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# Information Needs for Water Resource and Risk Management

## *Hydro-Meteorological Data Value and Non-Traditional Information*

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**Abstract**

Girons Lopez, M. 2016. Information Needs for Water Resource and Risk Management. Hydro-Meteorological Data Value and Non-Traditional Information. (Informationsbehov inom vattenförvaltning och riskhantering. Värdet av hårda hydro-meteorologiska data och mjuk information). *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1419. 74 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-9679-1.

Data availability is extremely important for water management. Without data it would not be possible to know how much water is available or how often extreme events are likely to occur. The usually available hydro-meteorological data often have a limited representativeness and are affected by errors and uncertainties. Additionally, their collection is resource-intensive and, thus, many areas of the world are severely under-monitored. Other areas are seeing an unprecedented – yet local – wealth of data in the last decades. Additionally, the spread of new technologies together with the integration of different approaches to water management science and practice have uncovered a large amount of soft information that can potentially complement and expand the possibilities of water management.

This thesis presents a series of studies that address data opportunities for water management. Firstly, the hydro-meteorological data needs for correctly estimating key processes for water resource management such as precipitation and discharge were evaluated. Secondly, the use of non-traditional sources of information such as social media and human behaviour to improve the efficiency of flood mitigation actions were explored. The results obtained provide guidelines for determining basic hydro-meteorological data needs. For instance, an upper density of 24 rain gauges per 1000 km2 for spatial precipitation estimation beyond which improvements are negligible was found. Additionally, a larger relative value of discharge data respect to precipitation data for calibrating hydrological models was observed. Regarding non-traditional sources of information, social memory of past flooding events was found to be a relevant factor determining the efficiency of flood early warning systems and therefore their damage mitigation potential. Finally, a new methodology to use social media data for probabilistic estimates of flood extent was put forward and shown to achieve results comparable to traditional approaches.

This thesis significantly contributes to integrated water management by improving the understanding of data needs and opportunities of new sources of information thus making water management more efficient and useful for society.

*Keywords:* water management, data resolution, non-traditional data, floods, modelling, social memory, precipitation, runoff, social media, interpolation, data value

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All vattenförvaltning kräver tillgång till data. Data behövs för att kunna fastställa t.ex. hur mycket vatten som finns och sannolikheten för stora översvämningar. De hårda hydro-meteorologiska data som normalt är tillgängliga har inte sällan en begränsad representativitet och påverkas av fel och osäkerheter. Dessutom är datainsamling nästan alltid resurskrävande och därför finns hårda data i begränsad utsträckning, eller inte alls, i stora delar av världen. Samtidigt har man under senaste decennierna fått tillgång till en oöverträffad – men lokal – mängd data i vissa områden. Spridningen av ny teknik har, tillsammans med integreringen av olika vetenskapliga metoder inom vattenförvaltning och praktik, påvisat värdet av mjuk information som potentiellt kan komplettera hårda data och förbättra möjligheterna till en god vattenförvaltning.

Denna avhandling presenterar studier som belyser vilka möjligheter vattenförvaltningen har vid olika tillgång på hårda data och mjuk information. Först utvärderades vilka krav som kan ställas på hydro-meteorologiska data för att korrekt kunna beskriva nyckelprocesser som nederbörd och vattenföring vid bestämning av vattenresurser. Därefter utforskades möjligheterna att förbättra översvämningsberäkningar med hjälp av mjuk information från sociala medier och rörande mänskligt beteende. Resultaten gav riktlinjer för att bestämma värdet av hydro-meteorologiska data. Till exempel visades att information om nederbördens rumsliga fördelning inte förbättras nämnvärt vid en mätartäthet över 24 regnmätare per 1000 km$^2$. Det relativa värdet av vattenföring visade sig också vara större än för nederbörd för att kalibrera hydrologiska modeller. Det visade sig att en befolknings minne av tidigare översvämningar påverkar effektiviteten hos tidiga varningssystem för översvämningar och deras möjlighet att begränsa skador. Slutligen har en ny metod föreslagits för att använda sociala medier för sannolikhetsberäkningar av översvämmade områden. Metoden visade sig leda till resultat som var jämförbara med traditionella metoder.

Avhandlingens huvudsakliga bidrag till en integrerad vattenförvaltning är att öka förståelsen för vilka data som krävs för olika förvaltningsmål och vilka möjligheter som finns att utnyttja mjuk information för att effektivisera vattenförvaltningen göra den mer användbar för samhället.

*Nyckelord*: avrinning, befolkningars minne, dataupplösning, datavärde, interpolering, mjuk information, modellering, nederbörd, sociala medier, vattenförvaltning, översvämning

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**Resum**

Girons Lopez, M. 2016. Necessitats d'informació per a la gestió de recursos i riscos hídrics: El valor de les dades hidrometeorològiques i la informació no tradicional. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1419. 74 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-9679-1.

La disponibilitat de dades és extremadament important per a la gestió de l'aigua. Sense dades no seria possible conèixer ni la quantitat d'aigua disponible ni la freqüència d'esdeveniments extrems. Les dades hidrometeorològiques normalment disponibles tenen una representativitat limitada, es veuen afectades per errors i incerteses i la seva recol·lecció requereix nombrosos recursos, cosa que produeix que moltes zones del món no estiguin adequadament monitoritzades. Així i tot, en les últimes dècades s'ha generat una quantitat de dades sense precedents però de manera localitzada. A més, la difusió de noves tecnologies, juntament amb la integració de diferents enfocaments han permès utilitzar una gran quantitat de dades "toves" per complementar i ampliar les possibilitats en la gestió de l'aigua.

Aquesta tesi presenta estudis que aborden algunes de les oportunitats ofertes per les dades per a millorar la gestió de l'aigua. En primer lloc es va avaluar la quantitat necessària de dades hidrometeorològiques per estimar correctament processos clau per a la gestió dels recursos hídrics. En segon lloc es va explorar l'ús de fonts no tradicionals d'informació per millorar l'eficiència de la mitigació d'inundacions. Per exemple, es va identificar una densitat màxima de 24 pluviòmetres per 1000 km$^2$ per estimar la distribució espacial de precipitació, per sobre de la qual les millores són insignificants. A més, es va observar que les dades d'escorrentia tenen un valor relatiu més gran per al calibratge de models hidrològics que les dades de precipitació. Pel que fa a la informació no tradicional, la memòria social d'anteriors inundacions es va identificar com un factor rellevant per a determinar l'eficiència dels sistemes d'alerta d'inundacions i, per tant, del seu potencial per mitigar danys. Finalment, es va proposar una nova metodologia per utilitzar informació provinent de xarxes socials per a realitzar estimacions probabilístiques d'extensió d'inundacions i es va demostrar el seu potencial per aconseguir resultats comparables als d'enfocaments tradicionals.

Aquesta tesi aporta avenços significatius per a la gestió integrada de l'aigua mitjançant la millora de la comprensió de les necessitats de dades i de les oportunitats presentades per noves fonts d'informació. D'aquesta manera contribueix a una gestió de l'aigua més eficient i útil per a la societat.

*Paraules clau*: gestió de l'aigua, resolució de les dades, dades no tradicionals, inundacions, modelització, memòria social, precipitació, escorrentia, xarxes socials, interpolació, valor de les dades

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**Resumen**

Girons Lopez, M. 2016. Necesidades de información para la gestión de recursos y riesgos hídricos: El valor de los datos hidrometeorológicos y la información no tradicional. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1419. 74 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-9679-1.

La disponibilidad de datos es sumamente importante para la gestión del agua. Sin datos no sería posible determinar la cantidad de agua disponible o la frecuencia de eventos extremos. Los datos hidrometeorológicos normalmente disponibles tienen una representatividad limitada, son afectados por errores e incertidumbres y su recolección requiere de abundantes recursos, lo cual causa que muchas zonas del mundo no estén adecuadamente monitorizadas. En contraste, en las últimas décadas se ha generado una cantidad de datos sin precedentes pero de manera localizada. Además, la difusión de nuevas tecnologías, conjuntamente con la integración de distintos enfoques, ha permitido usar una gran cantidad de datos "blandos" para complementar y ampliar las posibilidades en la gestión del agua.

Esta tesis presenta estudios que abordan las oportunidades ofrecidas por los datos para mejorar la gestión del agua. En primer lugar se evaluó la cantidad necesaria de datos hidrometeorológicos para estimar correctamente procesos clave para la gestión de recursos hídricos. En segundo lugar se exploró el uso de fuentes no tradicionales de información para mejorar la eficiencia de la mitigación de inundaciones. Por ejemplo, se identificó una densidad máxima de 24 pluviómetros por 1000 km$^2$ para estimar la distribución espacial de precipitación más allá de la cual las mejoras son insignificantes. Además se observó que los datos de escorrentía tienen un mayor valor relativo para la calibración de modelos hidrológicos que el de los datos de precipitación. Respecto a la información no tradicional, la memoria social de inundaciones pasadas fue identificada como un factor relevante para determinar la eficiencia de los sistemas de alerta de inundaciones y, por lo tanto, de su potencial para mitigar daños. Finalmente, se propuso una nueva metodología para usar información proveniente de redes sociales para realizar estimaciones probabilísticas de extensión de inundaciones y se demostró su potencial para conseguir resultados comparables a los de enfoques tradicionales.

Esta tesis aporta avances significativos para la gestión integral del agua a través de la mejora de la comprensión de las necesidades de datos y de las oportunidades presentadas por nuevas fuentes de información, contribuyendo a una gestión del agua más eficiente y útil para la sociedad.

*Palabras clave*: gestión del agua, resolución de los datos, datos no tradicionales, inundaciones, modelización, memoria social, precipitación, escorrentía, redes sociales, interpolación, valor de los datos

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*Per a la meva familia,*
*per donar-me sempre el seu suport.*

# List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I **Girons Lopez, M.**, Wennerström, H., Nordén, L.-Å., Seibert, J. (2015). Location and Density of Rain Gauges for the Estimation of Spatial Varying Precipitation. *Geografiska Annaler: Series A, Physical Geography, 97*, 167-179. doi: 10.1111/geoa.12094. © 2015 John Wiley & Sons, Ltd, reprinted with permission.

II **Girons Lopez, M.**, Seibert, J. (2016). Influence of Hydro-Meteorological Data Spatial Aggregation on Streamflow Modelling. *Journal of Hydrology, In Press, Accepted Manuscript.* doi: 10.1016/j.jhydrol.2016.08.026. © 2016 Elsevier, reprinted with permission.

III **Girons Lopez, M.**, Di Baldassarre, G., Seibert, J. (2016). Assessing the Impact of Social Memory on Flood Early Warning Systems. *Manuscript submitted on 20 June 2016 for publication in Water Resources Research.*

IV Rivera, S., **Girons Lopez, M.**, Seibert, J., Minsker, B. (2016). Probabilistic Flood Mapping Using Volunteered Geographical Information. *Manuscript.*

In **Paper I**, I contributed to defining the research question and study design, and performing the analysis. Additionally, I had the lead responsibility for writing the paper. In **Papers II** and **III**, I contributed to defining the research question and study design, performed the analysis, and had the lead responsibility for writing the papers. In **Paper IV**, I contributed to defining the scope and design of the study, performing the analysis, and writing the paper.

