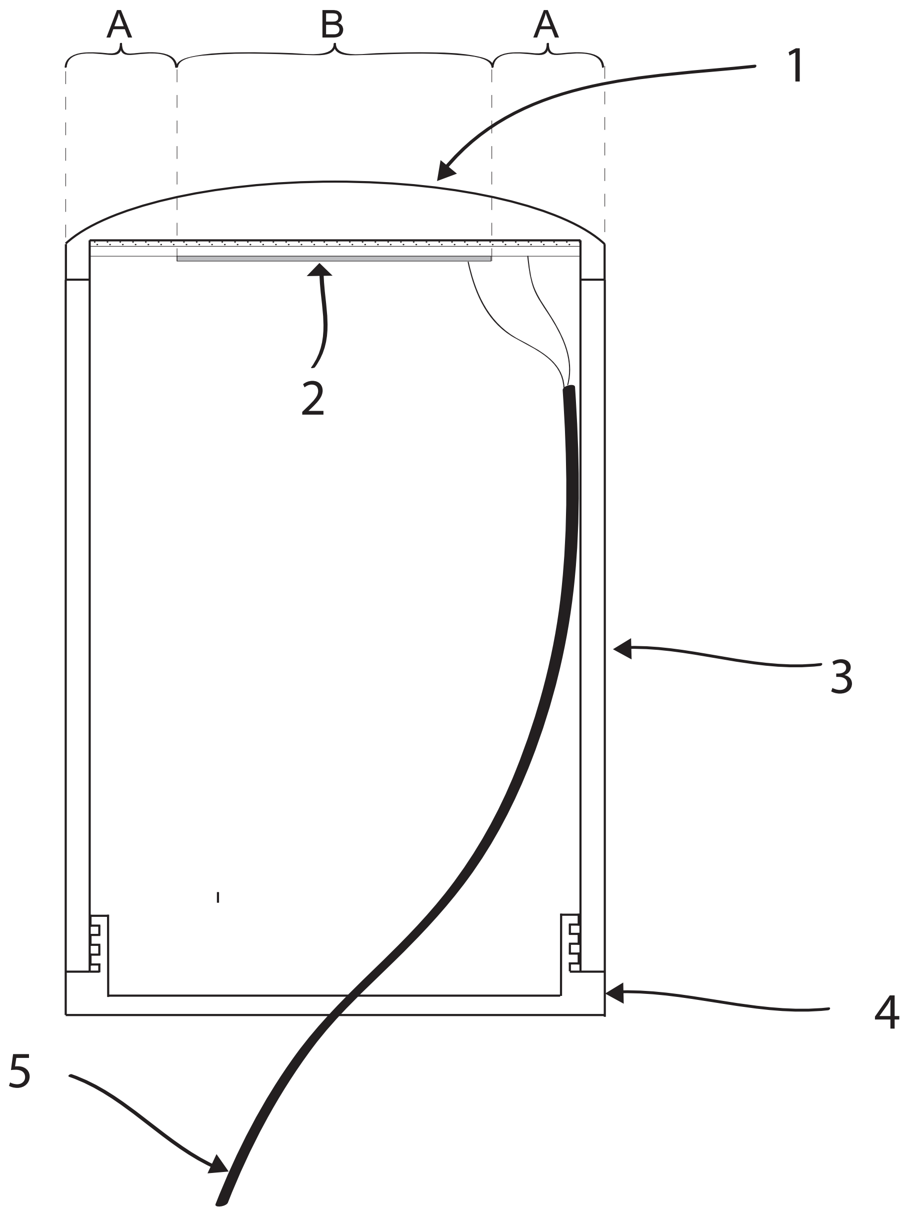

Figure 4.1: Schematic overview of the Delft-disdrometer. The top consist of a 40mm diamater convex disc made of PVC (1). Under the top, a piezo-disc (2) with a 25mm effective piezo element is glued. The top is connected to a PVC cylinder (3). The bottom of the cylinder is closed with a pvc-end-cap (4). A wire (5) is soldered to the piezo disc and connected to the electronics (not shown). The inside of the cylinder is filled with acoustic foam for additional damping and silica gel for moisture absorption.

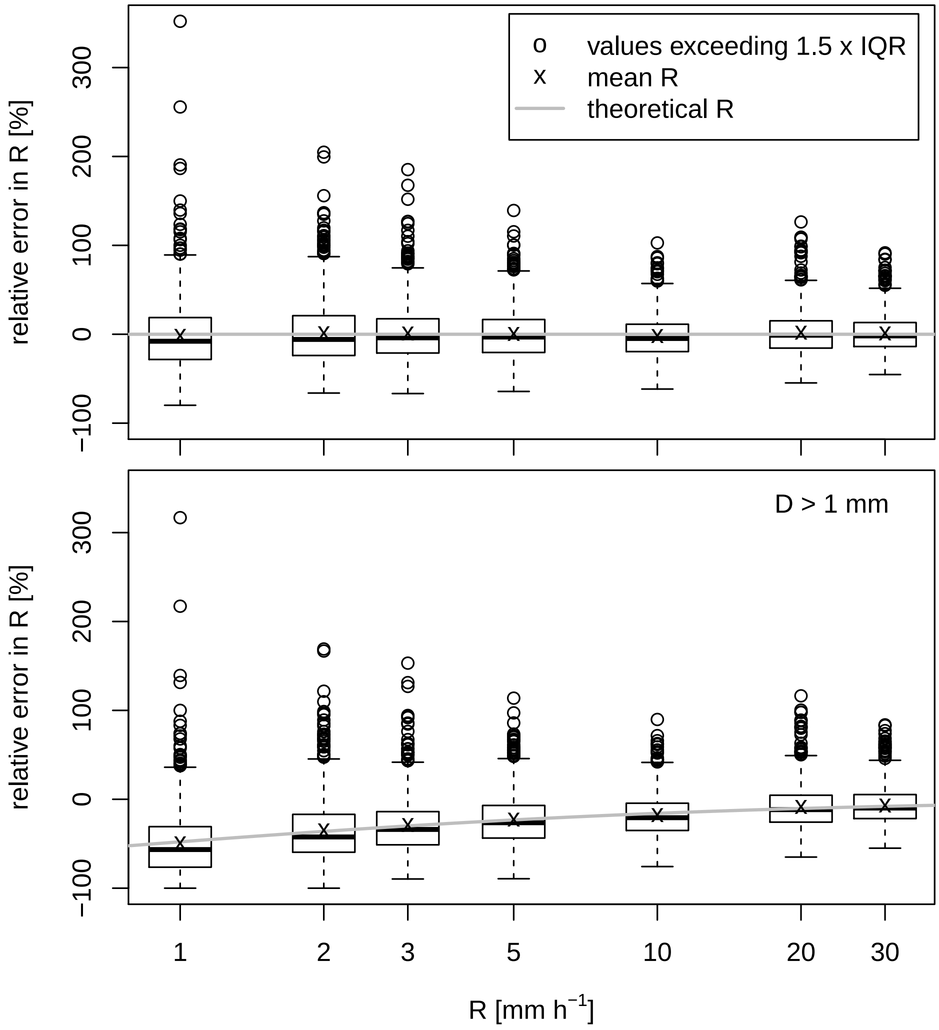

Figure 4.2: Numerical estimation of the spread due to the limited sensor size in estimated rainfall intensity as a function of true rainfall. The underlying drop size distribution was assumed to be the exponential distribution with $N_0 = 8000$ mm^{-1} m^{-3}. Simulations were carried out assuming an effective measurement area with a diameter of 25 mm, and an integration time of 1 minute. The spread diminishes for larger values of true rainfall intensity. In the upper graph, all drop-sizes are used. In the lower graph, only drops with an equivalent diameter greater than 1mm are considered. This additional cut-off introduces a bias in the estimation of rainfall intensity that diminishes for larger values of true rainfall intensity

Palmer [27], with $N_0 = 8000$ mm^{-1} m^{-3}. We assumed the terminal fall velocity to be related to the drop diameter by a power law [28], and the relation between the slope parameter and the rainfall intensity is consistent with the relations shown by

Uijlenhoet and Stricker [29]. One thousand simulations were carried out assuming an effective measurement area with a diameter of 25 mm, and an integration time of 1 minute, based on the theory from [25]. The upper graph in figure 4.2 shows the relative error in precipitation (R) and the spread therein as a function of the true rainfall intensity. The lower graph in figure 4.2 shows the same results, where only drops with diameters larger than 1.0 mm have been used for computing R. It is clear that there is significant scatter in the simulated R for a given true rainfall intensity. This effect decreases with increasing true R. It is also apparent that neglecting drops smaller than 1 mm introduces a bias. This bias is most severe for low rainfall intensities.

4.2.3. Electronics and Algorithm

Bagree ([30]) developed a dedicated PCB for the Delft-disdrometer that converts the analog signal from the piezo-disc to digital information. After passive analog band-pass filtering, the signal from the piezo is sampled by a 24-bit analog digital converter sampling at 128kHz and the digital signal is processed be a programmable IC. The PCB has two distinct operating modes: calibration and operation. In both modes, the software continuously monitors the digital input and triggers when a sample is larger than a preset threshold. After triggering, 600 samples, or 4.6ms of data, are stored to memory. In calibration mode, these 600 samples are all sent as output over a serial TTL (transistor-transistor logic) line. The calibration mode is used in calibration experiments where the drop sizes are regulated. Using the data from these calibration experiments, a look-up table is constructed that links signal energy (sum of squares of the amplitude of 600 samples) per drop to drop size. The lookup table contains 64 bins, each 0.1mm wide. In operation mode, the (signal)energy of the recorded drop is calculated and using the calibrated look-up table, the drop size is derived. Only the drop size bin is communicated over the TTL standard serial output, using only a single character reflecting the bin in which the recorded drop is measured.

4.2.4. Calibration

The goal of the calibration experiments was to find a relation between the size of rain drops and the measured signal energy. The calibration experiments were carried out in the laboratories of Delft University of Technology. Raindrops of known size were created using medical seringes. By using seringes of different diameters, drops of different sizes were created. The seringes were mounted 8m above the disdrometer. At this height, 2mm drops have reached between 95% to 99% of their terminal velocity [31][32]. Drop sizes and variation in drop size thus created was measured by collecting 10 samples, each containing 100 drops from the setup and measuring the collected volume. The standard deviation in drop size per drop was less than 1% of drop size. For each different seringe (i.e. drop size) about 100 drops were dropped on the sensors running in calibration mode. The calibration experiments were carried out for multiple prototypes to test whether a single set of calibration constants could be used for all disdrometers, or whether each disdrometer needed its own calibration constants.

4.2.5. Field Evaluation

The field evaluation was carried out to measure the accuracy of the Delft-disdrometer versus state-of-the-art rain gauges in a realistic situation. The location of the field test was the headquarters of KNMI in the town of De Bilt (Lat: $52.098832°$, Lon $5.176406°$). At this facility, a test field is available where a Thies LPM: (type 5.4110.00.210, software version 2.05 DWD) laser disdrometer and a Ott Parsivel: (type 70.200.006.9.0, software version 1.10) laser disdrometer are installed. Both the Thies LPM and the Ott Parsivel measure individual drops, but aggregate those in 22 and 32 bins respectivly, which are transferred once a minute. Finally, a KNMI electronic rain gauge, developed in house by the KNMI, is available at this site. KNMI uses the so-called English setup to measure the precipitation amount. In this setup the precipitation gauge is installed in a pit surrounded by a circular wall [33] in order to reduce the errors induced by wind field deformations. This KNMI electronic rain gauge measures the official precipitation record for ”De Bilt”. (WMO-GCOS station number 6260). Data was collected from October 18th 2012 until November 18th 2012.

4.3. Results

Of the seven Delft-disdrometers installed, four were operational throughout the experiment. The other three Delft-disdrometers failed because of moisture entering the devices. An improved enclosure will be implemented in the next version of the Delft-disdrometer. Below, first the calibration results, followed by the field evaluation result of the four functioning Delft-disdrometers will be shown.

4.3.1. Calibration

The results from the calibration experiment are presented in figure 4.3. As expected from Joss *et al.* [34] a power law describes the relation between drop size and signal energy. In figure 4.3 the signal energy is plotted on a dB scale using reference energy of 1. The differences between the calibration coefficients of the Delft-disdrometers is highly significant. Using one set of calibration coefficients for all four Delft-disdrometers could cause a difference of up to a factor two in estimated rainfall. Delft-disdrometer number one has very poor calibration results. This is due to the lower than expected energies found at 4.0mm. No cause for this poor performance was found. Excluding these measurements as outliers without cause would be unjustified. All four Delft-disdrometers show low-energy outliers for all drop sizes. This is believed to be caused by drops hitting the edge part of the disdrometer, where no piezo ceramic is present. Only a tiny fraction of the energy of the drop would be recorded by the piezo. The results of the calibration experiment show that for the Delft-disdrometer individual calibration is needed.

