Université rennes 1
Géosciences rennes

Habilitation a Diriger des Recherches

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Reshaping the Critical Zone with Hydrogeodesy

Soutenue le 22 février 2018 devant le jury composé de :

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A mes chers catepillars . . .

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Forewords and Introduction

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This document summarizes the research activities I have been leading during the last eight years within Geosciences Rennes and the "Environmental Dynamics" team. The developments undertaken are rooted in my doctoral work (Longuevergne, 2008); they have evolved at the rhythm of reflections and experiences, meetings and discussions. They have been enhanced by close team-wide interactions in Rennes, and collaborations with several researchers in France, Europe and all over the world. The originality of the research I have conducted owes a lot to constructive interferences with researchers from other disciplines, but also from a focused work specific topics.

The main contribution lies on the development and qualification of geodetic instruments as tools for hydrology, mainly driven by an instrumental and experimental approach. The first chapter introduces the concept of the *Critical Zone*, which is re-interpreted as a dynamic notion to better include the full role of groundwater within the water cycle on a wide range of temporal scales. As water is in permanent contact with rock, I also underline the physical interactions between the "Critical Zone" and the "Solid Earth", suggesting the opportunity to fertilize the reciprocal input of both discipline.

Among the Solid Earth tools, geodesy offers a wide range of highly accurate instruments, stable and well calibrated, which can be used to capture the spatio-temporal redistribution of water in the subsurface, from surface and space-borne observations. The second chapter explores their ability to estimate water storage and pressure changes and bring insights into the heterogeneous, and hidden Critical Zone. Quantifying water transfers in the Earth's subsurface is motivated by basic scientific questions and major challenges, such as the management of (water) resources, the exploitation and storage of resources and energy, the sensitivity of the subsurface to deformation, the understanding of the links between the external and internal envelopes of the Earth.

Then, the future challenges I want to explore are described in the third chaper, namely (1) the non-linear nature of fracture flow and transfer processes; (2) the imaging of subsurface flow and their control by heterogeneities; (3) the full representation of the groundwater role in the Earth's climatic system; and (4) the inter-relationship between the different compartments composing ecosystems, through a large-scale experiment.

The document concludes with a detailed curriculum including a list of publications (mostly in French).

The Critical Zone : What is the role of Groundwater ? 2

> Le chaos de Ciel-terre était comme un œuf de poule, Pankou était en son milieu. Au bout de 18 000 ans, Ciel-terre s'ouvrit, le clair et léger yang devint le ciel, l'opaque et lourd yin devint la terre. Pankou était au milieu. Chaque jour, il y avait 9 transformations. Le spirituel était dans le ciel, le sacré dans la terre. Le ciel de jour en jour s'élevait de 10 pieds, la terre, de jour en jour, s'épaississait de 10 pieds. Pankou, chaque jour, grandissait de 10 pieds. Il en fut ainsi pendant plus de 18 000 ans. Le ciel était immensément haut, la terre immensément profonde, Pankou était très grand. Le premier être, Pankou, sur le point de mourir, transforma son corps. Son souffle devint le vent et les nuages, sa voix le tonnerre et la foudre, son œil gauche le soleil et son oeil droit la lune, ses membres les pôles et les monts (les extrémités de l'univers (les pôles et les monts)), ses coudes, ses genoux et sa tête devinrent les cinq monts sacrés ; son sang et ses humeurs formèrent les fleuves et les rivières, ses muscles et ses veines, les reliefs de la terre, sa peau la terre des champs, ses cheveux et sa moustache la marche des étoiles, les poils de son corps la végétation, ses dents et ses os devinrent les métaux et les roches, sa moelle les perles et le jade, sa sueur la pluie, et sa vermine, disséminée par le vent, le genre humain.
>
> Xu Zheng, *Annales des cinq éléments*

Sommaire

Water is ubiquitous on Earth, from the mantle to the atmosphere. For ecosystems, water is both a key component - sustaining life, and a key actor - transporting energy and nutrients. As a liquid, water flows from high to low altitudes, where it becomes an asymmetric driver, connecting and structuring different elements of our usual landscapes. The recent notion of the "Critical Zone", this thin layer on which natural ecosystem and human relies, has reset the essential role of water within, and at the intersection of the Earth's biogeo-chemical and -physical cycles.