# Contents

# Abbreviations

| | |
|---|---|
| DEM | Digital Elevation Model |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| EEA | European Environment Agency |
| EM-DAT | Emergency Events Database |
| FEMA | US Federal Emergency Management Agency |
| FEWS | Flood Early Warning Systems |
| FOEN | Swiss Federal Office for the Environment |
| HADES | Hydrological Atlas of Switzerland |
| HBV | Hydrologiska Byråns Vattenbalansavdelning model |
| HEC-RAS | Hydrologic Engineering Center's River Analysis System |
| HRGA | Hydro Region Growing Algorithm |
| $I_{PCC}$ | Pearson Correlation Coefficient Index |
| $I_{RMSE}$ | Root Mean Square Error Index |
| IAHS | International Association of Hydrological Sciences |
| MeteoSwiss | Swiss Federal Office of Meteorology and Climatology |
| $PT_{sub}$ | Sub-catchment specific meteorological data aggregation |
| $PT_{Thur}$ | Catchment-wide meteorological data aggregation |
| PUB | Predictions in Ungauged Basins |
| $Q_{sub}$ | Sub-catchment specific streamflow data |
| $Q_{Thur}$ | Streamflow data exclusively at the catchment outlet |
| $R_{eff}$ | Nash-Sutcliffe model efficiency |
| $R^*_{eff}$ | Scaled model efficiency |
| Rad4Alp | Project for upgrading the MeteoSwiss radar network |
| RAPID | Routing Application for Parallel computatIon of Discharge |
| RdisaggH | Dataset of hourly fields of precipitation derived from a combination of radar and rain gauge measurements |
| RhiresD | Spatial analysis of daily precipitation covering the entire territory of Switzerland |
| SMHI | Swedish Meteorological and Hydrological Institute |
| SwissMetNet | Automatic monitoring network of MeteoSwiss |
| swisstopo | Swiss Federal Office of Topography |
| SYMAP | Synographic Mapping System |
| TabsD | Spatial analysis of daily mean temperature covering the entire territory of Switzerland |

| | |
|---|---|
| TmaxD | Spatial analysis of daily maximum temperature covering the entire territory of Switzerland |
| TminD | Spatial analysis of daily minimum temperature covering the entire territory of Switzerland |
| UNISDR | United Nations International Strategy for Disaster Reduction |
| VGI | volunteered geographical information |
| WMO | World Meteorological Organization |
| $\lambda$ | Social memory half-life |

# 1. Introduction

*In the beginning there was nothing,*
*which exploded.*

Terry Pratchett

Water is not evenly distributed on our planet. On the contrary, the contrasts between different areas and seasons can be quite remarkable. One of the most dramatic examples is perhaps the delta of the Okavango, in Botswana. Situated in a semi-arid environment, the mostly dry area comes to life with the seasonal floods, which can even double the size of the wetland-covered areas (McCarthy & Ellery, 1998). Even if it is generally not in such startling magnitudes, water availability is continuously shifting both in time and space everywhere on the planet. These shifts between the fluxes and reservoirs of water are governed by the water cycle. This cycle is dependent on different factors such as temperature changes at the Earth's surface and lower atmosphere, or variations in ocean water salinity (Durack et al., 2012). Additionally, a range of other factors such as topography and atmospheric circulation define the specific geographical distribution of water fluxes (Ambroise, 1995; Held & Soden, 2006). The combination of all these factors produce fluctuations in the water cycle of different magnitudes and wavelengths. Some of these fluctuations have positive effects for the development of societies, such as the Indian monsoon (Gupta et al., 2006) or the periodic floods of the river Nile (Bell, 1970), which renews the nutrients in the soil, thus favouring agriculture. Other fluctuations, however, are not so benign, such as the long drought spells that have been connected with the fading of large civilizations such as the Anasazi in present-day South-Western United States or the Classic Maya in Mesoamerica (Diamond, 2005; Lucero, 2002).

## 1.1 Water Management: Historical Perspective

Most societal functions depend on water: drinking water supply, food production, transportation, sanitation, etc. Nevertheless, we have little control on the distribution of water and only a limited understanding of its cycle. It is thus not surprising that the will to understand and master the water cycle and its fluctuations has been one of the main drivers of civilization (Jones, 2004). The rise of agriculture came together with the development of large hydraulic works in places like China, Egypt, or Sri Lanka. Simple methods to predict the magnitude of the fluctuations leading to dry or wet seasons — such as the nilometres — were also developed (Bell, 1970). Other examples of early water management include the Roman and Greek aqueducts (Mays et al., 2007) and watermills (Wilson, 2002) or the flood protection walls in ancient Mesopotamia (Morozova, 2005). These techniques continued to be used with small modifications for many centuries. It was not until the Age of Enlightenment that people started, once more, to show curiosity for the functioning of the natural world, leading to the development of modern science. The understanding of the water cycle greatly benefited from the new ideas, and the works of Darcy, Perrault, Marriote, or Halley, among others, made important contributions to water management and the understanding of various hydrological processes (Brown, 2002; Linsley, 1967). Approximately at the same time the first systematic measurements of hydro-meteorological variables started to be collected (Brunetti et al., 2006; Pekárová et al., 2003), paving the ground for further advances in hydrology.

The improved knowledge on the hydrological processes has made it possible to understand, anticipate, and reduce the risks of hydro-meteorological fluctuations (Rui et al., 2013). Society is, however, still poorly adapted to the variability of the natural environment. In the last century, vulnerability towards natural disasters has increased due to a higher population pressure and asset concentration in risk areas as well as the accelerating modification and degradation of the environment (Villagrán de León et al., 2006; Plate, 2002). Other factors such as poverty, disease, conflict, and population displacement exacerbate the vulnerability of populations towards natural disasters (Basher, 2006). Flood related disasters, for instance, are widespread and highly damaging: during the period 1994-2003 there were more than 2,000 flood events catalogued as natural disasters in the Emergency Events Database (EM-DAT), which caused over 200,000 fatalities (Guha-Sapir et al., 2004). The most outstanding feature of flooding events, however, is the high affected-to-killed ratio, which was over 13,000 for the same period; the highest for any type of natural disaster. Additionally, floods have very high costs with regard to infrastructure and food production.

Overall, while it has been clear for a long time that the hydrological system affects society (Dooge, 1988), the notion that societal development can also affect the hydrological system is a much more recent one (Sanderson et al., 2002; Vörösmarty & Sahagian, 2000). The expansion of impervious surfaces (Elvidge et al., 2007), the efforts to control and route flood waves (Dister et al., 1990), or the creation of water reservoirs (Vörösmarty et al., 2003), among other actions, have a significant impact on the natural hydrological processes and therefore need to be considered to adequately manage water resources and risks.

## 1.2 Current trends and limitations

Efficiently managing water resources and their associated risks requires adequate information about the different states and components of the system and their variability (Loucks & van Beek, 2005). Hydro-meteorological measurement techniques have been evolving and increasingly dense sensor networks have been deployed in order to gather the necessary knowledge to inform the different water management tasks. Data gathering, however, is expensive and time consuming, and requires a long-term commitment in order for it to be meaningful (Brown, 2002). Consequently, the available data is rarely sufficient for making informed decisions. Hence, hydrological models need to be used to compensate for this lack of data (Seibert, 1999). The advancement and increasing sophistication of hydrological models eventually reached a level where many people believed that they would make data gathering unnecessary (Silberstein, 2006). Yet, the limitations and constraints of current modelling approaches (Beven, 2006) combined with the complexity of the hydrological processes (Beven, 2000), the development of techniques that can exploit the information content of large hydrological datasets (Hall et al., 2002), and the recent developments in remote sensing (Schumann et al., 2009) and communication technology (Le Coz et al., 2016) have effectively shifted the balance back to recognizing the importance of data for water resource and risk management (Seibert & McDonnell, 2002).

Additionally, for a long time water management has been regarded as a purely technical set of single purpose actions that were carried out exclusively through engineering approaches (White, 1998). While these approaches have been successful in dealing with individual problems, ignoring the complexity and interconnections between the technical, environmental, and human systems may lead to unexpected consequences in the long term (Biswas, 2004; Pahl-Wostl, 2007). For this reason, increasingly integrated approaches for water management have been proposed, which aim at reconcile the different systems and interests affected by such actions (Al Radif, 1999; Basher, 2006). Nevertheless, applying the concepts of integrated water management has proven to be extremely challenging (Jeffrey & Gearey, 2006). Among other issues, the lack of adequate data has been identified as one of the main limitations: while data on the hydrological system are reasonably accurate, social dynamics are not easy to measure and therefore information on these processes needs to be obtained through empirical research (Di Baldassarre et al., 2015; Oki & Kanae, 2006). Consequently, these data are often of qualitative nature, context dependent, and difficult to validate.

## 1.3 Aims of the Thesis

In the light of the recent advances in water resource and risk management and its current limitations, this thesis aims to improve the knowledge on information requirements for water resources and mitigation of extreme events. Given the complexity of the interlinked human and hydrological systems new approaches that transcend the boundaries of traditional scientific disciplines are required (White & Howe, 2004). This way, this thesis not only aims to strengthen the disciplinary knowledge in the hydrological domain but it also attempts to incorporate methods and approaches from other disciplines to overcome some of the constraints and limitations of hydrological data.

More specifically, the aims of the thesis are divided in two main parts that delve into different aspects of information needs for water management:

I. Constraining the hydro-meteorological data needs for water resource management. The cases of sensor network density for precipitation interpolation (**Paper I**) and data resolution for rainfall-runoff modelling (**Paper II**) are considered.

II. Exploring the benefits and applicability of non-traditional sources of information to flood risk mitigation. First, the impact of social memory of past flooding events on the efficiency of flood early warning systems (FEWS) is assessed (**Paper III**), followed by the development of a new methodology to use publicly-available user-generated content to produce near-real-time probabilistic flood inundation maps (**Paper IV**).

# 2. Background

Data availability is crucial for water resource and risk management. Nevertheless, no single source of data provides the required information for the demands of adequate water management. Additionally, water management expands across many disciplines and areas of expertise, each with its own set of preferred data types and approaches (Bertrand-Krajewski et al., 2000). This often results in incomplete or skewed explanations for water management issues. Obtaining a holistic perspective of the different actors and feedback mechanisms in water management is thus imperative for achieving satisfactory answers (Vogel et al., 2015). In this context, being able to use and integrate different types of data and methods is paramount. The following sections introduce and describe the different types of information sources that were used to accomplish the aims of this thesis.

## 2.1 Hydro-Meteorological Data

Water management has traditionally been based on the collection of hydro-meteorological data such as rainfall or runoff (Jones, 1997). These are hydrological fluxes that — together with evapotranspiration and changes in water storage — determine water availability as well as its temporal and geographical variability. Therefore, knowing the magnitude and variability of these fluxes is key for planning and designing important issues such as fresh water supply or mitigation of extreme events.

Hydro-meteorological data, however, have always been scarce and its representativeness limited due to the constraints imposed by the "uniqueness of place" (Beven, 2000; Blöschl et al., 2007). Furthermore, key processes such as evapotranspiration, which effectively controls the water balance, are severely under-monitored (Kirchner, 2006). This is however changing in many parts of the world as hydro-meteorological data are becoming increasingly widespread. This boost in data availability is partially due to the increased emphasis and resources allocated to environmental data gathering in some areas (Isotta et al., 2014; Rauthe et al., 2013) but also due to the development of new techniques that allow to remotely gather spatially distributed data (Tang et al., 2009). Additionally, advances in the understanding of hydrological processes are making it possible to transfer information from gauged to ungauged basins with similar characteristics. This is a challenging task that has been the focus of the International Association of Hydrological Sciences (IAHS) Predictions in Ungauged Basins (PUB) decade (Hrachowitz et al., 2013).