4.3.2. Field Evaluation

The measured rain volumes of the Delft-disdrometers show good correlation with those of the KNMI electronic rain gauge. In figure 4.4 the data of the Delft-disdrometers are aggregated to hourly total rainfall and compared to the hourly

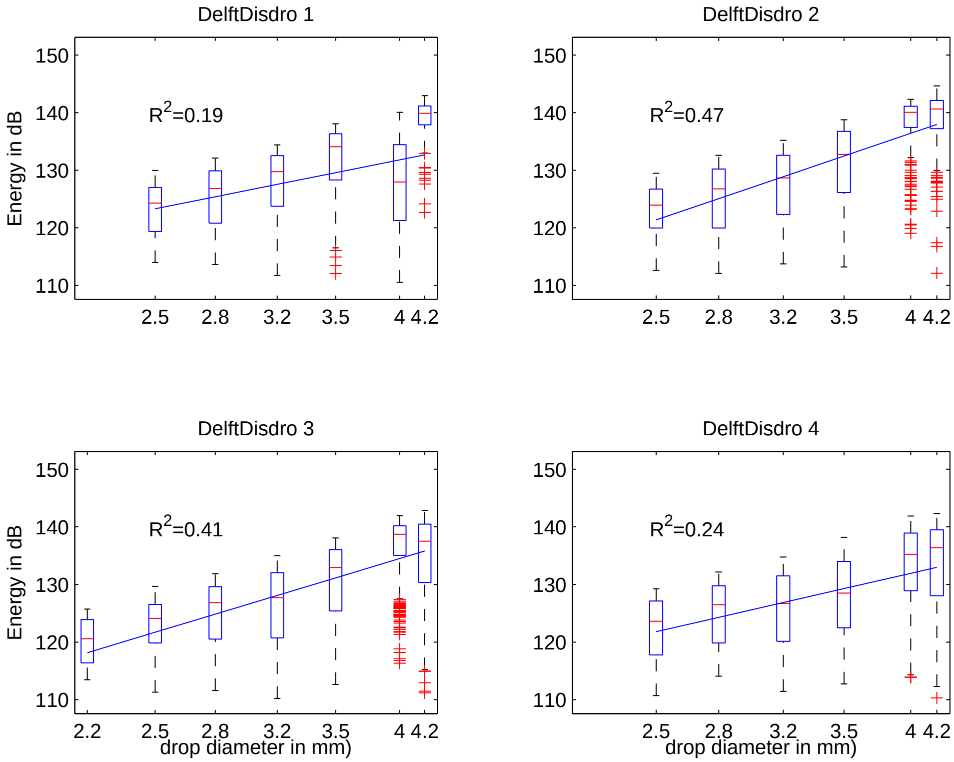

Figure 4.3: Calibration data for the Delft-disdrometers. The relation between the recorded signal energy (in dB) and drop sizes is shown using boxplots. Note that the drop size axis is plotted on a logarithmic scale. For all drop sizes, outliers with low energy are observed, most likely due to drops hitting the edge of the Delft-disdrometer. For Delft-disdrometer one, the experiment at $4\mathrm{mm}$ shows unexpected results. Since no cause for these unexpected results were found, they were not excluded as outliers. This has large implications for the estimations of precipitation volumes and drop size distributions of Delft disdrometer one.

values of the KNMI electronic rain gauge. Delft-disdrometer nr. 1, with the poorly correlating calibration results, shows under-estimation over the entire measurement period. The other three Delft-disdrometers under-estimate rainfall amounts for low intensity rain events, and over-estimate for high intensities.

For a single rain event, a storm with $20\mathrm{mm}$ of precipitation on the 29th of October, the drop size distributions as recorded by the Thies LPM, Ott Parsivel and the Delft-disdrometers are shown in figure 4.5. The cut-off in the drop size distributions for the Delft-disdrometers is due to the trigger mentioned in the electronics and algorithm section. The trigger-level is defined as a voltage, before calculating drop sizes. Since the Delft-disdrometers are individually calibrated, different cut-offs are observed per Delft-disdrometer. The drop size distributions measured for drops greater than $1.75\mathrm{mm}$ show good correspondence with the Thies LPM and the Ott Parsivel, although the relative large bin-sizes of the Thies LPM and the Ott Parsivel

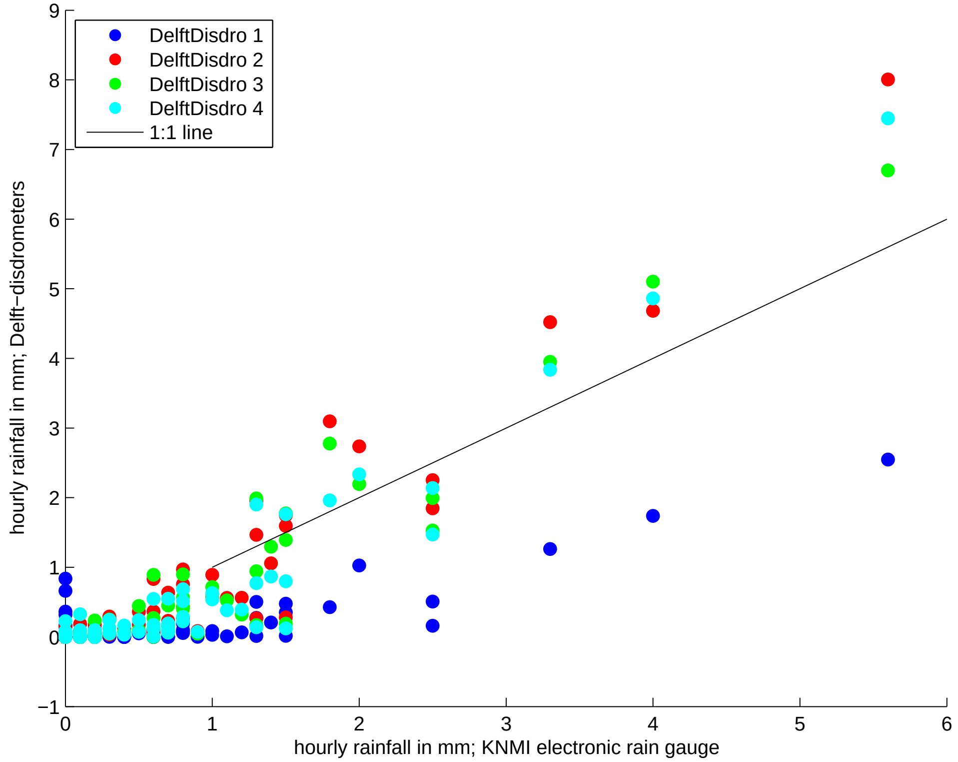

Figure 4.4: Hourly precipitation volumes measured using KNMI electronic rain gauge of WMO-GCOS station 6260 (de Bilt) compared with the Delft-disdrometers for the period October 18th 2012 till November 18th 2012

make comparison difficult.
In figure 4.6 the cumulative precipitation amounts for the 29th of October storm are shown. Cleary, Delft-disdrometer number one fails at measuring accurate precipitation volumes. This shows the importance of a good calibration of the individual Delft-disdrometers. Delft-disdrometers 2, 3 and 4, the Thies LPM, the Ott Parsivel and the KNMI electronic rain gauge show very similar results. The total rainfall values as measured by the different disdrometers (except Delft-disdrometer nr. 1) are all within 10% of the value measured by the KNMI electronic rain gauge. The measurement of the Ott Parsivel had the largest deviation from the measurement of the KNMI electronic rain gauge.

4.4. Conclusions and Discussion

The Delft-disdrometer, a prototype of a low maintenance disdrometer, proved capable of measuring precipitation volumes with comparable uncertainties as those of the industry standard Thies LPM and Ott Parsivel, when compared against

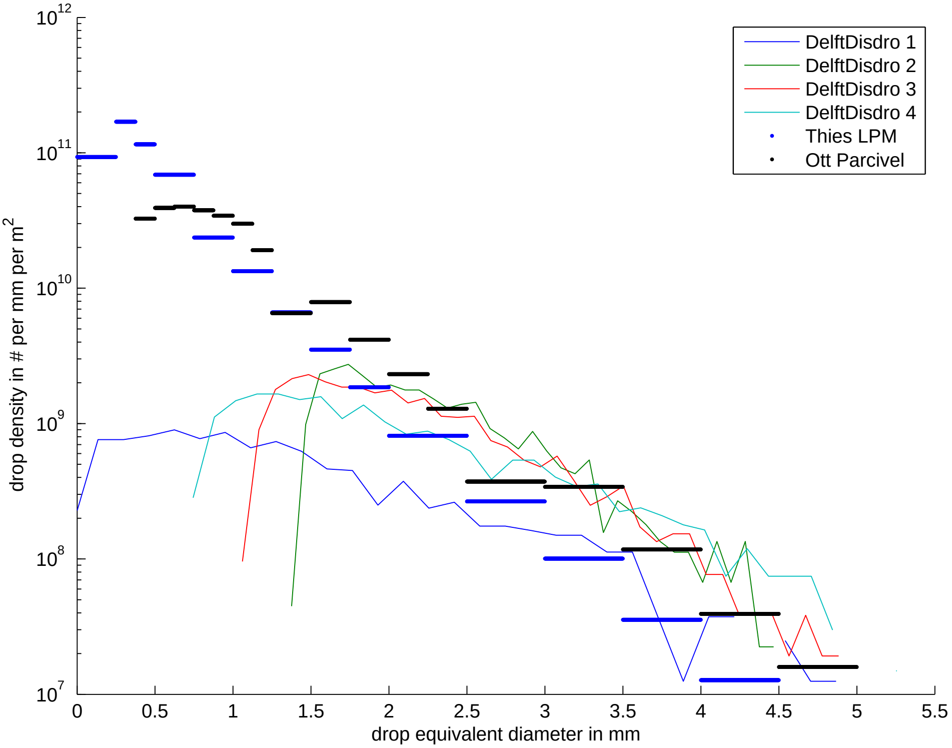

Figure 4.5: Drop size distributions as measured by the Delft-disdrometers, the Thies LPM and the Ott Parsivel on the 29th of October, during an event in which 20mm of precipitation fell.

the KNMI electronic rain gauge of WMO-GCOS station 6260 (de Bilt). The drop size distributions measured with the Delft-disdrometer are similar to those measured with the Thies LPM and the Ott Parsivel for drops of diameter greater than 1.75mm. Of the seven installed Delft-disdrometers prototypes, four survived the experiment. In a next prototype, additional measures will be taken the avoid seepage of moisture into the disdrometer. The calibration experiment showed that the Delft-disdrometers need individual calibration. This is a problem for the stated low cost goal. To keep the cost of calibration low either all sensors should be identical, or a novel method of calibration needs to be invented. The current prototype of the Delft-disdrometer is manually manufactured which may be the cause of the differences in calibration constant. A new, mass produced version of the Delft-disdrometer will, most likely, have lower variation in calibration constant between different Delft-disdrometers. The inability of the Delft-disdrometers to measure drops smaller than 1mm should also be addressed by lowering the trigger level. In order to accurately measure the parameters of the drop size distribution, smaller drops are essential. The experiments with this first prototype show that while it is feasible to measure precipitation with the low maintenance Delft-disdrometer, a

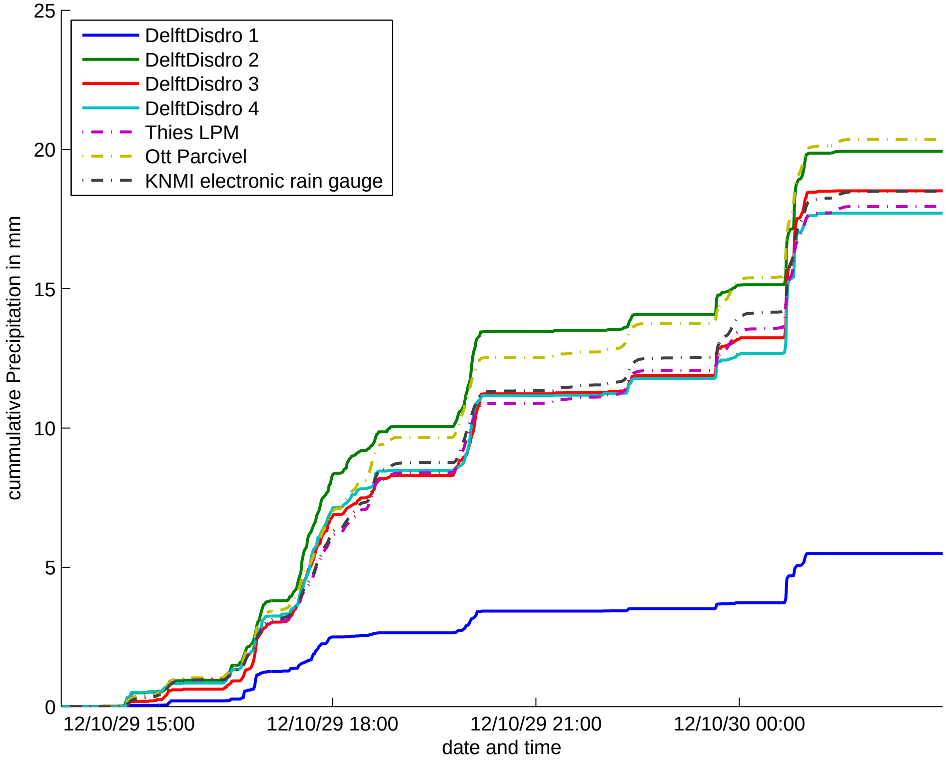

Figure 4.6: Cumulative precipitation volume as measured by the Delft-disdrometers, the Thies LPM, the Ott Parsivel and the KNMI electric rain gauge of WMO-GCOS station 6260 (de Bilt) on the 29th of October, during an event in which $20\mathrm{mm}$ of precipitation fell.

mass produced version that has identical calibration constants and a lower trigger level is needed for it to achieve its low cost target.