The essential part of continental water is hidden, stored in groundwater systems, where it flows and interacts with the lithosphere, surface and aquatic ecosystems, atmosphere and oceans. Water is in direct contact with the hosting aquifer rock, where both interact physically by a two way fluid-solid coupling. Therefore, aquifer structure, mechanics, flow and storage are intimately related. This opens new potentials to use rock deformation as a tool to image aquifer active structures and groundwater flow.

This chapter paves the way from the Critical Zone challenges towards the fundamental role of deformation to shape and inform about groundwater flow.

2.1 The Earth System

2.1.1 A complex system

If the Earth's history could be compressed in a single year, the age of Homo Sapiens would have begun 20 minutes before the end of the year, modern civilizations would be no more than the two last minutes, a human life : just a few milliseconds. Though, life appeared as single-cell organisms on February 25th, stromatolites begun to release oxygen in the atmosphere on March 20th and the Earth went through several mass extinctions, ice ages and continental ballets (e.g. Stanley, 2009).

The first developments on Earth's history popped up the last day after 23h59, during the 19th century. Since Charles Darwin (1809-1882), Life and Earth Sciences have integrated a historical dimension, a narrative dimension. But it's a strange story, a "once upon a time" that no human being has witnessed but which is inscribed in all living beings and the present configuration of our planet (J.C. Ameisen, *Sur les épaules de Darwin*). Darwin explored the evolution of the living and the Earth, and proposed that nature does not jump but rather acts by infinitesimal slow changes over times exceeding human's imagination. The pillar of his theory was inspired by the gradualist theory of the geologist Charles Llyel (1797-1875), his contemporary. His principles of geology propose that there is no need to postulate the existence of catastrophes to account for the gigantism and the extraordinary diversity of the reliefs of the planet. According to him, the geological evolution implies forces still operating in the present. The depth of geological times explains how trivial events at the scale of human life are able to carve landscapes. The single question was : to which extent are we able to observe, interpret and represent these operating forces ?

At the same period, thorough observations by Alexander von Humboldt (1769-1859) further underlined the complex interplay between Earth's internal, external and living systems, which motivated a holistic perception of the Earth as one interacting entity. Vladimir Vernadsky (1863–1945) granted to the biosphere the same role as a geological agent, generating a dynamic disequilibrium to promote the diversity of life. James Lovelock (1919-) further suggested the biosphere as a critical feedback mechanism within the Earth system. While the impact of the biosphere is obvious in several examples, the idea of the co-evolution of the different components of ecosystems, driven by external (astronomy) and internal (geological) drivers, seems more realistic (to me).

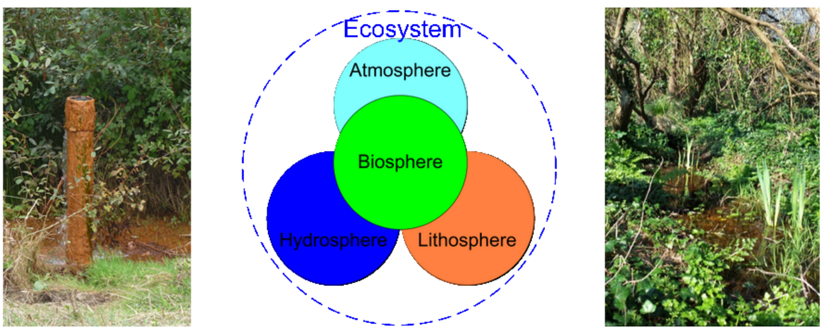

Figure 2.1 – *Representations of ecosystems. Left : Upwelling of iron-rich groundwater from an artesian well in Guidel (France), creating specific subsurface microbiotic ecosystems based on the oxydation of iron. Middle : the concept of ecosystem developed in this work, as the interlock and interplay of the litho, hydro, atmo and bio-spheres. Right : Groundwater-dependent ecosystem in Guidel (early March) benefiting from warm groundwater upflows*