Even with recent developments, hydro-meteorological data availability is not equally spread. While many areas are experiencing an unprecedented wealth of data, many others are seeing declines in hydro-meteorological measurement densities (Spence et al., 2007). Besides, a large percentage of the planet is either largely unmonitored (Bring & Destouni, 2009) or the available data are not readily accessible (Hannah et al., 2011). Therefore, in many parts of the world the limitations in hydro-meteorological data mean that trade-offs need to be made for many water management applications (Gough & Ward, 1996). In such circumstances the concept of *minimal dataset* becomes relevant as the accuracy of any study is strongly dependent on the available time and resources to gather the data (Stehr et al., 2008).

## Precipitation

Information on precipitation is one of the main prerequisites for adequate water management as this process controls how much water comes into the system. Precipitation data have traditionally been collected using rain gauges. These instruments measure precipitation at a given location and the temporal resolution depends on how often measurements can be checked. The latter widely depends on the accessibility of the instrument, meaning that rain gauges in remote locations tend to have lower temporal resolution (Frei & Schär, 1998). The main drawback of rain gauges is that, being point measurements, they are poor descriptors of the processes at the larger scale (Kirchner, 2006). Indeed, the errors in the estimation of the spatial variability of precipitation, in addition to the errors subject to the measurements themselves, are the main source of uncertainty of point precipitation measurements (McMillan et al., 2012). A number of methods have been developed to interpolate areal precipitation information from point measurements (see Haberlandt (2011) for a review). However, even with the best instruments and the most sophisticated interpolation techniques, errors remain significant for high temporal and spatial resolutions due to precipitation variability over small scales (Balme et al., 2006; Goodrich et al., 1995; McMillan et al., 2012; Wood et al., 2000).

In recent decades, new precipitation measurement techniques that transcend the limitations of point measurements such Doppler weather radars and satellite imagery have been developed and perfected. While these new techniques have many advantages over traditional rain gauges they also have significant limitations. Satellite imagery, for instance, makes precipitation estimations possible in parts of the world that were previously unmonitored (e.g. oceans) but their coarse resolution is still a major drawback for many applications in water management (Joyce et al., 2004). Conversely, radar measurements generally produce more accurate estimates at the catchment scale than rain gauges (Wood et al., 2000) but problems with signal interpretation, limited range, and high costs limit their adoption. Even in areas where radar measurements are available, they still need to be used in combination with rain gauges for calibration and validation purposes (Price et al., 2013; Vogl et al., 2012).

## Discharge

Discharge is the main variable of interest for hydrology, both in terms of water resources and risk management. Measuring discharge, however, is not straightforward. Direct measurements of discharge are labour intensive and impractical in large rivers. Additionally, these measurements are not feasible in circumstances of high runoff, which are the most interesting events for flood risk management and flood frequency analysis. Discharge estimation is usually done with the help of rating curves. This way after determining the relationship between discharge and water stage for a number of discharge magnitudes, estimations of discharge can be obtained by simple stage measurements (McMillan et al., 2012). Large uncertainties are however associated with this method due to discharge inter- and extrapolation problems (Clarke, 1999; Di Baldassarre & Montanari, 2009) and changing stream morphology (Jalbert et al., 2011).

A substitute for costly discharge measurements are rainfall-runoff models (Beven, 2001). These models use precipitation information — in addition to a number of other input data and boundary conditions — to produce predictions of discharge. They are a useful tool for designing water management policies and exploring different potential future scenarios as well as for gaining insight on aspects of the hydrological system that would otherwise remain unknown (Moradkhani & Sorooshian, 2009). Rainfall-runoff models can be grouped in different categories according to their underlying assumptions and complexity. This way simple lumped conceptual models coexist with fully-distributed physically-based models. The data requirements for each model type are obviously different, the most complex models requiring more and higher resolution data. Even if there has been a tendency to use increasingly detailed and complex models (Michaud & Sorooshian, 1994), the limitations in data availability, larger uncertainties, and comparable performances with simpler conceptual models mean that the latter continue to be a useful tool for water management purposes (Vansteenkiste et al., 2014).

## 2.2 Non-Traditional Sources of Information

The current paradigm of water risk management recognises the need of considering and integrating all relevant processes and actors in order to successfully reduce the negative consequences of extreme events such as floods and droughts (Basher, 2006; UNISDR, 2007). However, the limited understanding of the interactions and feedbacks between the hydrological, social, and environmental systems hinders the applicability of this framework (Di Baldassarre et al., 2013). Many efforts are however being put into reducing this gap, such as the current IAHS *Panta Rhei* (Everything flows) decade, which is focused on understanding the interactions and feedbacks between hydrology and society (Montanari et al., 2013).

In addition to improving water risk management practices, integrating data and approaches from different disciplines also contributes to the advancement of disciplinary and interdisciplinary science. The interdisciplinary domains of, for instance, socio-hydrology (Blair & Buytaert, 2016) or natural disaster science (Kappes et al., 2012) are making important contributions in this regard.

### Social Behaviour

The assessments and predictions made using only hydro-meteorological data — even the most accurate ones — do not produce satisfactory results by themselves. On the contrary, they usually need to be understood, communicated and applied by third parties (Feldman & Ingram, 2009). The complexity of the social dimension of water risk management is staggering: various actors are often responsible for particular aspects of water risk management at different levels and an even larger number of stakeholders, in addition to the general public, have differing opinions and interests on how the system should be managed (McEntire, 2006). It is therefore important to have knowledge on how people communicate and cooperate, how they understand uncertain predictions, or how they are likely to respond to certain situations such as flood warnings (Demeritt et al., 2007). Previous research has proven that understanding and taking into account social factors maximises the use of technical capabilities and contributes to reduce the casualties and damages from extreme events (Brilly & Polic, 2005; Parker et al., 2009).

The behaviour of individual citizens, and society in general, largely determines the efficiency of any risk mitigation action. Social behaviour depends on many different factors such as risk awareness, trust, or memory of past events (Burningham et al., 2008; Colten & Sumpter, 2009; Viglione et al., 2014). Additionally, social disengagement, perceived responsibilities, or even fatalism also need to be considered (Bubeck et al., 2012). The combination of these factors defines the degree of social preparedness, that is the ability to anticipate, prepare, and respond to an imminent or ongoing disaster (UNISDR, 2009). Consequently, if preparedness is low among different actors, the efficiency of any mitigation action becomes sub-optimal.

Social memory of past flooding events is one of the most relevant and well-studied factors behind preparedness (Folke et al., 2005). The impact of this factor can be appreciated in, for instance, the observed flood insurance coverage peaks after major flooding events, which are followed by a gradual decline thereafter (Hanak et al., 2011). This pattern corresponds to the functioning of memory, which peaks after a traumatising event and gradually decreases as time passes (Di Baldassarre et al., 2013; Parker et al., 2009).

## Volunteered Geographical Information

In addition to receiving information and acting on it, people can now also use the power of newly developed technologies to gather and share information about their surroundings in real time (Fraternali et al., 2012; Thakuriah et al., 2015). These new sources of data have the potential of providing valuable information to complement and extend the capabilities of traditional data sources (Horita et al., 2013).

Having first-hand information is specially relevant during flooding events, when decision makers and first responders need to be able to make rapid but crucial decisions on the scope and reach of damage mitigation actions. In order to do this they need real-time information of the event at hand (Chang et al., 2007), which is usually delivered in the form of flood extent maps (Schumann et al., 2016). These maps are normally produced for streams and their respective floodplains through hydraulic modelling (Merwade et al., 2008). This approach, however, needs a large amount of data on the morphology of the stream and flood plain — in addition information on discharge — which might not be available at the required spatial and temporal resolution. Additionally, large computational costs and uncertainties limit the applicability of these techniques (Di Baldassarre & Montanari, 2009; Schnebele et al., 2015). Alternative approaches such as remote sensing techniques have been used to address these shortcomings (Musa et al., 2015). These approaches, however, can be unreliable and expensive during flood events (Schumann et al., 2009). Other approaches such as cell automation models and storage-spill models have also been proposed to minimise the computational costs of generating flood inundation maps (Bernini & Franchini, 2013; Krupka, 2009). These approaches, however, are still dependent on the availability of discharge information.

Recently, developments in positioning and communication technology, in combination with the spread of social media, have enabled the use of new types of soft data (Thakuriah et al., 2015). These new approaches rely on publicly available georeferenced information generated and disseminated by the general public in real-time through services such as Twitter, YouTube, Flicker, or Facebook. The basic premise is that humans can act as intelligent sensors that observe their environments and synthesise and interpret local information (Fraternali et al., 2012). This type of information is usually referred to as volunteered geographical information (VGI) and, due to its high information content and almost immediate availability (Horita et al., 2013; McDougall, 2012), is increasingly being used in disaster management situations (Bennett et al., 2013; Sakaki et al., 2010).

## 2.3 Research Gaps and Opportunities

Several limitations have been identified in the current practices of water management research and practice. Nonetheless, some of the previously mentioned issues can also provide opportunities to improve knowledge and practice of water management. This is the case of, for instance, the unevenly distributed hydro-meteorological data: the wealth of data in some areas not only makes better water management possible in those areas but it might also be useful to determine minimum data density requirements for correctly characterising the hydrological fluxes, which is relevant for data-scarce areas. Moreover, this could provide insights on the relationship between measurement density and the accuracy of predictions of various hydrological processes. This potential was investigated in two studies that touch upon the hydro-meteorological data resolution needs for, on one side, producing adequate spatial precipitation estimates from point data (**Paper I**) and, on the other side, runoff estimation (**Paper II**).

Furthermore, the scarcity of data in many areas of the world combined with the lack of resources to deploy and maintain comprehensive data gathering sensor networks means that, in some circumstances, particular sensors might need to be prioritised. It is thus important to identify which type of data has the highest information content regarding the variables of interest and purpose of water management actions. This was further investigated in **Paper II**.

New methods that bring consilience to the scattered knowledge regarding water risk management are also needed. These methods should integrate the approaches and perspectives from different disciplines to provide insights on feedback mechanisms and trends within the complex socio-hydrological system (Blair & Buytaert, 2016). In this regard, the impact of social behaviour and preparedness on FEWS, which are one of the most widely used tools for flood damage mitigation, was studied through the development of a simple conceptual model in **Paper III**.

Finally, the full potential of social media data needs to be further investigated. The use of VGI for flood extent estimation has, at present, only been explored in combination with other sources of information such as remote sensing data (Schnebele & Cervone, 2013) or as low resolution estimates of local flooding conditions (Triglav-Čekada & Radovan, 2013). For this reason, the use of a new methodology using exclusively VGI data to estimate probabilistic flood extents for locations and times when no other data is available was explored in **Paper IV**.

Overall, the studies included in this thesis are individual pieces of work that combined contribute to the common aim of improving the knowledge base of information needs for monitoring, forecasting, and response actions within an integrated water management framework (Figure 2.1).