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5

Medicinal Footprint of the population of the Rhine basin

It is a very sad thing that nowadays there is so little useless information.

Oscar Wilde

The relation between pharmaceutical residues along the river Rhine and the demographic characteristics of the upstream population was studied. A sampling campaign was performed in which water samples from the Rhine were taken at 42 locations. Measurements were compared to a two parameter model with regional demographic data as main input. For 12 out of the 21 studied pharmaceuticals, a significant dominant demographic group could be identified. For 3 out of these 12 pharmaceuticals male elderly were the most contributing demographic group. A Monte Carlo analysis showed a high level of significance for the results of this study ($p < 0.01$). By combining environmental water quality data and demographic data, better insight was gained in the interplay between humans and their environment, showing the medicinal footprint of the population of the Rhine basin.

This chapter has been submitted for review to Environmental Review Letters as "Medicinal Footprint of the population of the Rhine basin" by R.W. Hut, N.C. van de Giesen and C.J. Houtman

5.1. Introduction

Thirty million people rely on the Rhine for their drinking water [1] and 37% of Dutch drinking water is prepared from river water, the Rhine being the main supplier [2]. It is, thus, of great importance to understand the processes generating pharmaceutical pollution of the Rhine.

In this paper, a relation between the concentrations of pharmaceuticals in the river Rhine and specific demographic groups living in the Rhine basin was studied. The main innovation concerns the combination of geophysical and demographic datasources with concentrations of pharmaceuticals. A two parameter model was developed using sampling point locations, measured concentrations, demographic groups and river discharge as input. The demographic groups considered were firstly all combinations of gender (male, female and total) and age (younger than 15, 15-65, older than 65 years and total). Secondly, the different nationalities living in the basin (German, Austrian, Belgian, French and Swiss) were considered. This approach allowed us to link different concentrations of pharmaceuticals to different dominant demographic groups in the Rhine catchment.

Pollution of river water with residues of pharmaceuticals has become a source of concern and topic of research[3]. Pascoe *et al.* [4] showed that exposure to pharmaceuticals in the environment has negative effects on fresh water invertebrates. Fick *et al.* [5] showed that therapeutic levels of pharmaceuticals were found in fish when exposed to waste water treatment plant effluent. Research on understanding the source of this contamination was undertaken by, among others, Nakada *et al.* [6], who compared discharge of pharmaceuticals from different rivers to the population living in the catchments of those rivers and found significant correlations. Sim *et al.* [7] showed that levels of pharmaceuticals in waste water treatment plant effluent could be linked to consumption of pharmaceuticals. Ter Laak *et al.* [8] linked the amount of pharmaceuticals sold in the Rhine basin to the residuals measured in the river at the catchment outlet. By using population estimations and pharmaceutical consumption data, van der Aa *et al.* [9] predicted that the amount of pharmaceuticals in the Rhine will rise by 17% in 2020, compared to 2007.

One would assume that pharmaceutical pollution accumulates in the river water with downstream distance. However, this has never been shown in the literature. In this paper, we combine datasources on demographics, elevation and river discharge with measured concentrations of pharmaceuticals in a two parameter model. This simple model accounts for decay of pharmaceuticals and incorporates the downstream logic of the watershed to identify the ”most contributing groups” per polluting pharmaceutical.

5.2. Methods Used

We used a two parameter model to predict pharmaceutical concentrations in the river Rhine with measured hydrologic and demographic data. A model is needed because direct correlation of concentration, or loads, of pharmaceuticals with demographic groups ignores the known process of degradation of pharmaceuticals in the river. The parameters in this model were estimated using measured concentrations from our sampling campaign. Parameter estimation was performed for different demographic groups. The groups considered were firstly all combinations of gender (male, female and total) and age (younger than 15, 15-65, older than 65 years and total). Secondly, the different nationalities living in the basin (German, Austrian, Belgian, French and Swiss) were considered. The group, either a combination of sex and age, or a nationality, for which the model fitted best to the measurements was considered "main contributor". Below the different datasources, the model and the method for significance testing are described.

5.2.1. Model

The model has two parameters to link population to pharmaceutical concentration. First is the emission factor C [ng/day person], the flux of pharmaceutical residual that is discharged into the river per individual. Second parameter is the decay-length L [km], the river length associated with the decay of the pharmaceutical. Using these two parameters, the concentration $\hat{c}_{i,j,k}$ $\left[\mathrm{ng/m^3}\right]$of a particular medicine i, caused by a demographic group j, at sample location k is predicted by:

$$\hat{c}_{i,j,k} = \frac{\sum_{n \in N_k} C_{i,j} P_{n,j} e^{\frac{-\Delta_{n,k}}{L_{i,j}}}}{Q_k} \tag{5.1}$$

5

where

- parameter $C_{i,j}$ [ng/day person] is the emission factor of pharmaceutical i for demographic group j
- parameter $L_{i,j}$ [km] is the decay-length of pharmaceutical i for demographic group j. Although available from literature (Kunkel and Radke [10]), the decay-length was optimized as a parameter because the circumstances in this specific river are likely to be different from those used for the assessment of literature values. Optimized decay-lengths that are close to reported literature values, provide extra confidence in the assumptions implicitly underlying the model.
- input N_k is the set of sampling points that are upstream of sampling point k plus k itself.
- input $P_{n,j}$ is the number of people in demographic group j that lives in the upstream area of sampling point n but not in the upstream area of any other upstream sampling point. For sampling points along the main river, not downstream of a tributary, this means that $P_{n,j}$ is the number of people living in the part of the catchment that is upstream of n, but not in the catchment of the next upstream sample point.
- input $\Delta_{n,k}$ [km] is the length, measured along the river, from sampling point n to sampling point k.
- input Q_k $\left[\mathrm{m^3/day}\right]$ is the river discharge at sampling point k.

The parameters $C_{i,j}$ and $L_{i,j}$ are estimated by minimizing the differences between predicted concentrations $\hat{c}_{i,j,k}$ and the measured concentrations $c_{i,k}$. For each combination of pharmaceutical and demographic group, the R-square statistic

$$R^2_{i,j} = \frac{\sum_{k=1}^{N} \left(\hat{c}_{i,j,k} - c_{i,k}\right)^2}{\sum_{k=1}^{N} \left(c_{i,k} - \bar{c}_i\right)^2} \tag{5.2}$$

is computed. Finally, for each pharmaceutical, the demographic group with the highest $R^2_{i,j}$ is marked as ”most contributing”.

5.2.2. Assumptions

By constructing the model as explained above, the following assumptions were made.

- It is assumed that steady state conditions hold: People discharge a continuous flux of pharmaceuticals per person into the river that does not change with time. Gerrity *et al.* [11] showed that during special events, in their case the NFL Superbowl, this assumption may not hold. The sampling campaign of this research, did not take place during any known event or holiday that would violate this assumption.
- Perfect mixing is assumed. The sample is representative for the water composition of the entire river cross section. To minimize the impact of this assumption on results, samples were always taken from the center of the river.
- A single demographic group is held responsible for the total pharmaceutical pollution. In reality, different groups contribute differently. The test performed in this research is a 1-step ANOVA using a non-linear model. Ideally, one would like to perform a multivariate (multi-step) analysis with all the groups as combined inputs. That would, however, lead to overparameterization, considering the number of samples. This assumption limits the interpretability of the emission factor.

5.2.3. Sampling and Chemical Analyses

Water samples were taken at 42 points along the river, each approximately 20-30 km from the the previous point. The sampling points were chosen between Liechtenstein, near the source of the river, and Emmerich, on the Dutch-German border where the Rhine delta starts. No specific permits were required for the described sampling campaign. None of the samples were taken at locations that are privately-owned or protected in any way. The sampling campaign did not involve endangered or protected species. The campaign was conducted from April 10th until April 13th 2011. The sampling team moved downstream with a velocity about equal to the stream-velocity to minimise the effect that discharge waves might have on the analyses. Since the sampling team needed to stop during the nights, the equality of sampling team velocity and stream velocity is a rough approximation. During the sampling campaign, and in the weeks before, less than 15mm of rain

in the Rhine basin. This is not enough to lead to discharge fluctuations that might influence the analysis [12]. Sampling points were downstream of bridges or ferries. The major tributaries of the Rhine (Aare, Neckar, Main, Lahn, Mosel, Sieg, Ruhr and Lippe) were also sampled just before they entered the main river. Samples were taken using stainless steel buckets, transferred to pre-rinsed bottles of green glass and cooled in melting ice directly after sampling.
Samples were extracted within one day upon arrival at the laboratory (april 14th 2011). Locations 18 and 24 were sampled and analysed in triplicate to determine the experimental error in this study. MilliQ-water (sampled and analysed in triplicate) served as blanc control for contamination during sampling and laboratory procedures. Analysis of pharmaceuticals was performed as described in Houtman et al (in prep.). In short, $100\mathrm{mL}$ volumes were extracted with solid phase extraction using Oasis HLB and eluted with methanol. Extracts were evaporated to $100\mu\mathrm{L}$ to which $1\mathrm{mL}$ milliQ water was added. Pharmaceuticals were analysed using an Ultra Performance Liquid Chromatograph (UPLC, Waters Acquity), equipped with a quaternary pump, combined with a Quattro Xevo triple quadrupole Mass Selective Detector (Waters Micromass) with electro spray ionisation. Quantification was performed using an external calibration series of seven concentrations.
The analysis method quantified forty one pharmaceuticals that are routinely tested for by Dutch drinking water companies. In those routine tests, the pharmaceuticals were selected according to their consumption volume, earlier detection, ecotoxicity and that represented most relevant therapeutic classes (analgesics, antibotics, antidiabetic, antidepressant/psycholeptics, anti-hypertension drugs, antilipaemic, beta blockers, cytostatics, diuretics, x-ray contrast agent, anti-epileptic, respiratory drug). Most (32) compounds had a method limit of detection (LOD) of $5\ \mathrm{ng/L}$ or lower, of which 18 compounds had an LOD between $0.1\ \mathrm{ng/L}$ to $1\ \mathrm{ng/L}$. Highest LOD was obtained for clofibrate $(85\ \mathrm{ng/L})$. The method was validated by calculating the recovery and standard deviation of surface water samples from 8 different locations and sampled on different days spiked with pharmaceuticals at a low level (resp. 0.5, 2.5 or $15\ \mu\mathrm{g/L}$) to determine limits of detection and at a higher level (resp. 0.5, 2.5 or $15\ \mu\mathrm{g/L}$) extracted and analysed at different days to determine reproducibility. The average recovery found was $91 \pm 14\%$ (error includes whole process from sampling to analysis). An average recovery of $84 \pm 19\%$ was found for the matrix Rhine surface water. Only pharmaceuticals that were detected in concentrations higher than their LOD in the Rhine water samples at 10 or more sampling points were included in the dataset used to estimate the parameters for the prediction model. This resulted in a dataset with concentrations for 21 different pharmaceuticals at 42 sample points.

5.2.4. Data Sources

The Hydrosheds digital elevation model [13] and the GPS locations of the sampling points were used to determine the upstream area (catchment) of each sampling point. The boundaries of these catchments were overlaid over the boundaries of the NUTS3 areas[1] from Eurostat. The population statistics per NUTS3 area in the

[1] The smallest available regional statistical unit

Eurostat online database [14] provided the population statistics per age group and gender per upstream area of each sampling point as counted on the first of January 2010.[2].

The different demographic groups are highly correlated with each other (general correlation coefficient greater than 0.99 i.e. people tend to live together). Because of this high correlation, large differences in emission of pharmaceuticals will show up as small differences in the R^2 and small differences should thus be interpreted as more significant compared to research where different inputs are not correlated with each other.

To derive the discharge at the sampling locations from the discharge at measurement stations along the river [15], [16], [17], [18] the schematization of the Rhine Alarm Model [19] was used. For some sampling locations, most notably in the city of Koblenz and in the tributaries Sieg, Ruhr and Lippe, only water levels and no discharge information could be found, even after contacting the respective authorities. These sampling locations were excluded from the analysis, although the effect of the populations of the tributaries is taken into account in subsequent downstream sampling points.