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In this work, I will follow more closely the definition of Arthur George Tansley (1871-1955). According to him, an ecosystem is defined in the sense of physics, as the indivisible system of biota and environment, where both organic-inorganic cycles are completely integrated. The different compartments (litho-, hydro-, atmo-, bio- spheres) are constantly interacting and participate to the functioning of ecosystems 2.1. This implies the need to gather beyond the classical disciplinary dichotomies to identify the actual dynamics of ecosystems.

There are indeed growing evidences of the self-organization and co-evolution of the different spheres, which are still not fully understood and remain as open questions, for example : (1) between the litho- and hydro- spheres, the clear link between volcanic system age and water flow organization (Yoshida & Troch, 2016), but also the idea that the amplitude of the hydrological cycle is a primary control of the shallow crust permeability (Rojstaczer et al., 2008) ; (2) between the litho- hydro- and bio- spheres, the alignment between seasonal water storage, eco-regions and soil orders (Berghuijs et al., 2014). Finally, the "anthropo" -sphere has now become a full agent on Earth's (Crutzen, 2002). His activities have been reshaping the Earth in many ways, destabilizing all the different components and blurring the defined equilibrium.

2.1.2 The crucial role of interfaces

The water molecule has notable properties : storing and regulating energy (high specific heat capacity, high latent energy of vaporization), reacting with its environment and dissolving substances. Therefore, water has an ubiquitous nature within the Earth System in general, playing an array of vital roles. It is both a key component - sustaining life, and a key actor - transporting energy and nutrients. As a liquid, water flows from high to low altitudes, where it becomes an asymmetric driver, connecting different biotopes/units and providing structure among them.

Water flow shapes ecosystems and ecosystemic services in many ways. Indeed, the multiplicity of water flow paths, within the heterogeneous surface and subsurface geological layers, favour a differential evolution of the waters (age, physical and chemical properties) (De Marsily et al., 2005; Alley, 2002). As these different waters converge to specific zones, called interfaces, they create gradients and host ecological, biogeochemical and hydrological processes favouring specific habitats and biodiversity (Sophocleous, 2002; Stegen et al., 2016; Krause et al., 2017). Such vital structures are manifold but generally localized at geological boundaries, and blurred by water flow (figures 2.2 and 2.3) :

— the water-atmosphere interface, in aquatic ecosystems or at shallow depth interface, accumulating energy ;
— the water-air interface in the subsurface (e.g. the capillary fringes between shallow saturated and unsaturated zones) ;
— the water-water interface between terrestrial upland and lowland aquatic ecosystems, groundwater-surface water interfaces, including those associated with riparian or hyporheic zones.

Topography and the substantial heterogeneity of geological layers promote both the divergence of water flow path and its convergence towards interfaces (Hubbard & Linde, 2011; Ben Maamar et al., 2015).

Figure 2.2 – *Cyanobacteria distribution in the Atitlan lake (130 km^2), Guatemala. This image was captured from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on NASA's Terra satellite. The complex spatial structure is inherited from the competing contributions of localized nutrient inflows (rivers, groundwater) and mixing generated by wind and lake hydrodynamics.*