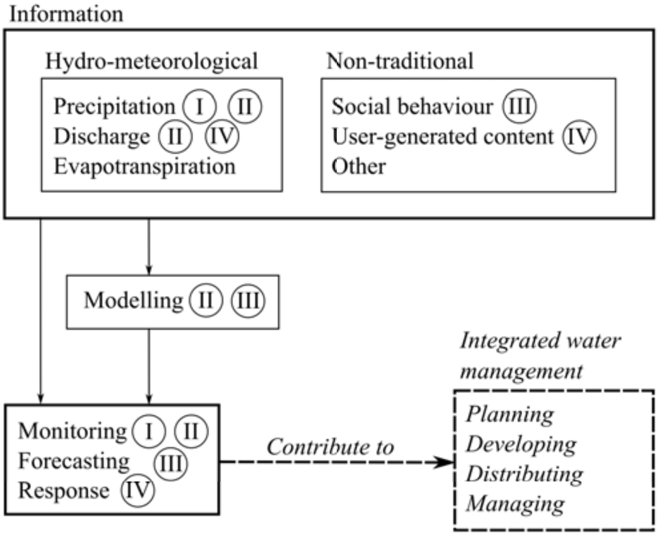

*Figure 2.1.* Conceptual framework of the contributions of the thesis. The contributions of the individual studies are represented by the Roman numerals of the corresponding paper.

# 3. Case Studies and Datasets

Different case studies were selected to carry out the investigations included in this thesis. The selection of each case study was done based on the characteristics of the catchment as well as the availability of the required type of information for each study. This way, the Thur River basin, located in North-Eastern Switzerland, was selected due to the availability of high resolution hydro-meteorological data, which was required for performing the analyses in **Papers I** and **II**. Similarly, the case study of the flood event that hit central Texas (USA) between the 24 and 26 May 2015 (commonly referred to as the *2015 Memorial Day flood*) was selected due to the abundance of social media data that was required for the analysis in **Paper IV**.

No suitable case study was selected for **Paper III**. The long series of combined hydrological and social behaviour data that would have been required for the objectives of this study do not exist at this point. Instead, a synthetic dataset of maximum annual flows created using a simple bivariate gamma distribution (Yue, 2001) was used as input data for this study. The limitations in data availability mean that the results and conclusions could not be tested against existing data and, therefore, that the scope of this study remained purely exploratory.

## 3.1 Thur River Basin

### Catchment Characteristics

The Thur is the largest non-regulated river in Switzerland and drains the front ranges of the Swiss Limestone Alps (Figure 3.1). Its catchment covers approximately 1,700 km$^2$ and is roughly divided in two main morphological areas: the southern headwaters, which are mainly composed of limestone, and the northern lowlands, primarily consisting of Molasse sandstones and Pleistocene unconsolidated sediments. Approximately a quarter of the catchment area is covered by forest but the main land-use types are agriculture in the lowlands and pastures in the highlands. Population is widely scattered with the largest

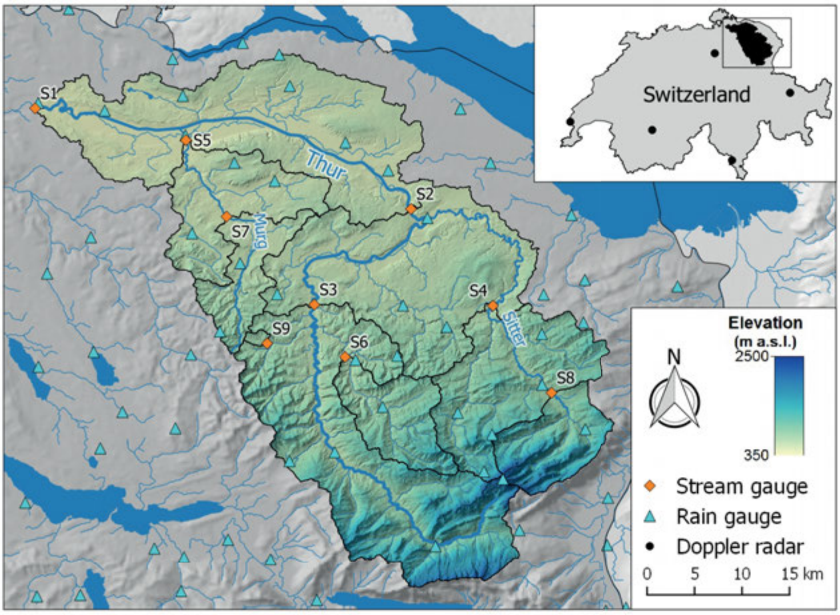

*Figure 3.1.* Location and topography of the Thur River basin. The main rivers within the basin as well as the location of the sensors from the MeteoSwiss meteorological and FOEN hydrological measurement networks used in **Papers I** and **II** are represented on the map. Data from swisstopo, MeteoSwiss, FOEN and the EEA.

settlements being St. Gallen (72,000 habitants) and Frauenfeld (23,000 habitants).

The climate of the Thur River basin is classified as alpine and pre-alpine with a snow-melt dominated flow regime (Yang et al., 2007). The average flow at the catchment outlet — situated at the town of Andelfingen — is 47 $m^3$ $s^{-1}$ with the 100-year high and low flows being 1,071 and 3.16 $m^3$ $s^{-1}$ respectively. The average annual rainfall is 1,350 mm, which is distributed over the year with a peak in the summer months. Rapid increases of discharge are not uncommon due to the steep terrain and short concentration times.

## Dataset

The Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) operates a monitoring network of up to 160 automatic meteorological measurement stations (SwissMetNet) which is complemented by a number of automatic rain gauges. These stations provide information every 10 minutes and are used to create local weather forecasts (Suter et al., 2006). Additionally, over 300 manual rain gauges providing daily data have been operated for a long period and provide valuable climatological information. The distribution of the sensors is reasonably balanced but areas of difficult access such as the high altitudes remain under-represented (Frei & Schär, 1998). Supplementing the regular rain gauge sensor network, a weather radar network consisting of five stations (Rad4Alp) is also operated by MeteoSwiss (Figueras Ventura et al., 2013). The stations cover the whole country and are mainly used for monitoring and forecasting precipitation events.

In addition to collecting a wide array of meteorological measurements, MeteoSwiss also develops a number of gridded data products based on those measurements. Two precipitation data products — RdisaggH and RhiresD — and three temperature data products — TabsD, TminD, and TmaxD — were used in **Papers I** and **II**. The considered precipitation data products have different scopes and data bases. RhiresD is a high-accuracy spatial analysis of daily precipitation amounts based on the available precipitation monitoring stations (Frei & Schär, 1998). This product covers a long period — extending for over 50 years — and has a spatial resolution of approximately 4 $km^2$. RdisaggH is an aggregation of the high-resolution rain gauge interpolation of RhiresD and a composite of hourly radar measurements (Wüest et al., 2010). This product is primarily intended for research purposes and is only available for a short period — 8 years — but at a spatial resolution of 1 $km^2$. Additionally, long-term monthly climatological average precipitation values based on regionally varying precipitation and topography relationships adjusted for the Alpine region were used as reference precipitation in **Paper I** (Schwarb et al., 2001). The temperature data products consist of daily mean (TabsD), minimum (TminD), and maximum (TmaxD) temperature values at a spatial resolution of about 4 $km^2$ derived from the available meteorological monitoring stations and covering a period of over 50 years (Frei, 2014).

Discharge data were obtained from the Swiss Federal Office for the Environment (FOEN) at 9 different locations within the Thur River basin (Figure 3.1, S1-S9). The data were available both as hourly and daily cumulative discharge information. The sub-basins defined by the stream gauging stations have significantly different contributing areas, elevation ranges, and land-cover types. One of the stations — Rietholzbach-Mosnang (S9) — is a research catchment representative of pre-alpine countryside conditions that has been operated for over 40 years (Gurtz et al., 1999).

Annual average potential evaporation values were obtained from the Hydrological Atlas of Switzerland (HADES) and a simple sine curve was used to distribute the values over the 12 months. Finally, a digital elevation model (DEM) with a resolution of 25 metres provided by the Swiss Federal Office of Topography (swisstopo) was used together with the precipitation and temperature datasets to calculate the respective elevation lapse rates. The DEM was also used to calculate the different elevation range areas required by the rainfall-runoff model in **Paper II**.

## 3.2 Shoal Creek Catchment

### Event and catchment Characteristics

The 2015 Memorial Day flood affected most parts of central Texas and was specially intense in the city of Austin, where it flooded over 200 homes and caused a total damage of about US$ 35 million. Additionally, 17 rescue operations needed to be carried out. The event lasted between the 24 and 26 May with the peak flow occurring on Monday 25 between 2:00 and 6:00 pm. The event produced localised flood depth of over 6 metres in the centre of Austin, just half a metre less than the 1981 flood event, which was the worst flood on record (Maddox & Grice, 1986).

The Shoal Creek catchment (Figure 3.2), located in central Austin was selected as a case study. The catchment is mostly urbanised, with over 45% of its surface being impervious. The dominant land use type is residential and commercial and around 60,000 people live within its boundaries.

### Dataset

The 2015 Memorial Day flood had a widespread social media coverage. During the peak hours of the flood event a large number of social media posts were issued by the people in Austin. Due to data accessibility policies and limitations in the geo-referencing of many posts, a total of 22 VGI points collected from social platforms such as Twitter, YouTube, Instagram as well as new media websites were included in the study. The sample size was comparable to those used by previous studies (Schnebele & Cervone, 2013; Triglav-Čekada & Radovan, 2013). Additionally, a total of 20 emergency related calls to the Austin 3-1-1 municipal service during the same time window were also included for the analysis.

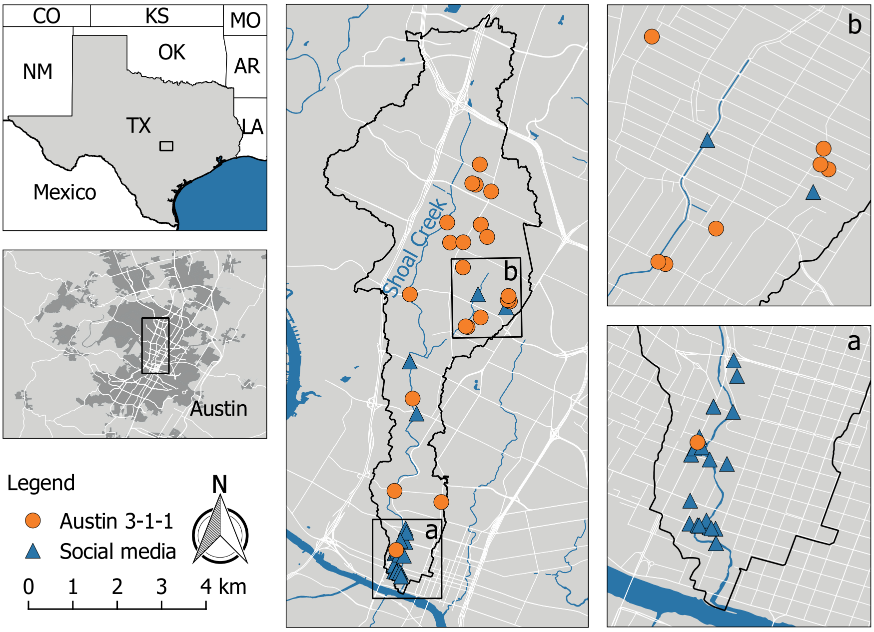

*Figure 3.2.* Shoal Creek catchment in central Austin, Texas, USA. The flood-related social media and municipal service calls (Austin 3-1-1) during the peak hours of the 2015 Memorial day flood used in **Paper IV** are geographically represented. Two areas of special interest are highlighted: downtown (a) and uptown (b).