5.2.5. Significance Testing

We tested the significance of the results by running a Monte Carlo simulation in which we repeated the complete analysis presented above, with for each Monte Carlo run a randomly shuffled order of demographic input per sampling point. The shuffling was done by randomly permuting the order of the index n in the $P_{n,j}$ input of equation 5.1, thus attributing the "wrong" people to the sampling points. This method ensured that all the distributions were the same, and only the order was changed. If we had also bootstrapped the values of the concentrations and/or discharge data, any covariance among these inputs might have been destroyed, resulting in overconfidence in our results. By only shuffling the order of the demographic input, we test whether the order of sampling points causes the observed results. For each Monte Carlo Run, for each pharmaceutical, the most contributing group and the corresponding R^2 were saved. It should be noted that we are not using a linear model and thus R^2 can not be interpreted as the percentage of variance explained, but higher R^2 does relate to better fitted models. The location of the R^2 of the actual (non-shuffled) results in the distribution of R^2s from the Monte Carlo runs, determines the significance level (p-values), per pharmaceutical.

Since a large group of pharmaceuticals was tested, statistically some of those would have to end up with a low p-value [20]. To test whether the overall results were significant we compared the average R^2 for all pharmaceuticals in the actual results to the distribution of average R^2s from the Monte Carlo runs to find the p-value for the overall results. Since the individual Monte Carlo runs use a randomised input, and comparison with individual end-members of distribution introduces uncertainties, a safety factor needs to be applied when the results indicate very high overall

[2] for NUTS3 areas that were partially lying in a catchment, the fraction of area inside the catchment was used to weigh the population statistics, thereby assuming uniform population density within a NUTS3 area

significance.
Finally, the catchment area per sample point was also used as an input to the model. Catchment area is strongly correlated with the amount of people living in the catchment. It would be an indication that the observed results are actually due to catchment area as explaining input and not demographics when the results using catchment area as input have a higher R^2 than the results using the correct demographics as input.

5.3. Results

Measured concentrations, aggregated in therapeutical classes, are shown in Figure 5.1. A complete table of measured concentrations per pharmaceutical is provided in the supporting material. Figure 5.1 shows a significantly increasing trend in measured total concentrations of pharmaceuticals with downstream distance, supporting the hypothesis that the concentration of pharmaceuticals is linked to the number of people in the upstream catchment.

The demographic groups that contribute most per pharmaceutical are shown in Table 5.1. For 12 of the 21 studied pharmaceuticals, a significant ($p < 0.05$) dominant demographic group could be identified. The R^2 values for all combinations of pharmaceuticals and demographic groups are presented in the supporting material. Careful analysis of the results per pharmaceutical produces interesting outcomes, both for the pharmaceuticals with a significant dominant demographic group, and for the pharmaceuticals without a significant dominant group.
All three pharmaceuticals that have elderly people as most contributing group show high correlations between concentrations and contributing group ($p < 0.01$). Apparently, elderly in Germany, France and Switzerland use similar above average quantities of these pharmaceuticals and thus correlate highly with the measured concentrations. This agrees with data for the Netherlands from the Dutch Foundation for Pharmaceutical Statistics that show that elderly people use exponentially more pharmaceuticals with age [21]. The results for the anti-epileptic carbamazepine are shown in figure 5.2 as an example of a pharmaceutical with a significant correlation (low p-value) with a demographic group. Carbamazepine concentrations correlate best with the demographic group ”male elderly”. This finding corroborates the work of van der Aa *et al.* (figure 1 of [9]) that, based on Dutch prescription data, showed that elderly males are the main consumers of carbamazepine.
If a pharmaceuticals has high p-values ($p > 0.05$) for all demographic groups, it is most likely that humans are not directly correlated with the main source of pollution. Other sources, such as industrial discharge, might, for some pharmaceuticals, cause the measured concentration pattern. For example; the psycholeptic diazepam has ”the French” as most contributing group, but a high p-value of 0.361. Measured and modelled results for diazepam are shown in figure 5.3. There is a sharp increase in diazepam at 300km from Konstanz, near the city of Strassbourg. Looking at the ratio’s of the concentrations of diazepam, temazepam and oxazepam (elaborated in the supporting material) we conclude that perhaps the diazepam measured here did not result from human consumption but came from another emission source.
Like diazepam, hydrochlorothiazide has a national group as most contributing group,

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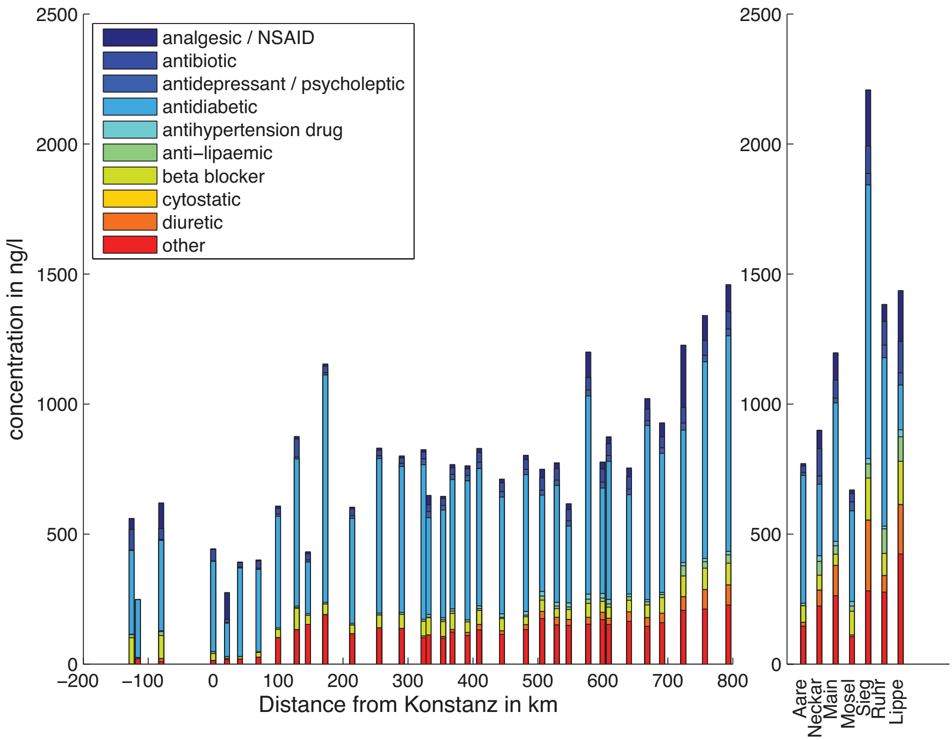

Figure 5.1: **Measured concentrations of pharmaceuticals, aggregated to therapeutic classes, in the Rhine (left) and its major tributaries (right).** The downstream increasing trend indicates that the relative increase of pharmaceutical loads is higher than the relative increase in water discharge. Since more people live in the lower part of the Rhine catchment, this supports the hypothesis that the concentration of pharmaceuticals at a sampling point is linked to the number of people living upstream of that sampling point.

namely Germans. However, for hydrochlorothiazide a much stronger correlation with its strongest contributing group was found ($p < 0.04$). Either Germans are consuming more hydrochlorothiazide than other nationalities in the Rhine catchment, maybe due to different prescription policies, or other activities that happen all over Germany cause more prominent emission.

Care must be taken when interpreting the results in a causal manner. For example, female children are the main contributing group for the beta blocker sotalol. It is unlikely that these children are actually excreting sotalol, since sotalol is predominantly prescribed to patients suffering from atrial fibrillation, a hearth condition of which the prevalence is strongly positively correlated with age. The actual group responsible for emission of sotalol in the Rhine must, however, be highly correlated with the presence of female children.

Since the number of people living in a catchment is highly correlated with catchment area, it was tested whether using catchment area as an input would result

Table 5.1: **Main contributing demographic group per pharmaceutical**

pharmaceutical	therapeutic class	most contributing group	R^2	p-value
carbamazepine	anti-epileptic	male elderly	0.98	< 0.001
primidone	antidepressant	male adults	0.98	< 0.001
temazepam	psycholeptic	Germans	0.96	< 0.001
bezafibrate	antilipaemic	Germans	0.97	< 0.001
losartan	antihypertension	male adults	0.94	< 0.001
sotalol	beta blocker	female children	0.97	< 0.001
lidocaine	analgesic (a.o.)	female adults	0.94	0.001
bisoprolol	beta blocker	male elderly	0.95	0.003
hydrochlorothiazide	diuretic	Germans	0.96	0.004
sulfamethoxazole	antibiotic	male elderly	0.95	0.009
oxazepam	psycholeptic	female children	0.93	0.034
atenolol	beta blocker	Swiss	0.84	0.05
lincomycin	antibiotic	Germans	0.76	0.065
metoprolol	beta blocker	Swiss	0.77	0.077
iopromide	x-ray contrast agent	female adults	0.84	0.083
phenazone	analgesic	Germans	0.69	0.113
diazepam	psycholeptic	French	0.77	0.361
atorvastatin	antilipaemic	Swiss	0.60	0.593
propranolol	beta blocker	male children	0.70	0.62
trimethoprim	antibiotic	male adults	0.64	0.824
metformin	antidiabetic	male children	0.79	0.852
Average			0.85	< 0.001

Main contributing demographic group per pharmaceutical is tabulated, including R^2 and p-value. Results are ordered according to p-value. 12 pharmaceuticals have a $p < 0.05$ significance. Of these 12, 4 have elderly male as most contributing group.

in a higher R^2 compared to using the number of people. The average R^2 over all pharmaceuticals, using catchment area as input, is 0.77. This is much lower than the average R^2 using demographics as input, which is 0.86. This shows that the relations found between concentrations of pharmaceuticals and demographic groups is not an indirect effect due to the correlation between catchment area and number of people living in the catchment.
Because of the large number of correlation operations performed for this research, it was important to test whether the total results (Table 5.1) could have been due to pure chance. The main hypothesis of this work is that there is a relation between concentrations of pharmaceuticals in the river and the people living in the upstream catchment. This was tested by considering the null-hypothesis that no relation exists between concentrations of pharmaceuticals in the river and the people living in the upstream catchment. A Monte Carlo analysis was done in which the demo-

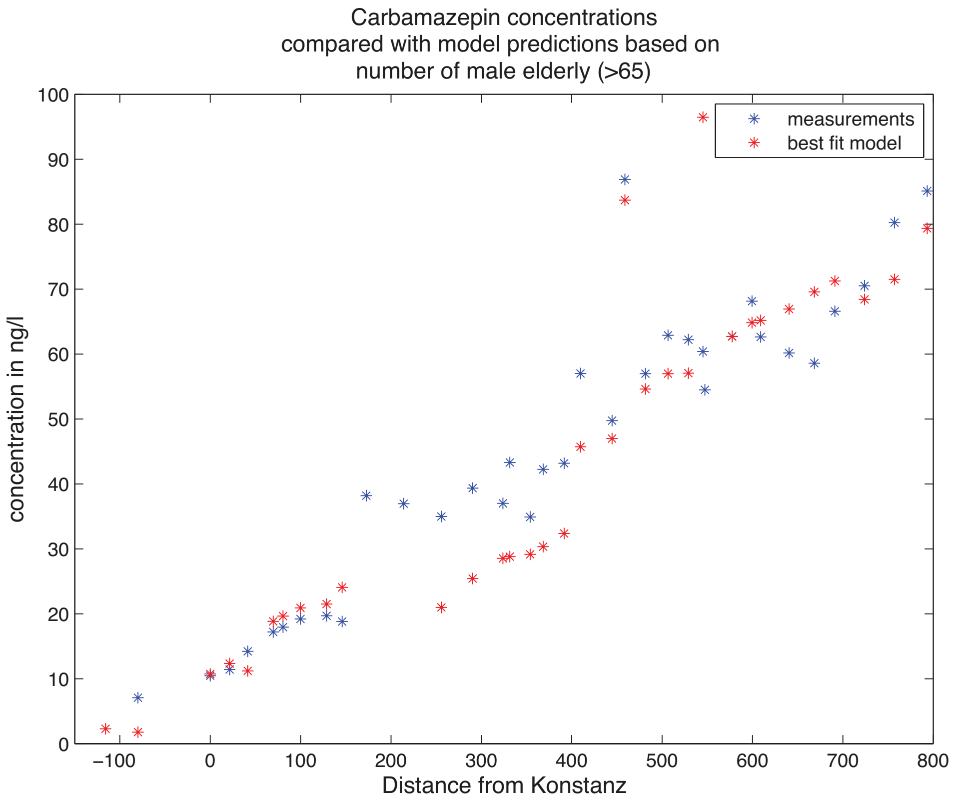

Figure 5.2: **Measurement and model results for the concentration of carbamazepine along the Rhine.** Carbamazepine had the best R^2 (0.98) when elderly males were used as explanatory variable. The high R^2 indicates that elderly males are to an important extent responsible for the carbamazepine found in the Rhine ($p < 0.001$). No model prediction is available for the two measurements around 200km because no discharge measurements were available for these sampling points.

graphic inputs were randomised over the sampling points for each Monte Carlo Run. As the cumulative distribution of R^2s of the Monte Carlo runs in figure 5.4 shows, not a single one out of the 1000 Monte Carlo runs has a higher R^2 than the actual non-shuffled results. Using a safety factor, we reject the null-hypothesis ($p < 0.01$) and conclude that a relation does exists between concentrations of pharmaceuticals in the river and the people living in the upstream catchment.

the results of Table 5.1 are highly significant .