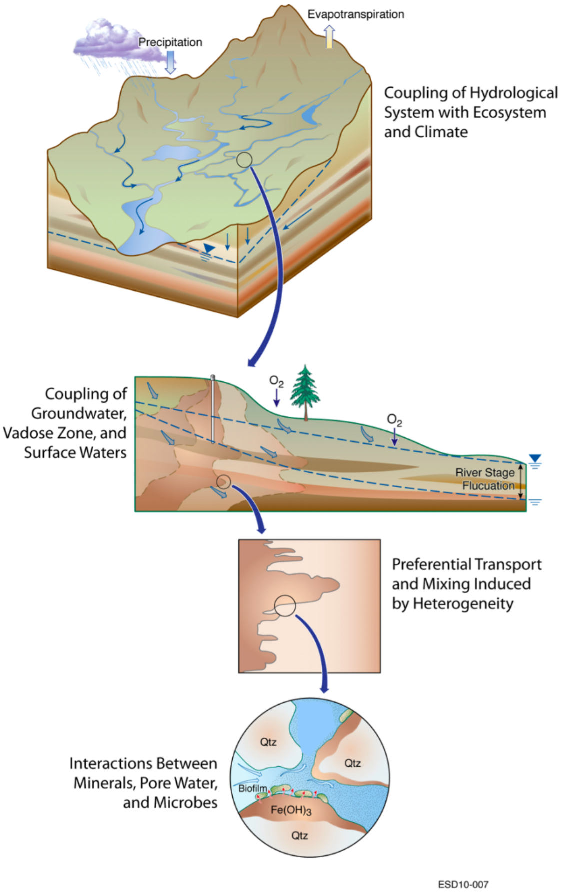

Figure 2.3 – *From system scale down to pore scale, interfaces develop when mixing different waters (here, oxygen-rich young water infiltrating in the subsurface and older water) and play a significant role in the emergence of hotpots, key factors for the functionning of biogeochemical cycles. Topography and the substantial heterogeneity of geological layers promotes both the divergence of water flow path and its convergence towards interfaces (figure from Hubbard & Linde, 2011).*

2.1.3 Current challenges

The question on the inter-relations between water flow and ecosystems, and how they will evolve under anthropogenic and climatic pressures remains as daunting challenges. Will ecosystems be mainly impacted by increasing water stress, requiring systematic restoration projects (e.g. Zedler & Kercher, 2005), or will interfaces contribute to maintain their resilience (Krause et al., 2017) ? These questions raise (among others) the issue of defining these interfaces at the intersection of subsurface water flow paths and their interactions. Such questions are by essence complex considering the multi-scale heterogeneity of geological layers, their long response time and the wide range of spatio-temporal scales covered by boundary conditions : spatially from focused recharge and pumping to continental-scale flow ; temporally from (more) intense rainfall events to interannual stresses.

The complex spatial structure of the cyanobacteria blum in Atitlan lake, as observed by satellite optical imagery (figure 2.2) is a meaningful example on how different processes - with different spatio-temporal signatures - interact, combine and shape the lake ecosystem. The spatial and temporal structures can be seen as emerging patterns, a collective behavior of smaller scale units, expressing the intricate interactions among compartments, which are key to decipher ecosystem functioning (Levin, 1992).

The challenge is now set : defining tools and methods to image how water flows within ecosystems, and how the heterogeneous structure of the geological media contribute to generate hotspots at movable interfaces. High spatial and temporal resolution over a wide range of scales is therefore required to capture emerging patterns driven by water flow and water flow paths in the subsurface.

2.2 The emergence of the Critical Zone

2.2.1 Water as a vector of interdisciplinarity

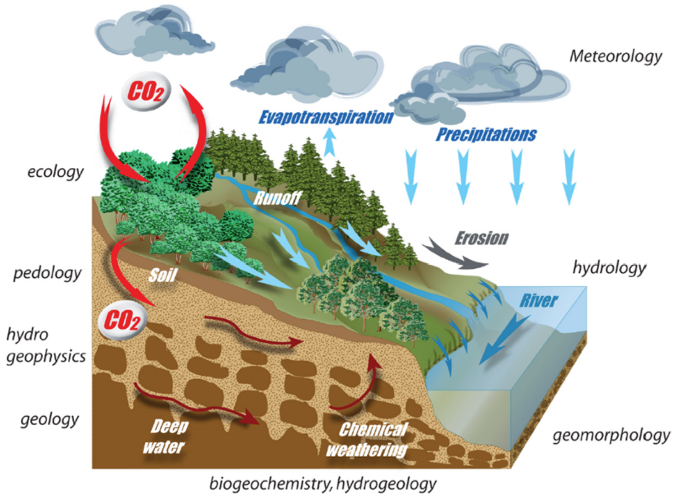

Figure 2.4 – *Studing the Critical Zone requires to go beyond the classical dichotomies among disciplines. As a Complex System, the CZ is a privileged meeting place where the ensemble is more than the single sum of the different compartments*