Additional data included the results of hydraulic modelling of the flood event, 25- and 100-year flood risk maps from the US Federal Emergency Management Agency (FEMA), and a high-resolution DEM. The hydraulic model results were obtained at an hourly resolution by HEC-RAS using model inputs from the ECMWF-RAPID coupled runoff forecasting and routing tool (Buahin et al., 2016).

# 4. Summary of Papers

> *If we knew what it was we*
> *were doing, it would not be*
> *called research, would it?*
>
> Albert Einstein

## 4.1 Paper I — Rain Gauge Density

The aim of this paper was to assess the performance of different rain gauge sensor network configurations for estimating the variability of spatial precipitation fields.

### Methods

A subset of the RdisaggH gridded precipitation data product at the location of the existing rain gauges was used as data for the study. This choice provided a high temporal resolution making it possible to analyse short and intense precipitation events. This point precipitation data was then interpolated for the entire Thur River basin following the same procedure as Frei and Schär (1998) in order to provide a consistent verification of the results. This way the temperature precipitation deviations from the long-term climatological average were interpolated using a modified version of the SYMAP (Synographic Mapping System) inverse distance weighing algorithm (Shepard, 1968). Finally, the interpolation accuracy was evaluated against a reference precipitation field. Since the *real* precipitation was not available, RdisaggH was chosen as surrogate reference information.

The cases of increasing and decreasing sensor network densities were evaluated by using two different indices — the Pearson correlation coefficient ($I_{PCC}$) and the normalised root-mean square error ($I_{RMSE}$) (Legates & McCabe Jr., 1999) — for the catchment average and two different grid-cell resolutions — 4 km$^2$ and 36 km$^2$ — in order to test the resolution-dependent errors. For the case of increasing sensor densities, virtual rain gauges were deployed at the locations with largest errors while for the case of decreasing densities, rain gauges were removed based on their accessibility. Additionally, the performance of the interpolation was assessed based on its capacity to reproduce two precipitation intensity thresholds, namely 5 and 10 mm h$^{-1}$.

## Results

Adding virtual rain gauges at the location of the largest interpolation error efficiently decreased the catchment-wide average and variability of the precipitation interpolation errors for both efficiency metrics (Figure 4.1). The magnitude of the error reduction decreased with an increasing rain gauge station density, becoming almost negligible when approximately 20 virtual rain gauges had been added. Conversely, when rain gauges were removed, the interpolation error increased exponentially. Even if the overall error reduction magnitudes where similar for both efficiency metrics used in the study, the locations of the largest errors and therefore the placement of the virtual rain gauges where generally not coincident.

Differences in interpolation performance could also be observed among the different sensor network configurations for representing the two different precipitation intensity thresholds (Figure 4.2). The estimation of the lower threshold — 5 mm h$^{-1}$ — was generally very accurate after the addition of 20 virtual rain gauges, with efficiency rates of over 80% over most of the basin (Figure 4.2e,f). Conversely, efficiency rates locally dropped down to 40% when the sensor density was reduced (Figure 4.2d). The effect was more dramatic for the higher precipitation intensity threshold — 10 mm h$^{-1}$— where a higher efficiency rate variability could be observed along the basin (Figure 4.2a-c). In this case the efficiency rates locally dropped down to 20% when the sensor network density was decreased in the high elevations (Figure 4.2a).

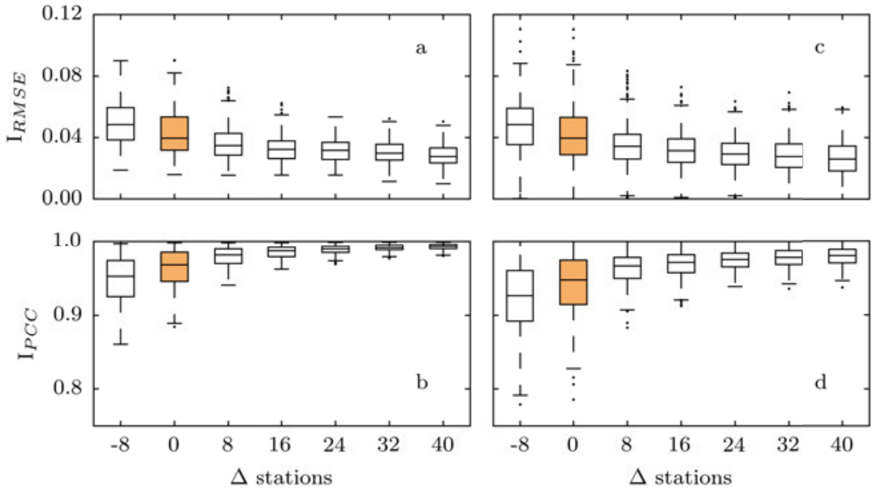

*Figure 4.1.* Catchment average performance (mean and range) for different rain gauge network configurations and different interpolation resolutions. (a) $I_{RMSE}$ at 36 km$^2$ resolution. (b) $I_{RMSE}$ at 4 km$^2$ resolution. (c) $I_{PCC}$ at 36 km$^2$ resolution. (d) $I_{PCC}$ at 4 km$^2$ resolution. The box representing the existing configuration is shadowed.

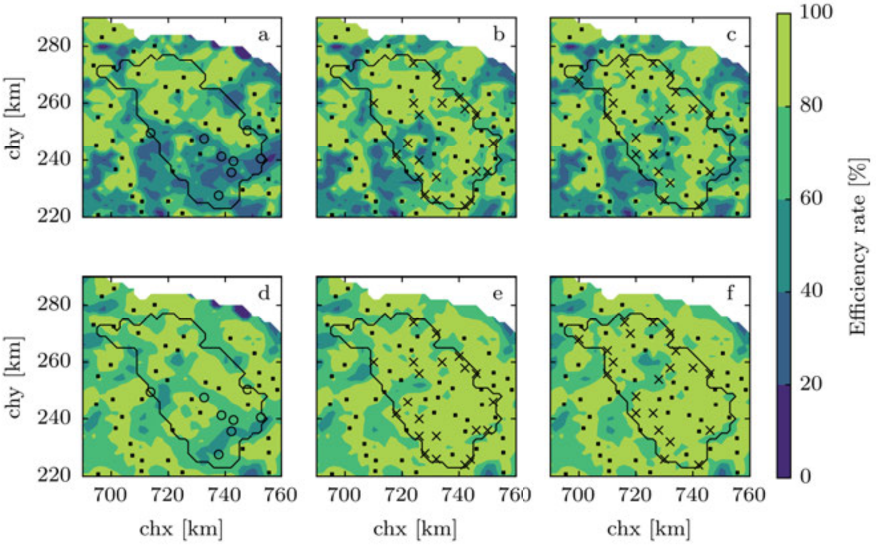

*Figure 4.2.* Performance of two characteristic rain gauge network configurations for estimating two predefined precipitation intensity thresholds at a resolution of 36 km$^2$. (a) Estimation of the 10 mm h$^{-1}$ threshold after the removal of eight rain gauges. (b) Estimation of the 10 mm h$^{-1}$ threshold after the placement of 20 rain gauges ($I_{RMSE}$). (c) Estimation of the 10 mm h$^{-1}$ threshold after the placement of 20 rain gauges ($I_{PCC}$). (d) Estimation of the 5 mm h$^{-1}$ threshold after the removal of eight rain gauges. (e) Estimation of the 5 mm h$^{-1}$ threshold after the placement of 20 rain gauges ($I_{RMSE}$). (f) Estimation of the 5 mm h$^{-1}$ threshold after the placement of 20 rain gauges ($I_{PCC}$). The existing rain gauge network is represented by the solid squares, the stations removed by empty circles and the stations added by crosses. Map coordinates — chx and chy — correspond to the CH1903 Swiss coordinate system.

## 4.2 Paper II — Hydro-Meteorological Data Aggregation

The aim of this paper was to assess the hydro-meteorological data needs for adequately simulating streamflow as well as to study the relative importance of the different data sources.

### Methods

The HBV model (Bergström, 1995; Lindström et al., 1997) was selected for this purpose because of its simplicity, computational efficiency, and low input data requirements. HBV is a semi-distributed model originally developed by the Swedish Meteorological and Hydrological Institute (SMHI) that has been successfully applied in many settings around the world, including the river Rhine, of which the Thur is a tributary (Berglöv et al., 2009). RhiresD and TabsD precipitation and temperature data products were used as input data for this study. The data were aggregated into catchment and sub-catchment averages — named $PT_{Thur}$ and $PT_{sub}$ respectively — and divided into two independent periods for the analysis. The analysis itself was divided into three different steps: (i) assessment of the model performance at each stream gauge location when calibrated with $PT_{Thur}$ data respect to when calibrated with $PT_{sub}$ data; (ii) assessment of the model performance at the internal sites when calibrated at the outlet using $PT_{Thur}$ data respect to $PT_{sub}$ data; and (iii) assessment of the relative importance of meteorological and streamflow data resolution for calibrating the model.

Two different measures for evaluating the performance of the model were used. First, the model efficiency, $R_{eff}$ (Nash & Sutcliffe, 1970), which is one of the most widely-used metrics in hydrological modelling, was used. This measure is a good indicator of model performance for individual set-ups but it is not equally informative when using parameter sets calibrated for one catchment for estimating streamflow at a different catchment. For this reason a new scaled model efficiency, $R^*_{eff}$, was introduced (Eq. 4.1).

$$R^*_{eff} = \frac{R_{eff} - R^{min}_{eff}}{R^{max}_{eff} - R^{min}_{eff}} \tag{4.1}$$

This way, $R^*_{eff}$ is dependent on the best achievable efficiency for a specific location and period, $R^{max}_{eff}$, and the efficiency that would be obtained without any prior information, $R^{min}_{eff}$. This alternative efficiency measure provided meaningful comparisons between model performances in independent locations and periods.

## Results

Using semi-distributed meteorological input data produced generally better results when calibrating the model at the different stream gauge locations (Figure 4.3). This trend was however not general: while consistent results were obtained for the Sitter and the lower Thur, a larger variability was observed at the locations along the Murg and the upper Thur. Better results were also achieved by using $PT_{sub}$ data for calibrating the HBV model at the outlet and transferring the resulting model parametrizations to the internal sites. Yet, no significant trends could be identified for any of the tested basin characteristics (catchment area, mean elevation, forest area). The $R^*_{eff}$ metric generally produced clearer trends than $R_{eff}$.

Focusing on the relative importance of meteorological and streamflow data for model calibration, model set-ups involving using streamflow information in the internal sites generally achieved higher performances for both efficiency measures (Figure 4.4). Additionally, the use of $R^*_{eff}$ revealed that model parametrizations that would perform rather poorly when discharge information for calibration was only available at the outlet, would achieve high performances when more detailed discharge information was available, even at the expense of reducing the resolution of the meteorological information.