5.4. Discussion

The logic of watersheds and pollution patterns helps us in understanding a broad range of phenomena. The methodology of this research could be used more widely as it offers a way of monitoring an indicator of population health, without

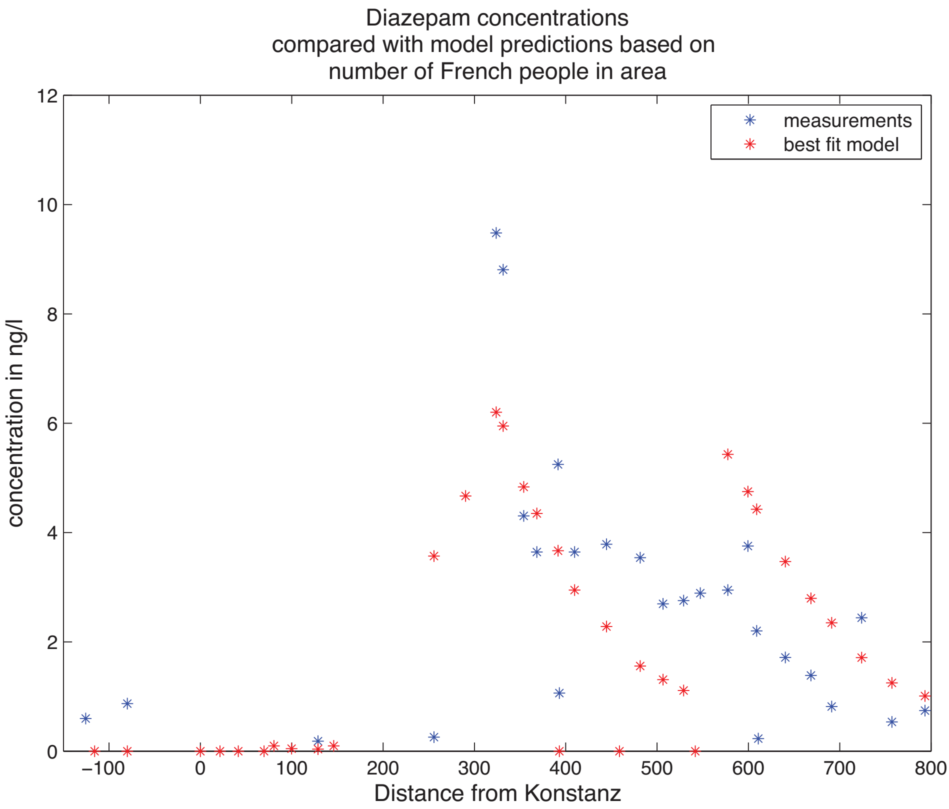

Figure 5.3: **Measurement and model results for the concentration of diazepam along the Rhine.** Diazepam had the best R^2 when French people were used as explanatory variable. The low R^2 of 0.77 and high p-value of 0.361 indicate that most likely another process is dominant in explaining the concentration of diazepam in the river Rhine.

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having to use surveys. This holds especially true for illicit drugs and over the counter (non-prescribed) pharmaceuticals, for which data on sales or usage are usually not available, as Thomas *et al.* [22] suggested.

The results show that there is a relationship between concentrations of pharmaceuticals in the river Rhine and the demographic characteristics of the people living upstream in the Rhine basin. For 12 out of 21 pharmaceuticals, the relationships between demographic group and concentrations of pharmaceuticals are significant ($p < 0.05$). However, care must be taken with the interpretation of these results. These correlations do not show causal relations per se. Other processes that are highly correlated with population density of certain groups might be the cause of pollution with pharmaceuticals. For the 9 pharmaceuticals with p-values higher than 0.05, it is concluded that either the dataset is not rich enough to pinpoint the dominant demographic group, or another process that does not correlate highly

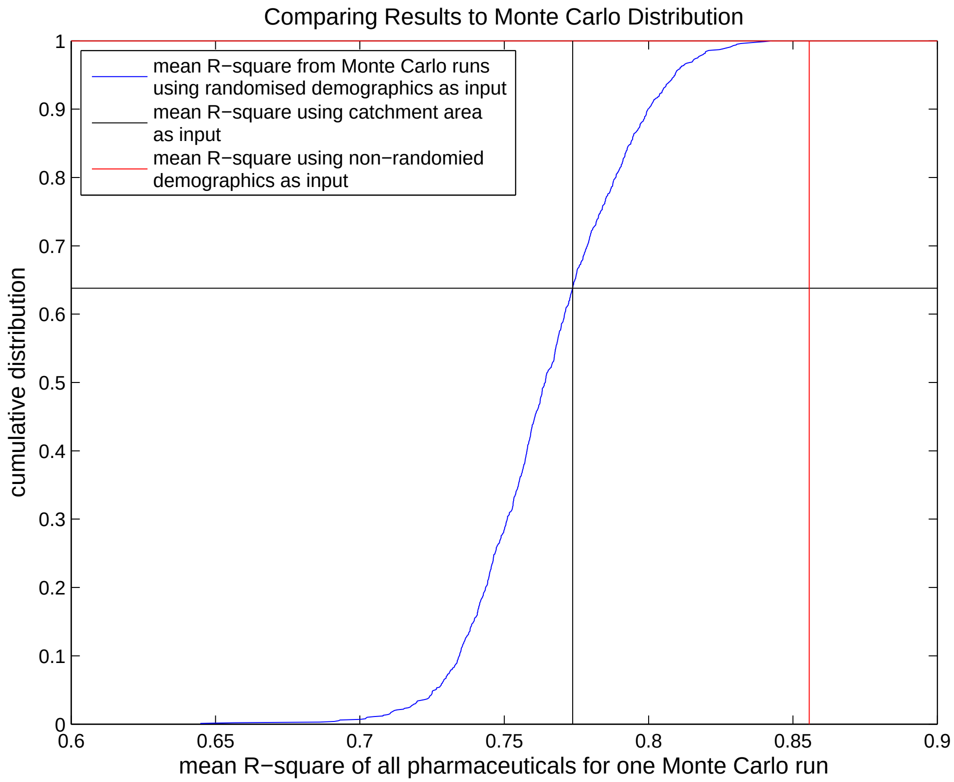

Figure 5.4: **Distribution of mean R^2 from a thousand Monte Carlo runs in which the order of the demographic inputs was randomised.** The black lines indicate the results using catchment area as input. The red lines indicates the real, non-randomised demographic data is input, showing that there is a higher than 99% chance that the results are not due to chance.

with demographics causes the pollution. The pollution of diazepam that seems to originate upstream of the city of Strassbourg is an example of this.
A strong correlation between a specific pharmaceutical and a specific demographic group should be seen as a starting point for new research questions. For example: "do female children really take large quantities of the beta blocker drug sotalol, or do these children cause irregular heart beat symptoms in their (grand)parents?", or "do differences in national health policies related to medicine explain why Germans are the most contributing group for temazepam, bezafibrate and hydrochlotorhiazide?".
This research showed that the combination of demographic data with environmental data allows for insight in the interplay between humans and their environment.

Acknowledgments

We like to thank Stijn de Jong and Jop Jansen of Delft University of Technology for preparing and taking part in the fieldwork trip. We like to thank Laurene Bouaziz and Wouter Berghuijs of Delft University of Technology for their help in collecting the online discharge data for this research. We like to thank Olivier Hoes of Delft University of Technology for his help with the GIS-analyses. Finally, we would also like to thank Scott Tyler of the University of Nevada, Reno, for coining the phrase "medicinal footprint".

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6

Conclusions and look into the future

the only difference between screwing around and science is writing it down

Adam Savage[1]

[1] http://www.youtube.com/watch?v=BSUMBBFjxrY

Hydrology is a science that suffers from the tragedy of locality. Hydrologists try to understand the hydrological cycle and all of the processes that it includes such as rainfall, snowmelt from a glacier, evaporation from a field of maize or discharge of groundwater into a river. The tragedy lies in the fact that, for example, detailed study of groundwater discharge from a meadow into a small alpine stream might lead to insight into the functional form of discharge from said meadow, but applying the insight gained to a new meadow would require detailed information on the new meadow: topography, soil composition, etc. Hydrologic processes can, in general, not be described by universal laws that are independent of local variables. Astronomers can predict the movement of planets assuming a universal[2] gravitational constant. Hydrologists have to measure the hydraulic conductivity of every field they work in.

The fundamental laws that describe the behaviour of water are well understood: Darcy's law for saturated groundwater flow, the Richards equation for flow in unsaturated soils, the Navier-Stokes equations for open water flow, and for shallow water the depth-integrated version of the Navier-Stokes equations "the Saint Venant Equations". To make predictions on scales that are relevant for human daily lives, that is from field to catchment and basin scale, one has to integrate those laws spatially. The spatial heterogeneity of the needed constants (for example hydraulic conductivity), topography (including soil layers locations) and inputs (mainly rainfall) are such that averaging over spatial scales will generally introduce errors that severely limit predictive capabilities.

Given the tragedy of locality, the advances in hydrology in the last few decades are remarkable [1]. To deal with the tragedy, hydrologists have either taken a holistic view of their study area (catchment) [2], or tried to model field and catchment responses by statistical methods. See, for example, the website of the statistical hydrology community [3] and the impressive list of references therein. Both these developments have a strong focus on using increasingly sophisticated methods on existing data. In the Introduction, I argued that the development of low-cost sensors, the rise of open source hardware and the easy access to datasets outside of (classic) hydrology, are an opportunity that can help reduce the tragedy of locality.

6.1. Low-cost Sensors

Low-cost sensors allow scientists to increase the spatial resolution of their measurements. This not only allows for better insight into the spatial resolution, but also gives the opportunity for more temporal resolution. For example, if a single rain gauge is used for a large area, the measurements will only be representative of the entire area when integrated over relatively large timescales. This limits the time-resolution for any rainfall-runoff model that uses these rainfall measurements as input. Berne *et al.* showed that in an urban catchment of $100\mathrm{ha}$ a two-kilometer spatial and three-minute temporal resolution is needed [4]. With an ever-increasing demand for more accurate (and timely) flood forecasting, more rainfall measurements are needed, both in time and space. The drop in cost of sensors achieved

[2] pun intended

by economies of scale in consumer electronics have allowed scientists to use these lower-cost sensors in “first proof-of-concept” research. In Chapter 2 I mentioned that “Technology developed for mass-manufactured consumer electronics, with low cost if acquired in bulk, may offer valuable applications for geosciences, where the spatial density and extent of sensors is often an important constraint on the amount of information that can be obtained from a natural system.” Chapter 3 showed an example where an off-the-shelf accelerometer is used to turn a simple bucket into a rainfall and evaporation recorder.

6.2. Open Source Hardware

The advent of widely available open source hardware such as the Arduino platform has allowed researchers to easily connect the low-cost off-the-shelf sensors mentioned above to logging or telemetric solutions. This has greatly reduced the threshold for non-electronically-educated professionals to build their own measurement equipment. The open source spirit of not only sharing the result of one’s work, but also writing a tutorial on how to recreate it are essential if others are to build on it. Although Lee [5] published his work on hacking a Wiimote in a peer-reviewed journal, the variant on his work presented in chapter 2 would not have been possible without the detailed “how- to” guides published on his personal website.

6.3. Looking Beyond Hydrology

The free sharing of (research) data has taken flight over the last decade. Numerous datasets have been made accessible to everyone, including researchers. Many of those sources are not primarily collected for hydrologic research, but can still contain value for hydrologic research. Satellite data is the prime example of this type of information but it is certainly not the only kind. The human impact on the water cycle and on hydrological systems is recognised more and more in hydrologic literature [6] [7]. It makes sense to use demographic and other ”people-science” datasets to fully understand the interaction between humans and the water system. Chapter 5 is an example where demographic data and water quality data is used to link pollution in the river Rhine to specific demographic groups.

6.4. Challenges

There is a distinction between a scientist who wants to do a measurement to show that a particular measurement can be done and a scientist who wants to do a measurement because they need the measurement data as input to answer their research question. However, career-wise, both have the same incentive: publish as many-peer reviewed articles as possible. For those who need measurements as input for their research, an academic article on a proof-of-concept does not usually give enough information to build their own version of the device. In addition, proof-of-concept versions of devices are generally not robust enough for long outdoor measurement campaigns, limiting their usability. What is generally needed is a "product" built from the proof-of-concept that can be easily used by others and does not rely on intimate knowledge of the internal functioning of the device or method. Any engineer in an R&D department knows that a successful proof-of-concept does not guarantee a working product. For most academic researchers that work on proofs-of-concept, there is little (academic) incentive to follow up on proof-of-concept research because this follow-up work is considered engineering and generally not (peer-reviewed) publishable. For example, the work by Varhole *et al.* on the LOCUS-X snow-depth sensors is published in the Journal of Atmospheric and Oceanic Technology [8]. However, after having read the paper, a scientist is not able to completely rebuild the LOCUS-X, nor does the paper provide information on how and where a sensor could be acquired. One way to solve the problem of scientists not being able to use the information in proof-of-concept articles is for the authors of the article to go commercial and clearly state so in the article: the proof-of-concept versions of the weather stations sold by Sensorscope were developed at EPFL [9]. The disdrometer presented in chapter 4 is now brought to market by TU Delft spinout company Disdrometrics.