Following the need to better represent water as an agent in ecosystems, the concept of "Critical Zone" (CZ) was proposed (NRC, 2001) as the "life support system that integrates climate and soil to the deepest weathering". The Earth's CZ is defined by its fluids as the "heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources". The CZ therefore joins - and expands - Tansley's vision of the ecosystem (Richter & Billings, 2015; Gaillardet, 2014).

Basically, the CZ is a holistic framework reconciling geological, hydrological and biological cycles. It provides fertile ground to encourage interdisciplinary research exploring the interactions among the land surface, vegetation, and water bodies, and extends to the unsaturated vadose zone and saturated groundwater zone. CZ science is the integration of Earth surface processes (such as landscape evolution, weathering, hydrology, geochemistry, and ecology) at multiple spatial and temporal scales and across anthropogenic gradients (figure 2.4).

NRC (2001) also underlines the fragility of this finite and thin layer (with respect to the Earth's radius) on which the natural ecosystem relies. The CZ is also critical for humanity because this is where we live, where we build our cities, from which we extract our food and our water and where we release most of our wastes. Humans have now become geological agents (Crutzen, 2002; Waters et al., 2016), destabilizing the "natural environment" in many ways (Rockstrom, 2009). This raises the question of sustainability and our own future remains as a major challenge and a societal concern.

2.2.2 Water Flow and Storage in the CZ

Water can be transiently stored over a wide range of temporal scales in the different compartments of the CZ (Aeschbach-Hertig & Gleeson, 2012), consumed by humans and ecosystems, exchanged with the atmosphere and oceans. Each storage compartment (unsaturated zone, river and lakes, groundwater systems) plays its own role and interacts, so that all together they shape the CZ.

The unsaturated zone (soil) is one of the most dynamical compartment, gathering rainfall and providing feedback to the atmosphere as evapotranspiration. Water storage,

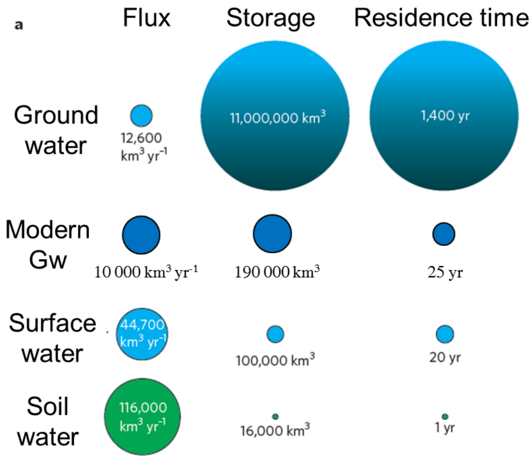

FIGURE 2.5 – *Water flow, storage and residence time for different storage compartments. The "modern" portion of groundwater significantly contributes to the water cycle. Adapted from (Aeschbach-Hertig & Gleeson, 2012; Gleeson et al., 2015).*