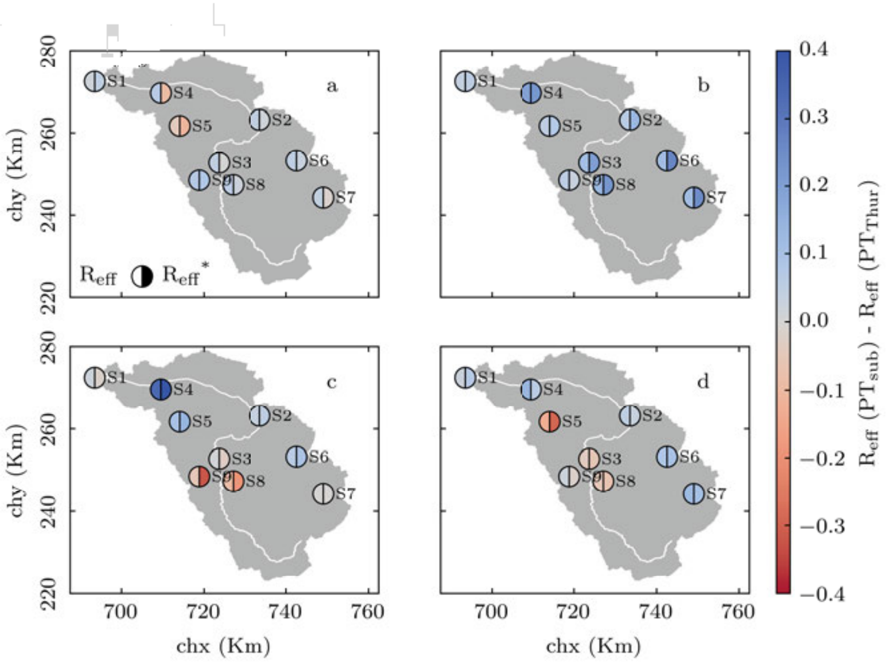

*Figure 4.3.* Geographical distribution of model performance for the different set-ups: (a) calibration in period 1, (b) validation in period 2, (c) calibration in period 2, and (d) validation in period 1. Two different performance measures are considered: $R_{eff}$ on the left side of the circle and $R^*_{eff}$ on the right side. The colour and shade indicate the relative model performance when calibrated with the different input data aggregations ($PT_{sub}$ and $PT_{Thur}$). The stronger the shade of the colour, the more pronounced the performance difference. Map coordinates — chx and chy — correspond to the CH1903 Swiss coordinate system.

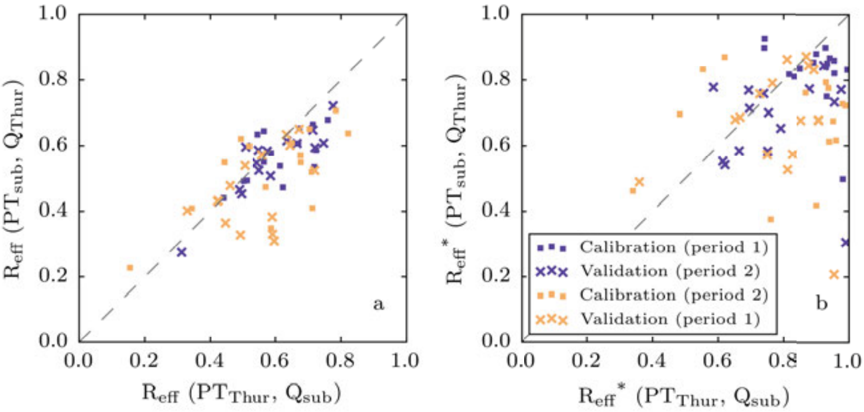

*Figure 4.4.* Model performance comparison between two different data availability cases: $PT_{Thur}$ and $Q_{sub}$ (x-axis), and $PT_{sub}$ and $Q_{Thur}$ (y-axis). Model performance values were obtained using the $R_{eff}$ (a) and $R_{eff}^*$ (b) efficiency measures. The dashed lines represent an equal performance for the different data aggregate combinations.

## 4.3 Paper III — Social Memory

The aim of this paper was to assess the impact of social memory of past flooding events on the efficiency of FEWS.

### Methods

Since no experimental data was available a simple conceptual model were developed to explore the existence of any trends and get insights on the functioning of the system. A number of routines were included in the model: first, a probabilistic forecast was generated based on input discharge magnitude following the conceptualization made by Ambühl (2010). This forecast was then evaluated by a simple contingency table to determine the warning outcome. That is, whether a flood event would be successfully warned for or missed, or if a false alarm would be issued. Thereafter, the consequences associated with the warning outcome were calculated. For instance, if an alarm was successfully issued, the flood damage was assumed to be reduced by mitigation actions. The efficiency of these mitigation actions was assumed to be dependent on the preparedness level, which in turn was assumed to correspond to the social memory of past events. Finally, the social memory level was updated based on the estimated consequences following the conceptualizations made by Di Baldassarre et al. (2013) and Parker et al. (2009).

The social memory of past events was evaluated through its half-life, $\lambda$. That is, the necessary time to reduce the social memory level by one half. The model performance was evaluated by the *relative loss*, which was defined as the ratio between the losses incurred when a FEWS was operational and the losses that would occur if no FEWS would be in place. The term loss in this context was applied in a generic way encompassing all expenses related to the occurrence of floods (i.e. costs of the mitigation measures and the warning system, and direct damages from flooding events). This way, a relative loss value larger than one mean that the losses were greater than those produced by the climatological variability.

### Results

A preliminary sensitivity analysis of the model parameters showed that social memory of past events was one of the most sensitive parameters. The impact of this parameter on the model performance could be appreciated by

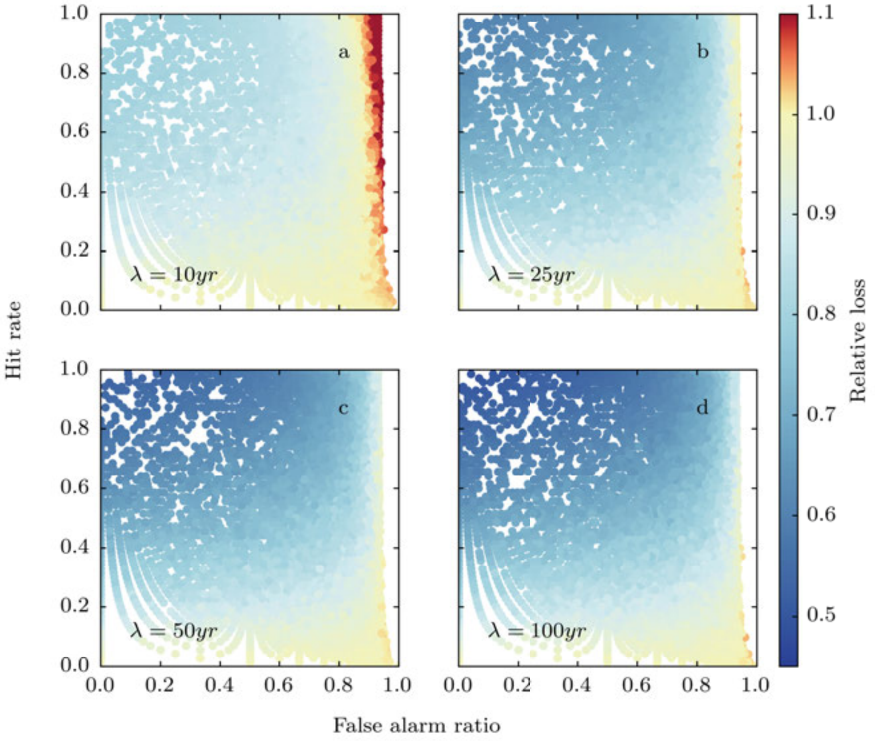

*Figure 4.5.* Model efficiency (relative loss) for different flood forecasting performances as given by the hit rates and false alarm ratios, and social memory half-life times: (a) 10 yr (b) 25 yr (c) 50 yr and (d) 100 yr.

comparing the relative losses of different model set-ups representing a range of warning system performances, as expressed by the combination of different hit rate and false alarm ratio combinations (Figure 4.5). For a given memory half-life time, relative losses were highest for high false alarm ratios and/or hit rates and lowest for a combination of high hit rates and low false alarm ratios. Increasingly long memory half-life times significantly decreased the relative losses across all the warning system performance spectrum.

Additionally, relative losses were found to be strongly dependent on the climatic setting and return period of flood events (Figure 4.6). For the same memory half-life time relative losses decreased for increasing frequency of high magnitude events. The average level of social memory as well as the performance of the warning system were also consistently higher under these circumstances.

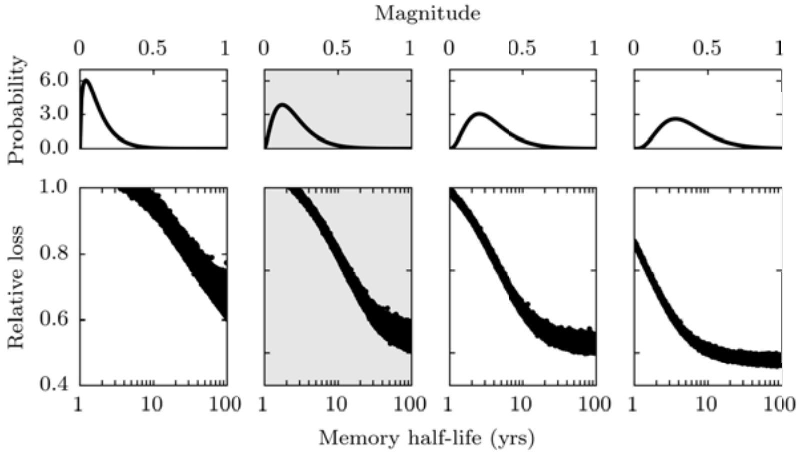

*Figure 4.6.* Model efficiency sensitivity respect to the social memory half-life time (bottom row) for different hydrological regime scenarios (top row). The scenario used for the sensitivity analysis — default scenario — is highlighted.

## 4.4 Paper IV — Social Media Data

The aim of this paper was to investigate the feasibility of using volunteered geographical information (VGI) to generate reliable probabilistic flood inundation maps to help decision-makers and first responders in emergency situations.

### Methods

The flood extent estimation procedure was composed of three main steps. First, the most likely path of water flow between the VGI location and the closest stream was identified using a least-cost algorithm. The path of least topographic gradient was selected in this case following the assumption of downstream flood type. Then, an algorithm combining region-growing techniques and hydrological concepts, named Hydro Region Growing Algorithm (HRGA), was developed. This way, given a seed (initially the VGI location reported as being flooded), neighbouring areas were iteratively included in the flooded region if their elevation was lower than the water surface elevation at the seed. Basic hydrological principles were used for the extrapolation such as assuming a local flat water slope in the surroundings of the VGI location and a constant water head along the stream's centreline. Finally, the probability of a specific location being flooded was estimated by a series of HRGA Monte Carlo simulations using random initial water depth values between predefined thresholds. The probability of a given location being flooded was then estimated by dividing the number of simulations representing that location as flooded over the total number of simulations.