Closing the gap between prototype and products requires more than sharing information or always starting your own company: economics come into play as well[3]. Whether a start-up or an established producer of hydrological sensing equipment, producers will only turn a prototype into a product if they believe a market for the product exists. All the (academic) hydrologists together are not big enough a market to justify the cost of developing a product. Therefore, most hydrological sensing equipment developed by commercial parties is aimed at commercial parties such as (large-scale) farmers or governmental organisations such as NOAA and the USGS in the US, or the KNMI in the Netherlands. These organisations have different incentives and demands than academic hydrologists. For example: deviating from current industry standards is often considered a risk: a meteorological service would rather invest in a proven technology for an operational service than invest in a new technology that still suffers from teething problems. Especially in governmental organisations, choosing innovative novel methods over proven methods is considered both financially and politically risky and generally avoided. This leads to a very conservative market for hydrological sensing equipment.

Unsurprisingly, new breakthroughs in hydrological observations often stem from developments outside of hydrology. For example, distributed temperature sensing (DTS) using fibre-optic technology was developed in the oil and gas industry before it was introduced in hydrology by Selker *et al.* [10]. For producers of DTS systems, the potential market in the oil and gas industry was apparent from the start, justifying the investment needed to develop the first systems. This is not to say that hydrologists cannot influence the producers of sensing equipment. Close collaboration between hydrologists and producers of DTS system in workshops led to communication between the parties and ultimately to producers that pushed

[3]the following paragraph is based on my own observations, including numerous discussions with hydrologists prof. dr. ir. Nick van de Giesen, prof. dr. John Selker, dr. ir. Steven Weijs and economist Michel Frijns. Since the paragraph is not based on actual economic research, it should be read as a hypothesis: my view on how the world works

the developed novel systems with specifications specifically suited for hydrological research.

In chapter 1 I argued that low cost sensors, open hardware and open data have the potential to help further hydrological understanding. Currently a lot of MacGyvering is needed to connect everything together, as was illustrated in figure 6.1. Economically, the market for innovative hydrological sensing equipment is formed by a small group of academics and might be limited, but the market for low-cost sensors and open source hardware is potentially a lot bigger. A problem is that not all hydrologists are, nor want to be, MacGyvers. Most hydrologists belong to the "need the measurement data as input to answer their research question" group. For them it has to be a lot easier than it currently is to integrate low-cost sensors with open source hardware and open data.

In the design of most sensors, significant amounts of work are spent on designing and debugging the communication between the sensor and loggers or communication devices, including internet servers. Most hydrologists are not (also) trained in (micro-)electronics and figuring out how to connect different sensors to a single logger or communication device is currently something that every MacGyvering hydrologists has to learn for himself. No standard exists that allows for easy plug and play connection of sensors, loggers, communication devices and internet-servers within hydrology. Such a standard would make it a lot easier for hydrologists who "just want the data" to use the work of hydrologists who have built prototype devices. Deciding upon such a standard would require input from the hydrological community and advice from electrical and software engineers. An example standard that I would support would be to use I^2C [11] with an agreed-upon data format between sensors and loggers or communication devices, and use MQTT [12] to upload data from the communication devices to the internet. This setup was developed and used during a workshop for the TAHMO project [13], successfully connecting 21 sensors from different designers to a single central communication unit and through to the internet [14]. Not surprisingly, both I^2C and MQTT are supported on the Arduino.

Connecting different data sources is currently often just as problematic as connecting a sensor to the internet. Different file formats in data and different standards to approach online data make it hard to combine data from different sources. For open data to be truly valuable to hydrologists standards are needed. It would be ideal if the selection of data needed for the work presented in chapter 5 could have been written in a small piece of code that in one line selects an entire catchment from the hydrosheds database, on the next line selects the population per municipality from the Eurostat, in a third line selects the discharge data from a currently non-existing repository, and finally in the fourth line imports the concentration of pharmaceuticals measurement results from a file. This would allow hydrologists to focus more on their area of expertise and less on ICT related issues. Luckily a few standards for geoscientific data like Network Common Data Form (NetCDF) [15] and WaterML [16] are currently emerging.

For low-cost sensors, open source hardware and open data to have a lasting impact in hydrology and bring about those advances in hydrological understanding, the following critical steps need to be taken:

- MacGyvering hydrologists need to document their work in such a way that other hydrologists, as well as interested producers of sensors or open source hardware, can reproduce their work efficiently. Academic articles are generally not the correct medium for those kinds of publications. The "experimental hydrology wiki" [17] is a good step in this direction although it currently focusses on commercially available measurement devices. A website that offers step-by-step instructions like instructables.com [18] is well suited for this. Since individual scientists have no incentive to publish these instructions, journal editors could play a major role by demanding that articles on novel measurement techniques are accompanied by step-by-step instructions on how to recreate the measurement device. The newly proposed "Measurements and Observations in the XXI century" (MOXXI) working group of the International Association of Hydrological Sciences (IAHS) aims to work together with the experimental hydrology wiki and provide a platform for these instructions.

- Producers of sensors and open source hardware need to provide plug and play functionality between their devices. Connecting a sensor to, for example, an Arduino-based logger or a Raspberry Pi-based communication device should be as easy as plugging in a USB device in an Apple Macintosh Computer. If producers can deliver this functionality at reasonable costs, they open up a big market of researchers that want to have the freedom to mix and match any combination of sensors, loggers and communication devices to fit their specific research without having to worry about the electronic and software issues of connecting everything together.

- Geoscientific data needs to be stored in standardised formats, whether online or on local files. Online data repositories need to be easily accessible, for example using simple Application Programming Interfaces (API's). By removing the difficulties in connecting different data sources, scientists of different disciplines can more easily share their data and work together. Hydrologists have no incentive to publish their data and/or use standardised formats. Here again, journal editors can play a role by demanding that all data on which presented conclusions are based is made publicly available. Some journals like PLOS ONE have already implemented a policy to this end [19].

If these steps are taken, it might seem that the MacGyvering hydrologists are no longer needed. I would argue that if these steps are taken, the MacGyvering hydrologists would move on to new projects and introduce yet undiscovered new fields into hydrology. Maybe the data gathered in large circular particle accelerators can be used to make statements on deviations in the gravitational field induced by changes in alpine snow cover. Maybe advances in laser technology will finally allow for the development of a handheld mass spectrometer to measure water quality instantly in the field. MacGyvering hydrologists will continue to provide a valuable role in the hydrological community.

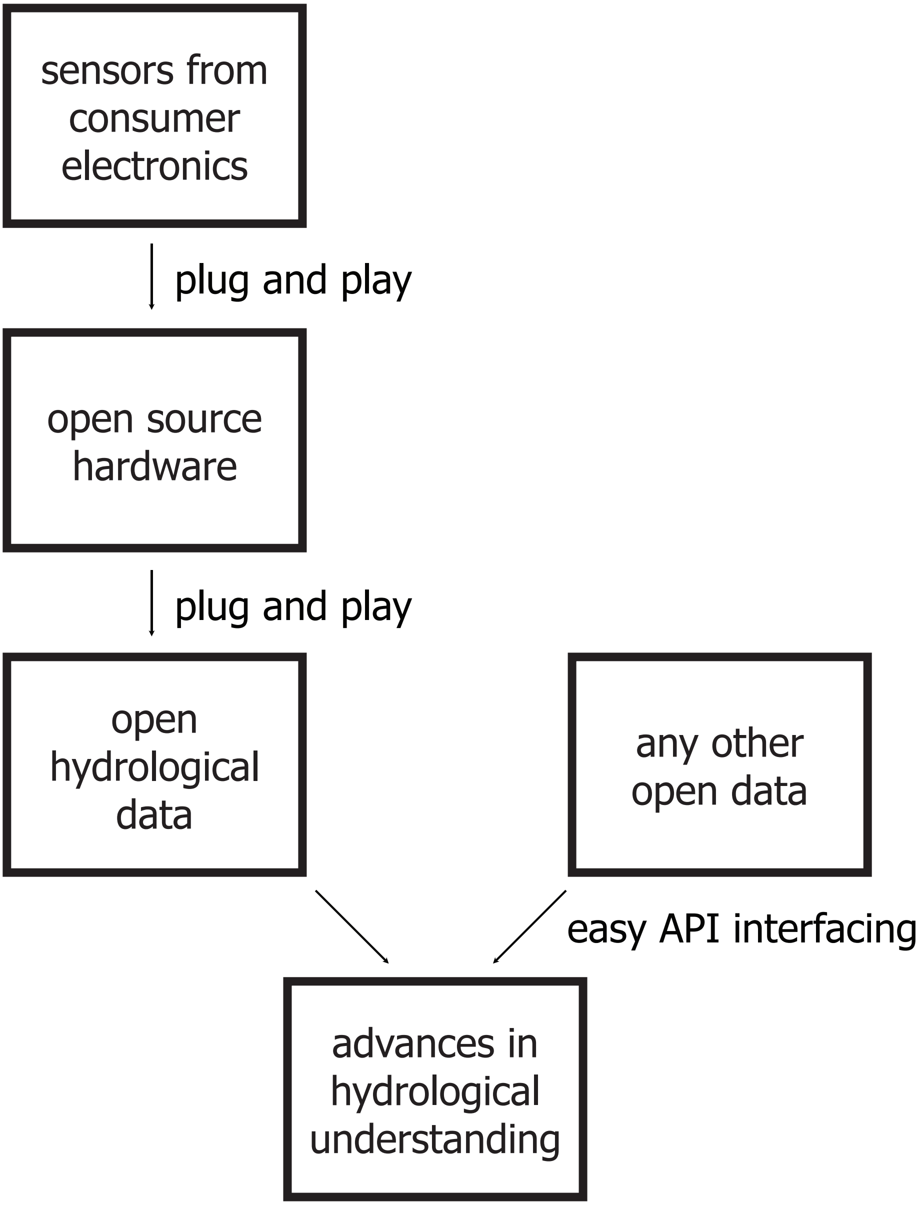

Figure 6.1: **Overview of how sensors from consumer electronics, through plug and play, should be connected to open source hardware.** Further plug and play connections allows the (online) publishing of the data collected in open repositories. Finally some easy interfacing to connect different data sources will ultimately lead to new advances in hydrological understanding.

6.5. Perspective

If the above challenges can be overcome, the opportunities of low-cost sensors, open source hardware and freely available datasources give hydrologists the tools to deal with the problems associated with the tragedy of location [4]. However, this will not mean that the tragedy of location will be overcome, just that the boundaries will be pushed back. Before satellite data became widely available, the tragedy was that a single model for a catchment did not account for the heterogeneity within the catchment. With satellite data, catchments can be divided into pixels, so now the focus is on sub-pixel heterogeneity. This points out that sensors becoming cheaper and more data becoming available are not "revolutions" of the last few years, but are constant processes that seem to have accelerated in the last few years[5]. The example with which I started this thesis, the astronomical spyglass of Galileo, was in Galileo's time a very expensive piece of equipment accessible only for very wealthy individuals. With mass production, the price of spyglasses, or binoculars and telescopes as we now call them, came down significantly to the point where it was standard equipment for any geo-scientist going on fieldwork in the 19th century, then called "expedition" or "adventure". Laser, a technique not seen outside of laboratories before 1970, is now incorporated in the toy gun on my key-chain and occasionally attached to sharks [20]. The current situation, in which low-cost sensors, open source hardware and freely available data help to further hydrological understanding, is not unique, but it is one in an ever-continuing list of technological changes.

6

The research that is presented in this thesis fits that tradition of ever-continuing technological change. What sets the research presented in this thesis apart is the focus on developments outside of hydrology for the benefit of hydrology. In chapter 2 it was shown that the advent of motion-sensing technology in game consoles proved useful for measuring water levels. In chapter 3 we used an off-the-shelf accelerometer that is advertised for roller coaster comparisons [21] to measure rainfall. The price reduction in piezo elements over the last decade facilitated the development of the acoustic disdrometer presented in chapter 4. And finally, by looking at a demographic data source, in this case population statistics from Eurostat, insight into the dominant factors causing pollution of the Rhine with pharmaceuticals was presented in chapter 5. I urge fellow scientists, and hydrologists in particular, to keep looking outside of their own field, to other fields of science. But I also urge scientists to look to general media, to spot new social developments, new developments in technology, or newly available datasources. Looking outside of their field will help scientists to realise new breakthroughs in their own fields.

[4] most hydrologists would argue that the tragedy of location is exactly what makes it fun to work in hydrology

[5] this, again, would require proper historical and economical research, the results of which I would be very interested in

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Summary

Advances in scientific understanding follow a cyclic pattern where new observational techniques lead to novel theoretical insight. From novel theories, in turn, hypotheses are derived that cannot be tested using current observations and thus create a demand for even newer observational techniques. Hydrology has recently experienced a period of great advances in theoretical understanding with hydrological models gaining considerably in complexity. Currently, the state of the hydrological science is at a point where further increases in complexity of hydrological models can no longer be supported by available data. The information content of currently used data is too low to uniquely identify the numerous parameters in hydrological models. Therefore new, and above all, different observational methods are needed to unlock thus far hidden hydrological data.

In this thesis it is argued that three developments can be greatly beneficial to help hydrologists unlock new data:

- The occurrence of sensors in nearly every (consumer) device and the associated drop in the cost of those sensors
- The rise of the "open source hardware" movement, which promotes sharing hardware designs.
- The online sharing of research results and large data sets

To be able to use these developments successfully in hydrology, pragmatic researchers are needed. Scientists whom, using a "MacGyver" attitude towards science, can show proof-of-concept results of how these new developments can best benefit hydrology. In this thesis, four such proof of concepts are presented, summarised below.

Using the Wiimote as a sensor in water research

An example of how consumer electronics can be used for hydrology is given in chapter 2. The $40 "Wiimote" (an input device belonging with the Nintendo® Wii™game system) is a device that contains three accelerometers and an infrared camera with built-in source tracking. It communicates by Bluetooth®. Because of the efforts of the hacking community it is easy to let the Wiimote communicate with a standard personal computer. Using a floating evaporation pan as an example, it is shown that the Wiimote, although it may have potential drawbacks when used in field campaigns, is a good addition to the hydrologist's bag of tools. This first proof-of-concept work can inspire other scientists to consider using consumer electronics based sensors in their work.

A resonating rainfall and evaporation recorder

In chapter 3 a novel method of measuring rainfall and evaporation is presented. The device is basically a collection vessel (bucket) placed on top of a slender rod that is securely fixed at its base. As the vessel is deflected, either by manual perturbation or ambient forcing (for example, wind), its oscillatory response is measured by a miniature accelerometer. This response can be modeled as a damped mass-spring system. As the mass of water within the collection vessel changes, through either the addition of precipitation or by evaporative loss, the resonant frequency experiences an inverse shift. This shift can be measured and used to estimate the change in mass of water. This concept was tested by creating a simple prototype which was used in field conditions for a period of one month. The instrument was able to detect changes in mass due to precipitation with an accuracy of approximately 1mm.

Design, calibration and field evaluation of an acoustic disdrometer designed for distributed measurements

Another novel raingauge is presented in chapter 4. The "Delft-disdrometer" is an acoustic disdrometer: a raingauge that measures the size of individual raindrops by recording the sound that impacting raindrops make when they hit the sensor. The Delft-disdrometer is specifically designed to be low maintenance, thus allowing the installation of dense networks without incurring large upkeep costs. In a field evaluation, the Delft-disdrometer was compared to existing rain gauges and disdrometers. Results show that the Delft-disdrometer is capable of measuring precipitation intensities with comparable uncertainties as those of the industry standard Thies LPM and Ott Parsivel. For drops bigger than 1.75mm, the Delft-disdrometer measured drop size distributions similar to the drop size distributions measured by the Thies LPM and Ott Parsivel. The inability of the Delft-disdrometers to measure drops smaller than 1mm is an issue that should be addressed in future iterations of the design. The experiments with this first prototype show that it is feasible to measure precipitation intensities with the low maintenance Delft-disdrometer.

Medicinal Footprint of the population of the Rhine basin

The final example is given in chapter 5. By using freely available demographic data the relation between pharmaceutical residues along the river Rhine and the demographic characteristics of the upstream population was studied. A sampling campaign was performed in which water samples from the Rhine taken at 42 locations. Measurements were compared to a two parameter model with regional demographic data as main input. For 12 out of the 21 studied pharmaceuticals, a significant dominant demographic group could be identified. For 3 out of these 12 pharmaceuticals male elderly were the most contributing demographic group. A

Monte Carlo analysis showed a high level of significance for the results of this study ($p < 0.01$). By combining environmental water quality data and demographic data, better insight was gained in the interplay between humans and their environment, showing the medicinal footprint of the population of the Rhine basin.

Conclusions and look into the future

In the ongoing cycle between new observational methods and new theories, hydrology is due for a round of new observational methods. Because of the complexity of current day hydrological models, richer datasets are needed to test the predictions (hypotheses) that those complex models make. More spatially distributed measurements of well known hydrological variables, as well as novel measurements of previously thought unmeasurable, or unimportant, variables are needed. Sensors designed for use in consumer electronics are often cheaper than sensors specifically designed for scientific research, because of the economies of scale achieved in the production of consumer electronics. Using these sensors normally required both hydrological insight as well as skills with (micro)electronics. However, the advent of the open hardware movement, spearheaded by the Arduino platform, has significantly lowered the threshold for hydrologist to build their own sensors. And finally: not all new data need to come from sensors: by looking at data sources outside of hydrology, such as the demographic data used in chapter 5, additional hydrological insight can be obtained. However, before the benefits of low cost sensors, open source hardware and open data can be reaped by all hydrologists three steps need to be taken. Work on innovative measurement techniques should be accompanied by step by step instructions on how to recreate the measurement device. Producers of sensors and open source hardware need to provide plug and play functionality. Geoscientific data needs to be stored in standardised formats, whether online or on local files. The work presented in this thesis shows examples of how lower cost sensors based on consumer electronics, open source hardware and open data sources from outside of hydrology can help hydrology move into the next phase of its ever continuing cycle.

Samenvatting

Het voortschrijden der wetenschap is te vergelijken met de wandelpas van het cortège. De rechtervoet die de theoretische kant van de wetenschap voorstelt kan pas een stap zetten, wanneer de linkervoet, die de metingen en observaties voorstellen, een stap heeft gezet en vice versa. De hydrologische wetenschap hinkelt al een tijdje op zijn rechtervoet: de afgelopen periode kende een groot aantal doorbraken en nieuwe inzichten op theoretisch vlak in hydrologie. Hydrologische modellen zijn zo complex geworden dat de data die gebruikt wordt om de modellen te kalibreren niet genoeg "informatie" bevatten om de parameters van de modellen uniek te kunnen schatten. Daarom hebben hydrologen nieuwe, en vooral andere, meetgegevens nodig.

In dit proefschrift wordt beargumenteerd dat er drie ontwikklingen gaande zijn die hydrologen kunnen helpen met het verkrijgen van nieuwe meetgegevens.

- Het verschijnen van sensoren in nagenoeg alle (consumenten) elektronica, en de daarbij behorende daling in de kosten van deze sensoren
- Het opkomen van de "open source hardware" beweging, die aanmoedigt om blauwdrukken van hardware kosteloos te delen
- Het online delen van onderzoeksresultaten, publicaties en gegevens

Om deze ontwikkelingen tot nut van de hydrologische wetenschap te maken zijn pragmatische onderzoekers nodig. Onderzoekers die, met een "MacGyver" houding, door middel van zogenaamde "proof-of-concepts" kunnen laten zien hoe de bovengenoemde ontwikkelingen hydrologie verder kunnen helpen. In hoofdstukken 2 tot en met 5 van dit proefschrift worden vier van deze "proof-of-concepts" gepresenteerd. Hieronder volgt een korte samenvatting van deze vier hoofdstukken, gevolgd door algemene conclusies.

De Wiimote gebruikt als sensor hydrologie

In hoofdstuk 2 wordt een voorbeeld gegeven van hoe consumenten elektronica in de hydrologie gebruikt kan worden. De "Wiimote" (een $40 kostende controller behorende bij de Nintendo® Wii™spelcomputer) bevat drie acceleratiemeters en een infra-rood camera met ingebouwd bron-volg-algorithme. De "Wiimote" communiceert met de Wii via Bluetooth®. Gebruik makend van handleidingen die hackers online publiceren is het relatief makkelijk om de Wiimote met een standaard PC te laten communiceren. Een drijvende verdampingspan is als voorbeeld gebruikt om te laten zien dat de Wiimote, hoewel hij potentiele nadelen bij gebruik in het veld heeft, zeker een goede toevoeging is aan de verzameling meetapparatuur van hydrologen. Hopelijk inspireert dit eerste "proof-of-concept" werk andere wetenschappers om consumenten elektronica als meetapparatuur te gaan gebruiken.

Een trillende regenval- en verdampingsmeter.

Een nieuwe methode om regenval en verdamping te meten wordt uit de doeken gedaan in hoofdstuk 3. Het idee is in feite niet veel meer dan een emmer op een stok te plaatsen. Aan de stok zit een acceleratiemeter die de trillingen van het apparaat meet. Deze trillingen worden, onder andere, veroorzaakt door de wind. De reactie van het apparaat op de wind kan gemodelleerd worden als een gedempt massa-veer systeem. Wanneer de massa van het water in de emmer veranderd, door regenval of verdamping, zal de resonantie frequentie van het apparaat wijzigen. Deze wijziging kan gemeten worden en dus worden gebruikt om de massa verandering uit te rekenen. Dit idee is getoetst door een prototype te maken en deze een maand lang buiten te testen. Dit prototype kon massaveranderingen veroorzaakt door regen meten met een nauwkeurigheid van circa $1\mathrm{mm}$.

Design, kalibratie en veld test van een akoestische disdrometer ontwikkeld voor ruimtelijk gespreide metingen

Een andere nieuwe regenmeter wordt in hoofdstuk 4 gepresenteerd. De "Delft-disdrometer" is een akoestische disdrometer: een regenmeter die de grote van regendruppels meet door te luisteren naar het geluid dat de impact van druppels maakt als ze de sensor raken. De "Delft-disdrometer" is ontworpen om onderhoudsarm te zijn, waardoor grote netwerken van deze regenmeter geinstalleerd kunnen worden zonder hoge onderhoudskosten. In een veld test is de "Delft-disdrometer" vergeleken met andere regenmeters en disdrometers. De resultaten van deze veldtest tonen aan dat de Delft-disdrometer in staat is om de intensiteit van regen te meten met vergelijkbare onzekerheden als de geldende standaarden in de industrie: de Thies LPM en de Ott Parsivel. Voor druppels groter dan $1.75\mathrm{mm}$ werd door de Delft-disdrometer, de Thies LPM en de Ott Parsivel identieke verdelingen van druppel-grotes gemeten. Dat de Delft-disdrometer niet in staat is om druppels kleiner dan $1\mathrm{mm}$ waar te nemen is een probleem dat in nieuwere versies opgelost dient te worden. De experimenten met dit eerste prototype tonen aan dat het reëel is om de intensiteit van regen te meten met de onderhoudsarme Delft-disdrometer.

Voetafdruk van het medicijngebruik van de bevolking van het stroomgebied van de Rijn

Het laatste voorbeeld wordt gegeven in hoofdstuk 5. Door gebruik te maken van gratis beschikbare demografische gegevens kan de relatie tussen medicijnresten aangetroffen in de Rijn en de demografische eigenschappen van de bevolking van het stroomgebied worden bestudeerd. Op 42 locaties langs de Rijn zijn water monsters genomen die zijn geanalyseerd op medicijnresten. De gevonden meetwaarden zijn vergeleken met de voorspelling van een simpel model met slechts 2 parameters. Het model heeft regionale demografische gegevens als belangrijkste input. Voor 12 van de onderzochte 21 medicijnen kon een dominante demografische groep worden aangewezen. Voor 3 van deze 12 medicijnen bleken "oudere mannen" het meest bij te dragen aan de gemeten medicijnresten. De resultaten van dit onderzoek hebben een hoge mate van significantie ($p < 0.01$), wat is aangetoond met een Monte Carlo analyse. Door waterkwaliteitgegevens te combineren met demografische gegevens heeft deze studie een beter inzicht opgeleverd over de wisselwerking tussen mensen en hun leefomgeving. Dit onderzoek geeft inzicht in de medicijn-voetafdruk van de bevolking van het stroomgebied van de Rijn.