### Results

The performance of the HRGA was evaluated against the results from the hydraulic model and, in those areas where they were not available, against FEMA flood risk maps. The HRGA-derived flood extents corresponded well with those from hydraulic modelling (Figure 4.7) and were generally corresponding with the 25-year return period areas (Figure 4.8). Moreover, the HRGA succeeded to recreate locations outside the 25-year return period area that were reported as being flooded, such as the intersection between W Koeing Lane and Woodrow Avenue (Figure 4.8), which was reported as being flooded during the event (D. R. Maidment, personal communication, 2015). In some other areas, however, discrepancies were apparent, such as in the

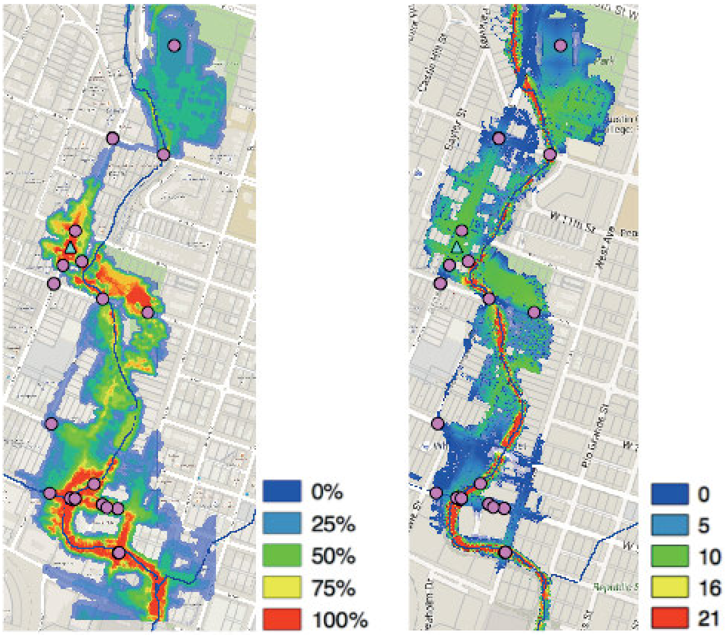

*Figure 4.7.* Flood extent map for downtown Austin and location of the VGI locations used for generating the map (Fig. 4a). Left: HRGA probabilistic extent (legend: probability of being flooded). Right: HEC-RAS modelled flood depth (legend: flood depths in feet). Circles and triangles represent VGI point data.

northern section of the downtown area, where the HRGA failed to reproduce a large area along the stream as being flooded (Figure 4.7).

Overall, the proposed method achieved an 82% overlap with the results from the hydraulic model in the downtown area (Figure 4.7) while for the north-eastern area (Figure 4.8) the method achieved an 81% overlap with the 25-year flood risk area and a 72% overlap with the 100-year flood risk area.

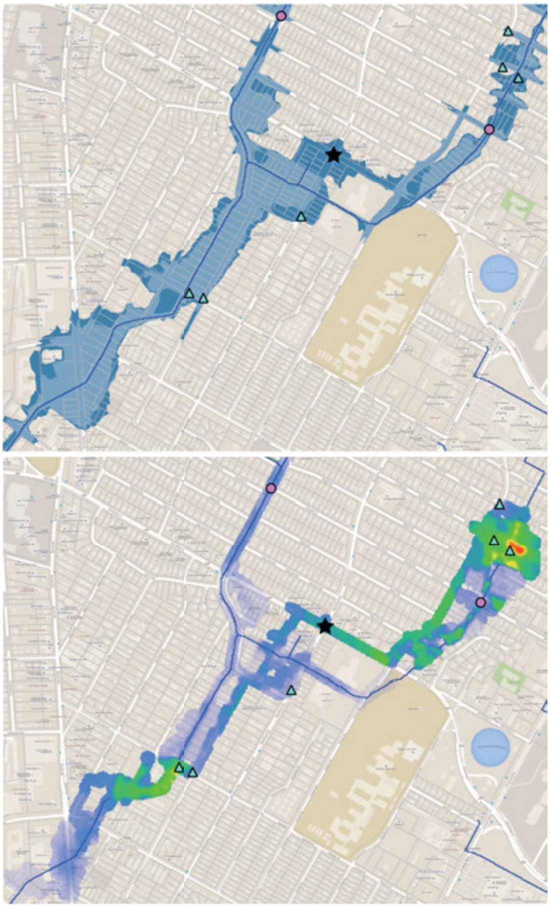

*Figure 4.8.* Flood extent map for a non-modelled and ungauged stream located north-east from downtown Austin (Fig. 4b). Left: FEMA 25 (light blue) and 100 years return period flood map (dark blue). Right: HRGA probabilistic extent. Circles and triangles represent VGI point data. The star represents the location between W Koeing Lane and Woodrow Avenue which was flooded during the event (D. R. Maidment, personal communication, 2015).

# 5. Discussion

> *Knowledge is knowing a tomato is a fruit;*
> *wisdom is not putting it in a fruit salad.*
>
> Miles Kington

Information availability is key to water resource and risk management. The lack of data not only makes it difficult to understand the different hydrological and social processes but also hinders societal resilience. Hereby, this thesis introduces a series of studies that contribute, on one side, to the assessment of hydro-meteorological data needs and, on the other side, the introduction of new methodologies to incorporate different types of data for improving water risk management.

## Hydro-Meteorological Data

Hydro-meteorological data availability is highly uneven around the globe, leading to large inequalities regarding the water resource and risk management possibilities. Nevertheless, areas with high measurement densities can be used to provide guidelines for sensor network requirements in less favoured areas. The results from **Paper I** and **II** provide indications on data resolution needs for obtaining adequate estimates of precipitation and streamflow data. For instance, **Paper I** shows that, while an extremely dense rain gauge sensor network is not needed for producing correct estimations of spatial precipitation fields, it is important to ensure that the remote areas, especially those situated in high elevations, are well represented. Similarly, **Paper II** shows that, in many cases, having more detailed meteorological information does not necessarily translate into better streamflow prediction. Furthermore, **Paper II** also shows that detailed streamflow data is more important for model calibration than meteorological data. Currently, the situation is usually the opposite, with streamflow sensor networks being less dense than those for measuring other hydro-meteorological parameters (WMO, 2008).

Several initiatives aiming at engaging the general public in environmental data collection have been developed in recent years (Johnson et al., 2014; Lüthi et al., 2014). These initiatives not only are a powerful tool to foster scientific literacy and making water management more inclusive at the community level but can also successfully be used to complement standard hydro-meteorological measurement sensor networks. Indeed, combining the approaches presented in **Papers I** and **II** with crowd-sourced informal measurements has the potential to improve water management practices in data scarce areas.

Conversely, in those regions with a high sensor network density it is not always worth using the full resolution of the available data. Results show that a rain gauge density of 24 rain gauges per 1,000 km$^2$ is enough for correctly estimating the spatial variability of the phenomenon at an hourly interval in areas with complex terrain (**Paper I**). Similarly, as shown in **Paper II**, in many cases having more detailed meteorological information does not imply achieving higher model performances than using less detailed information, which supports the conclusions of Lobligeois et al. (2014). Therefore, the general perception that more detailed data is always better (Rauthe et al., 2013), needs to be reassessed, and the available resources distributed in a more efficient way. Rationalizing hydro-meteorological sensor networks to adequately fit the needs of both scientific advancement and water management is the best way of preventing declining sensor network densities and the interruption of valuable hydro-meteorological data time series.

The applicability of the findings presented in **Papers I** and **II** is, however, restricted by the effect of the "uniqueness of place" (Beven, 2000). Indeed, required measurement densities may change in different climatological and hydrological settings than those used for the study. For this reason it is important to have efficiency measures that take into account these constraints. The introduction of a new scaled model efficiency measure, $R^*_{eff}$, in **Paper II** allowed for a better assessment of model performances across independent locations and periods. More specifically, while the model efficiency, $R_{eff}$, produced near-neutral indications on the preferable meteorological data aggregate for model calibration in each period and sub-basin, $R^*_{eff}$ provided clearer and more consistent guidance. Nevertheless, the applicability of this new efficiency measures needs to be further explored.

## Non-Traditional Sources of Information

Applying the concepts of integrated water management is a challenging task (Jeffrey & Gearey, 2006). Many relevant types of data such as social memory (**Paper III**) are either difficult to measure and quantify, or their information content is difficult to extract, as it is the case of geo-referenced VGI (**Paper IV**). Nevertheless, overcoming these challenges allows decision-makers and first responders to obtain valuable information for improving the efficiency of flood risk mitigation actions in ways that would not be possible by using only traditional hydro-meteorological datasets. For instance, the results from **Paper III** show that residual damages from flood events can be further mitigated by taking into account the level of social preparedness. Similarly, for the 2015 Memorial Day flood in the Shoal Creek catchment in Austin, Texas, no updated flood extent information was available for a section of the flooded area, which could be compensated by the use of VGI (**Paper IV**).

These results, however, need to be taken with caution. As previously discussed, information on social behaviour is not only difficult to measure and quantify but it can also be held to subjective interpretations (Wolf, 1978). In order to compensate for the lack of data and the subjective nature of social behaviour, the study presented in **Paper III**, draws from well-established principles from the literature, that in combination with simplifications of the considered processes, allowed to construct a simple conceptual model that can provide broad insights and trends on the interactions and feedback mechanisms between different aspects of the studied system (Blair & Buytaert, 2016). Nevertheless, the analysis of the results as well as their implications are constrained by the large simplifications and uncertainties inherent of using such approaches.

Even if there is still room for improvement, new data types such as VGI have proven to be valuable additions to well-established measurements as they might complement them in places and times when the latter might not be available (**Paper IV**). Related work by other groups is currently ongoing (Schnebele et al., 2015; Triglav-Čekada & Radovan, 2013) but further research is needed in order to constrain the limitations and uncertainties inherent to this type of data. Even so, VGI can already provide reasonable estimations of flood extent, which are extremely valuable for decision-makers and first responders alike. An additional challenge from the methodology presented in **Paper IV** would need to fully automate the process (including data gathering and analysing) in order for it to be meaningful for its purpose.

Overall, involving the population in data collection might have positive side effects such as fostering preparedness and risk awareness and therefore increasing social resilience towards floods. Initiatives to involve people in providing real-time information about floods are already being implemented and proving to be a valuable source of information in several cities around the world (Chun & Francisco, 2015). For these reasons, in addition to improving hydro-meteorological sensor network densities, resources should also be allocated to fostering social preparedness and pro-active approaches towards flood risk (Colten & Sumpter, 2009). Among other actions, and as indicated by the results from **Paper III**, memory preserving efforts are important in keeping high levels of preparedness, even when no flooding occurs (Komac, 2009).

## Integrated Water Management

The importance of interdisciplinary approaches for integrated water management can be appreciated from the results obtained in the studies included in this thesis. Combining different approaches and methodologies allows for a more complete representation of a complex system as well as an improved estimation of the connections between its different elements. Even so, many problems and limitations still need to be solved. For instance, most of the work remains essentially disciplinary in its base. **Papers I** and **II** are undoubtedly focused on hydro-meteorological processes, while **Paper III** presents an assessment of social memory without delving in the complexities of the hydrological and economical aspects of FEWS. Fully integrating the methodologies from different disciplines is therefore still an issue.

Furthermore, integrating the different aspects of water management makes the resulting system of study larger and more complex. This increased complexity is translated into the inherent uncertainties of the processes encompassed by the system, which also become more significant. For instance, the uncertainties related to the appraisal of flood damages, which was only considered as a boundary condition in **Paper IV**, widely exceed the limitations of hydrological predictions (Apel et al., 2009) and are likely to significantly affect the obtained results. For this reason, a strong commitment to identifying and quantifying the sources of uncertainty and their propagation through the entire system is needed.

Overall, this thesis only covers a small subset of the large range of approaches, methods, and sources of information relevant for integrated water management. Further research is therefore needed, both in improving the understanding of individual components of the system, such as overcoming the constraints of the limited representativeness of hydro-meteorological data, as well as in integrating and understanding the connections between different components of the system. The results obtained, however, contribute to improve the understanding of the information needs and the use of new sources of information to make water management more efficient and useful for society.

# 6. Conclusions

Effective integrated water management requires adequate information about all the relevant processes in order to make the right decisions and take pertinent action in every location and under any circumstances. The wide range of interconnected systems, such as hydrological, social, economical, etc. and the multitude of approaches used to gather information on each of them means that a combination of both disciplinary expertise and the flexibility of interdisciplinary approaches is required to produce significant results.

This thesis covers some of the issues related to the scarcity and lack of representativeness of hydro-meteorological data and explores the use of non-traditional sources of information to complement and compensate the limitations of hydro-meteorological data. More specifically, the main contributions are:

I. The identification of rain gauge sensor network density thresholds for the estimation of spatially distributed precipitation fields. More specifically, **Paper I** shows that rain gauge densities higher than 24 stations per 1000 km$^2$ do not significantly improve the accuracy of spatial precipitation estimations.

II. The determination of hydro-meteorological data resolution requirements for adequately estimating streamflow under different conditions. Even if sub-catchment specific meteorological data generally translates into better estimations of streamflow, **Paper II** shows that using catchment specific data produces comparable results in many cases. Moreover, the availability of high resolution streamflow data is found to be more important for hydrological model calibration than detailed meteorological data.

III. The scaled efficiency measure for evaluating hydrological model performance, which was introduced on **Paper II** can provide valuable insight on the potential of applying model parametrizations in different locations and periods.

IV. The assessment and quantification of the impact of behavioural information on flood risk engagement. **Paper III** shows that social memory of past flooding events is an important factor for mitigating flood-related damages. This is especially relevant in circumstances where flood return periods are shorter than the half-life time of social memory. The results also stress the importance of promoting and preserving social memory.

V. The use of non-traditional sources of information can be beneficial for flood extent mapping. **Paper IV** shows that the use of volunteered geographical information for flood extent mapping can contribute to overcoming the limitations of currently-used methods of flood mapping during flooding events such as the limited temporal and spatial resolution as well as the lack of data.

The work carried out in this thesis contributes to improving the assessment of data needs for various aspects of water management and represents a step forward in the complicated path of combining datasets and approaches from different disciplines into the integrated water management framework.

# 7. Acknowledgements

*So long, and thanks for all the fish*

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Dolphin

This is the most difficult part of the thesis to write. As I sit alone in the office at 1 am I am thinking about one of many lunch conversations in the LUVAL fikarum: What are letters? What's the meaning of words? How can we even read? And it all feels quite appropriate right now. There are so many people that have made this journey through the PhD such an enriching and memorable experience that it is hard to find the words to thank you!

First of all, to my supervisors. Because even if at times the challenges have been many I have always had your support and advise. Thanks Jan for always checking in through my screen, for your great advice and enriching conversations. Somebody else will have to take the Vasaloppet challenge now. Sven, thank you for always having your door open and for making CNDS happen. Also, for having patience with my bad Swedish! Thomas, thank you for your always creative ideas and enthusiastic attitude! Thanks also to Giuliano, who stepped in for the last sprint with great ideas. Next race I'll beat you!

And my co-authors Barbara, Hjalmar, Lars-Åke, and Sammy. The papers would not have been the same without your valuable contributions.

Second to my office. Even if it has changed places a couple of times during the PhD I always had the luxury to share it with the best officemates ever: Adam and Jean-Marc. It is impossible to find smarter, more talented, funnier and nicer people to spend 8 hours a day with. I love the nonsense talks, office workouts (!), ephemeral Christmas music band reunions, ... Adam, I feel I have abused your wisdom quite a lot during these years, and JM, thanks for refreshing the daily routine!

And LUVAL/Geo. I can hardly imagine a better department to be at than this: nice, smart, and funny people, a relaxed and cosy environment, and fika on Thursdays. What else can a PhD student ask for? A huge thank to you fellow colleagues and friends, present and past, for all laughs, the support, and for making this place feel like home: Reinert, Bea, Eduardo, Diana, Martin, Nino, Magnus, Saba, Kaycee, María, Lebing, Audrey, Estuardo, Carmen, Korbinian, Dorothée, José-Luís, Steffi, Jochen, Ida, Tom, Ester, Allan, Anna, Tito, Peggy, Michael, Viveca, Elías, Veijo, Zhibing, Aggela, Fred, Abi, Bojan, Sílvia, Peter, Roger, Caterina, Fritjof, Claudia, Erik, Christian, Daniel, ... I have learned a lot from all of you! Thanks also to Tomas, Anna, Leif and Taher for always being so helpful.

To the CNDS family. Even if we don't see each other that often it feels like being a part of a big family. It has been a terrific experience! Plunging into this interdisciplinary roller-coaster has been an eye-opener in many ways. I have learned so much from all of you — junior and senior — and it has been so much fun as well!

Till Uppsala, till alla som har gjort staden känna sig som hemma. Till glada Philochoros och folkdansgrupp på Geo. Till Wudang Pai, för att vara en oas av lugn och ro. To the good friends Alex, Sara, Víctor, Nilsa, Helga, Chris, the Björgúlfsson family, Friedel, Adam, José Luís, Agnes, and many more.

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Gràcies a la gent de casa, per cuidar-me i animar-me quan més ho he necessitat, i per totes les alegries i moments compartits. Gràcies als terrassencs, gràcies als geòlegs, merci aux grenoblois! Tots vosaltres teniu una gran part de responsabilitat en que ara estigui tancant la pàgina del doctorat.

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Thank you.

# 8. Sammanfattning på svenska (Summary in Swedish)

Att förstå och styra naturmiljön har varit en av de viktigaste drivkrafterna i samhällsutvecklingen, från utvecklingen av akvedukter och vattenkvarnar under antiken till användningen av moderna satellitdata idag. Men vi kan bara styra vattnets naturliga fördelning i begränsad utsträckning och vår kunskap om det hydrologiska kretsloppet är fortfarande begränsad. Samhällets sårbarhet för hydrologiska extremhändelser har ökat under de senaste hundra åren på grund av ökad befolkningstäthet, ökad koncentration av resurser i riskområden, landskapets omformning, och miljöförstöringen. Forskning kring vattenförvaltning och dess praktik har utvecklats mot mer övergripande och heltäckande tillvägagångssätt för att hantera de utmaningar som följer av sammanlänkningen av samhällssystem och hydrologiska system och återkopplingar mellan dem.

Information om olika processer och tillstånd i ett system är avgörande för att kunna förvalta systemet på ett bra sätt. Från ett vetenskapligt perspektiv är information om nederbörd, avrinning och avdunstning grundläggande för all vattenförvaltning. Dessa flöden styr vattnets tillgänglighet och variabilitet i tid och rum. Information om dessa flöden finns ofta på många olika ställen och är ofta inte homogen och jämförbar. Dessutom är dess representativitet ofta begränsad. Den geografiska tätheten hos denna sorts mätningar har trots allt ökat i många delar av världen vilket har möjliggjort en bättre vattenförvaltning. Hårda hydrologiska data är dock inte de enda relevanta informationskällorna för vattenförvaltningen. Information om effekter och skador av extrema händelser som översvämningar och torka är också viktig. Dessutom är kunskap om människors beteende under extrema händelser avgörande för att maximera potentialen hos tekniska verktyg som t.ex. översvämningsprognoser. Den tekniska utvecklingen har vidare gjort det möjligt för människor att observera och sprida information om sin omgivning i nära realtid. Denna nya och oftast mjuka information har potential att komplettera befintliga hårda data för att förbättra riskhantering och skadebegränsning.

Denna avhandling syftar till att öka kunskapen om informationsbehov inom vattenförvaltning och riskhantering genom studier som berör olika aspekter av vattenhushållningen. Tillvägagångssätten i delstudierna varierar från disciplinära till tvärvetenskapliga. Målet har varit att förbättra kunskapen såväl om enskilda processer som om hur samhällssystem och hydrologiska system är sammankopplade och återkopplade. Avhandlingen består av två huvuddelar. Den första belyser förhållandet mellan tätheten hos hydro-meteorologiska givarnät och skattningen av avrinning och areell nederbörd. Den andra belyser möjligheterna att använda icke-traditionell, mjuk information såsom befolkningars minne av tidigare översvämningar och realtidsinformation från sociala medier rörande översvämningar för att förbättra hanteringen av översvämningar och begränsa deras negativa konsekvenser.

Floden Thurs avrinningsområde i nordöstra Schweiz användes för att utvärdera tätheten i hydro-meteorologiska givarnät för mätning av vattenföring och areell nederbörd eftersom det finns en stor mängd hårda data i detta område. Olika metoder från interpolationstekniker till hydrologiska modeller användes. Resultaten visade att en ökad mätartäthet över tröskeln 24 regnmätare per 1000 km$^2$ gav obetydliga förbättringar i skattningen av arealnederbörd. Omvänt, när mätartätheten minskades i avlägsna och högt belägna områden kunde nederbördsskattningen påtagligt äventyras, med risk för att skyfall som orsakade stora översvämningar nedströms inte blev upptäckta. Tillgången på detaljerade nederbördsdata bidrog också till förbättrade skattningar av vattenföring. Samtidigt kunde användningen av begränsade nederbördsdata på vissa platser ligga till grund för lika bra vattenföringsberäkningar som mer detaljerade nederbördsdata. Jämförelsevis visade sig detaljerade vattenföringsdata, snarare än nederbördsdata, mest påtagligt förbättra hydrologiska modellresultat.

Befolkningars minne av tidigare översvämningar är en av de viktigaste faktorerna bakom samhällets beredskap, d.v.s. förmågan att reagera på en översvämning på lämpligt sätt. Denna faktor, och därmed dess inverkan på effektiviteten hos olika åtgärder är dock svår att uppskatta då det finns mycket lite data för analys av samhällsminnet. En enkel teoretisk modell utvecklades därför grundad på väletablerade fakta och grova förenklingar som ett första steg för att uppskatta minnets inverkan på tidiga varningssystem för översvämningar, en vanligt verktyg för att hantera översvämningsrisker. Resultaten visade att med tidiga varningssystem kunde man minska storleken på samhällsskadorna betydligt mer när befolkningens minne hölls vid liv och endast avtog långsamt. Detta underströk vikten av att vidmakthålla befolkningens minne mellan översvämningar för att minimera skaderisken.

Slutligen studerades användningen av information från sociala medier för att i nära realtid uppskatta omfattningen av en stor översvämning i centrala

Texas, USA, i maj 2015. Denna händelse valdes på grund av sociala mediers stora påverkan och tillgången till användbar information. Det är viktigt både för beslutsfattare och för den personal som först kommer till platsen att känna till omfattningen på en översvämning för att kunna rädda liv och begränsa skador. Tyvärr är etablerade metoder för att få sådan information begränsade i tid och rum och förutsätter stora mängder traditionella data. Detta var grunden till att utveckla en enkel metod för att uppskatta omfattningen på det översvämmade området genom att extrapolera översvämningsinformation som delats av enskilda medborgare i realtid. Den föreslagna metoden lyckades korrekt återge översvämningens omfattning lika väl som traditionella metoder, vilket belyste potentialen hos dessa nya informationskällor för riskhantering och åtgärdsplanering.

Resultaten från delstudierna bidrar på ett övergripande sätt till olika aspekter av det allmänna målet att förbättra kunskapen om vilken information som ger stor nytta för vattenförvaltning och för hantering av översvämningsrisker. Bidragen tillför förhoppningsvis viktig kunskap om hur ny, mjuk information kan komplettera effektivt utnyttjade traditionella data för att förbättra vattenförvaltning och en praktiskt användbar riskhantering.

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