Conclusies en een blik in de toekomst

In de wandelpas der wetenschap is het tijd dat de hydrologische wetenschap een stap zet met de linkervoet der observaties. Vanwege de complexiteit van hedendaagse hydrologische modellen zijn er rijkere meetgegevens nodig. Deze meetgegevens zijn nodig om de voorspellingen (hypotheses) die deze complexe modellen maken te toetsen. Wat nodig is zijn meer ruimtelijk verspreide metingen van bekende hydrologische variabelen. Maar ook nieuwe metingen van variabelen die tot noch toe onmeetbaar, of onbelangrijk, zijn bestempeld zullen onmisbaar blijken. Sensoren die ontwikkeld zijn voor gebruik in consumenten elektronica zijn over het algemeen goedkoper dan soortgelijke sensoren ontwikkeld voor wetenschappelijk gebruik. Dit komt, onder andere, door de schaalvoordelen die gehaald kunnen worden bij massa productie. Het gebruik van sensoren uit consumenten elektronica vergde tot voor kort zowel kennis van het vakgebied waarin de sensoren toegepast gaan worden (hydrologie) en van (micro)elektronica. Echter: sinds de opkomst van de open source hardware beweging, met het Arduino platform als vaandeldrager, is steeds minder kennis van (micro)elektronica nodig om zelf een, op consumenten elektronica gebaseerde, sensor te bouwen. En tot slot: niet alle nieuwe gegevens hoeven van sensoren te komen. Door te (blijven) kijken naar gegevens die buiten hydrologie verzameld worden, zoals de demografische gegevens die in hoofdstuk 5 gebruikt worden, kan meer inzicht in de wisselwerking van hydrologie met andere disciplines verkregen worden. Echter: voordat goedkope sensoren, open source hardware en gegevens uit andere velden dan hydrologie door alle hydrologen nuttig gebruikt kan worden moeten er drie dingen veranderen. Wetenschappelijke tijdschriften moeten eisen dat bij artikelen over nieuwe meetapparatuur een stap bij stap handleiding gepubliceerd wordt waarin wordt uitgelegd hoe de nieuwe meetapparatuur na te bouwen. Producenten van sensoren en open source hardware moeten ervoor zorgen dat hun apparatuur op een "plug and play" manier aan te sluiten is. Aardwetenschappelijke gegevens moeten volgens standaard methode opgeslagen worden, of dat nu online, of lokaal is. Het werk dat in dit proefschrift gepresenteerd wordt geeft voorbeelden van hoe met sensoren uit consumenten elektronica, met hulp van de open source hardware beweging en met gegevens uit andere velden dan hydrologie, de hydrologische wetenschap de volgende stap (met links) kan zetten.

Dankwoord

So I find that teaching and the students keep life going, and I would never accept any position in which somebody has invented a happy situation for me where I don't have to teach. Never.

Richard Feynman

Bovenstaande quote van Feynman is niet voor niets gekozen: lesgeven en contact met studenten "keeps life going". Als de studenten die ik begeleid heb gedurende mijn promoveren half zo veel geleerd hebben van mij, als ik van hen, dan heeft Nederland er een stel heel slimme ingenieurs bij. Dus bedankt Coen, Jos, Yho Mee, Bart, Dirk, Wouter, Nilanjana, Arjan, Inge, Miranda, Rick, Boy Santhos, Ravi, Bouke en Nadine. Ook alle studenten die de afgelopen jaren "meten aan water" of het veldwerk in Luxemburg hebben gevolgd: jullie energie was aanstekelijk. En natuurlijk: Stijn: van student, via collega tot mede-ondernemer: het was een super avontuur dat nog niet klaar is!

Het begeleiden van zo veel studenten gedurende een promotie is misschien ongebruikelijk, maar werd mogelijk gemaakt door de ruimte die ik kreeg van mijn promotor. Nick, heel erg bedankt voor alles: voor de wijze lessen en de praktische lessen (en ja, dangling modifiers zijn lui), voor de steun voor de kwaliteit van mijn werk, ook als reviewers die kwaliteit niet zagen, maar bovenal voor het vertrouwen om me mijn eigen gang te laten gaan, om bijvoorbeeld mijn eigen sessie op congressen op te zetten. Of het vertrouwen om me als aanjager naar voren te duwen in projecten zoals TAHMO. Je hebt me de water-wereld ingetrokken en ervoor gezorgd dat ik me er thuis voel.

I would like to thank all the members of my committee, your comments have greatly improved the quality of this thesis. Special thanks go to prof. John Selker. My two stays at Oregon State University were wonderful, not only for the excellent academic environment in your group, but even more so because of the hospitality that you and your family showed me: many thanks to you, Laurie, Julia and Jordan. To prof. John Cohn: your presentations are legendary and our conversation always inspiring.

Also a big thanks to the co-conveners of the MacGyver sessions: Theresa Blume, Wim Luxemburg, John Selker (again), Steven Weijs and Andy Wickert. The sessions were always tons of fun, stood out in the otherwise boring poster-hal and brought people from all of hydrology together. Im proud of those sessions and could not have organised them without you.

Mijn collega's van water management en hydrologie zorgen met z'n allen voor een erg goede sfeer. Van water-archeoloog, via water-rechtskundige tot water-wiskundige zijn jullie de meest diverse groep wetenschappers die ik ooit in één groep ben tegengekomen. Met name wil ik in noemen: Maurits, voor het mij binnenhalen als rare natuurkundige. Olivier, voor alle civiele kennis, ongevraagde pragmatische levenstips en liften naar huis. Luciano, Gerrit en Steven, voor de fundamentele discussies over signalen, statistiek en informatie. Susan, for continually asking what the point is. To all my international colleagues: your presence enriches our group, both academically and culturally. Your presence has, for sure, enriched my life. De groep is niet compleet zonder de grote groep aan student-assistenten die ook mij en mijn werk ondersteund hebben: Jop, Job, Laurènne, Emma, Wouter, en ik vergeet vast nog namen. En natuurlijk dank voor de steun en toeverlaat in de strijd met de academische bureaucratie: Betty, Luz en Petra!

Ook buiten de watermanagement groep is er een aantal TU-ers die ik wil bedanken. Kees van Beek (en Martin en Paul), voor het als een oude gilde-meester de geheimen van het vak micro-electronica overdragen. Roy Meijer voor alle communicatie hulp en ruggespraak. Rob Speekenbrink (en team), voor TEDxDelft. Tanja, voor een super strak georganiseerde TAHMO competitie. Niet werk-gerelateerd, maar net zo belangrijk: mijn "we moeten NU koffie / lunch / bijpraten" vrienden: José, Jasper, Felienne, en Suzanne.

Tijdens mijn promotie ben ik met collega's twee bedrijven gestart. Het is erg leuk om ook deze kant van de kennismarkt te ervaren en ik zou dit avontuur niet graag met andere aangegaan zijn dan met jullie: Stijn, Olivier, Jeroen en Nick.

In 2013 heb ik, naast zeer waardevolle adviezen en leuke avonden, van Kathelijne, Wiljan, Rick, Sander, Martijn en vooral Kai een flinke, en broodnodige, schop onder mijn kont gekregen om mijn proefschrift af te gaan maken, waarvoor dank.

Het klinkt misschien ongepast, maar hier moeten ook wat Haarlemsche locaties genoemd worden. Belangrijke stukken van dit proefschrift, en nagenoeg alle stellingen, zijn namelijk geformuleerd terwijl ik door de stad slenterde met een Garrone-ijsje, achterin café Briljant, of aan de stamtafel van de Gooth, waar elke donderdag de week even doorgenomen moet worden. Michel, Jorrit, Ruben: dank voor het wekelijks aanhoren van mijn verhalen, voor het delen van die van jullie en voor alle onzinnige film-qoutes, game-reviews en semantische-meta-filosofisch-economische-discussies. Rutger: thanks for being a friend. Maarten, Joris, Tim, Patrick, Tom: dank voor de vele ontspannende avonden D&D: dat er nog vele mogen komen! Maar wel 3.5 dan, 4 is een boardgame.

Marijn en Beau: jullie zijn gezellige schoonouders en daarnaast bleek het uitermate nuttig om een een apotheker en chemicus in de buurt te hebben toen ik onderzoek naar watervervuiling door medicijnresten ging doen (hoofdstuk 5).

Een eigenzinnig proefschrift schrijven had nooit gelukt zonder eigenzinnige opvoeding. Pa en ma: jullie hebben me eerlijk (er is geen prijs voor je best doen) en bovenal zelfstandig (zelf doen!) opgevoed. Je moet eruit halen wat erin zit en vooral onbekende nieuwe dingen blijven proberen (of dat nou tartaar of arduino is). Zonder deze kwaliteiten zou dit proefschrift niet tot stand zijn gekomen. Peter: dat ik bij mijn broertje aan kan kloppen voor adviezen hoe een bedrijf op te zetten, maar vooral, hoe de "echte mensen wereld" werkt, heeft me de afgelopen jaren meerdere malen voor cruciale fouten behoed.

Mensen die mijn werkkamer zien, of mij een dag door Delft volgen, krijgen mogelijk de indruk van een chaotische, ongecontroleerde storm. Maar elke storm heeft een oog: een centrum van kalmte waar de drukte omheen raast. Ineke: jij bent het oog van mijn storm. Bij jou en Luuk ben ik thuis en rustig. Laat het bovendien gezegd zijn dat ik meer over statistische methode van jou geleerd heb, dan in 5 jaar natuurkunde opleiding. En Luuk: ooit leg ik je dit boekje uit, maak je borst maar nat. Maar voor nu: lekker overal om blijven lachen. Het is aanstekelijk en dat je er bent maakt de wereld een stuk leuker.

Rolf Hut
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2008–2013	PhD in Water Resources Management Delft University of Technology *Thesis:* New Observational Tools and DataSources for Hydrology *promotor:* prof. dr. ir. N. C. van de Giesen

Work

2005-2007	Statistics Netherlands (Centraal Bureau voor de Statistiek, CBS) statistical researcher
2008-2010	Statistics Netherlands (Centraal Bureau voor de Statistiek, CBS) senior statistical researcher
2008-2013	Delft University of Technology (PhD) researcher

Other

2009-2013	convener of the "MacGyver" sessions on "new observational tools and unintended use of measurement equipment" at the AGU fall meeting and the EGU General Assembly
2012-2013	Student representative on the board of the AGU Hydrology section

List of Publications

10. **R.W. Hut**, N.C. van de Giesen and C.J. Houtman, *Medicinal Footprint of the population of the Rhine basin*, Under review for publication in Environmental Review Letters.

9. **R.W. Hut**, S.A.P. de Jong, N.C. van de Giesen, H. Leijnse and M. de Haij, *Design, calibration and field evaluation of an acoustic disdrometer designed for distributed measurements*, in preperation for submission to Sensors.

8. M Hrachowitz, H H G Savenije, G Bloschl, JJ McDonnell, M Sivapalan, J W Pomeroy, B Arheimer, T Blume, M P Clark, U Ehret, F Fenicia, J Freer, A Gelfan, Hoshin Gupta, D A Hughes, **R W Hut**, A Montanari, S Pande, D Tetzlaff, P Troch, S Uhlenbrook, T Wagener, H Winsemius, R A Woods, E Zehe, and C Cudennec, *A decade of Predictions in Ungauged Basins (PUB) - a review*, Hydrological Sciences Journal, (2013).

7. Stewart, R. D., **Hut, R.**, Rupp, D. E., Gupta, H. & Selker, J. S., *A resonating rainfall and evaporation recorder*, Water Resour. Res 48, W08601, (2012).

6. **Hut, R. W**., Weijs, S. V. and Luxemburg, W. M. J., *Using the Wiimote as a sensor in water research*, Water Resour. Res **46**, W12601, (2010).

5. PJ van Overloop, IJ Miltenburg, X Bombois, AJ Clemmens, RJ Strand, NC van de Giesen, and **R Hut**, *Identification of resonance waves in open water channels*, Control Engineering Practice, **18**, 863872, (2010).

4. Ertsen, M. and **Hut, R.**, *Two waterfalls do not hear each other. Sand-storage dams, science and sustainable development in Kenya*, Physics and Chemistry of the Earth, Parts A/B/C 34, 1422, (2009).

3. RO Quilis, M Hoogmoed, M Ertsen, JW Foppen, **R Hut**, and A Vries, *Measuring and modeling hydrological processes of sand-storage dams on different spatial scales*, Physics and Chemistry of the Earth, Parts A/B/C 34, 289298, (2009).

2. **R Hut**, M Ertsen, N Joeman, N Vergeer, H Winsemius, and N Van de Giesen, *Effects of sand storage dams on groundwater levels with examples from Kenya*, Physics and Chemistry of the Earth, Parts A/B/C 33, 5666, (2008).

1. **Hut, R.**, Boone, M. & Gisolf, *Cochlear modeling as time-frequency analysis tool*, Acta Acustica united with Acustica 92, 629636 (2006).

When I approached Rolf Hut to be a speaker for the first TEDxDelft in 2010, Rolf was already known as a guy that approached seemingly difficult problems in an unconventional way. We wanted to challenge him to improve his performance but he turned the challenge straight back at us: “I want you to make it rain inside the TU Delft Aula Congress Centre”...... and we did. An early version of the Delft-disdrometer listened to the sound of raindrops falling down producing a beautiful consumer-electronic beep proving the rain gauge did exactly what it should do.

Rolf’s catching enthusiasm, energy and persuasion made his performance at TEDxDelft memorable and he established his name as the tinkering TU Delft scientist with the general public. Rolf remains to be involved in TEDxDelft as the spiritual father of a scrapheap challenge in 2012 and a race on tram rails in 2013. And we love it!

In this thesis, Rolf presents the research that first earned him his reputation of tinkering TU Delft scientist. Rolf presents examples of hacked consumer electronics, novel sensors and smart data hacks that illustrate his vision that sensors from consumer electronics, open source hardware and open access to data sources will bring about the next breakthrough in hydrological understanding.

Rob Speekenbrink, founder TEDxDelft.

TU Delft Delft University of Technology

ISBN 978-94-6186-212-9