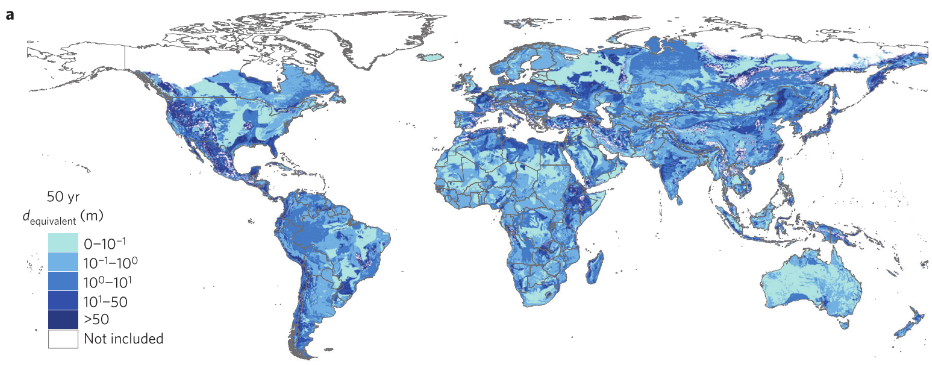

FIGURE 2.6 – *The global distribution of modern groundwater (25 yr residence time) as an equivalent water thickness if it was extracted and pooled at the land. From Gleeson et al. (2015)*

though, is limited, so that the typical residence time (transit time) is limited to a single year. As the world's largest accessible store of freshwater, groundwater (GW) has limited exchanges with the surface. Although the mean residence time is $\sim 1400\ yr$, it is distributed over a wide range. The modern portion of GW storage (i.e. defined by the shortest water paths, residence time $< 50\ yr$), contributing to the water cycle cannot be neglected (Gleeson et al., 2015), and is globally equivalent to twice the amount of water stored as surface water 2.5, representing an equivalent water thicknesses of a few meters (figure 2.6), with high spatial variability.

The mean residence time is here defined as the average time spent by the fluid in a volume, and computed as the ratio between storage in the compartment and the steady-state outflow (or inflow) within this store (under the stationarity hypothesis). When dealing with flow, the notion of response time is more appropriate, and defined as the time required for the (physical) system to react to an input (deviation to steady-state). Response times are generally much shorter than residence time : while pressure variations travel fast, water drops can take ages, interacting with rocks and transporting solutes and nutrients. At hillslope scale, the typical residence time is tens of years, while response time is of the order of days. At watershed scale, the typical response time as measured in rivers is $\sim 1\ day$ for surface water, a few days for the shallow subsurface and generally several tens of days for groundwater systems (Andermann et al., 2012; Brutsaert, 2008), but can range to millions of years for the largest aquifer systems (Rousseau-Gueutin et al., 2013). In essence, groundwater conserves the memory of past events, much beyond the typical residence time of surface ecosystems.

2.2.3 Groundwater, invisible but omnipresent

GW is hosted in thick and complex heterogeneous aquifers, where water flows in both horizontal and vertical directions over depths up to kilometers, locally intercepting the surface where it interacts with rivers or wetlands, and therefore atmosphere and ocean (Alley, 2002). GW flow is strongly influenced by topography, creating shallow (local) to deep (regional) circulation loops towards minimum topography (Toth, 2010; Goderniaux et al., 2013), and modulated by significant heterogeneities.

GW influence on Earth's system is globally prevalent (figure 2.6) as it forms environmental gradients not fully captured by the climate (Fan, 2015). As an example, groundwater appears shallow in topographic depressions under all climates, a result of lateral convergence from topographic high to lows. GW sustains river and ecosystems (Fan et al., 2013), control surface energy balance though atmospheric feedback (Bierkens & van den Hurk, 2007; Maxwell & Condon, 2016) and condition chemical weathering and the CZ evolution (Maher & Chamberlain, 2014).

Ground water is also an ubiquitous source of high-quality freshwater. These characteristics promote its widespread development, which can be scaled and localized to demand (Taylor et al., 2013). As a buffer, it is supporting food security (Scanlon et al., 2012), adaptation to climate variability, and is now deeply embedded in international food trade (Dalin et al., 2017). The increasing climate variability is expected to intensify the strategic importance of GW (Gerten et al., 2013). Despite these vital contributions, IPCC highlighted the critical need to improve understanding of GW behavior and response to climate change and anthropic use (Bates et al., 2008).

2.2.4 The (not so) specific case of fractured aquifers

Fractured rock aquifers are widespread structures on the Earth, covering 1/3 of continental surfaces, but more than 80% at $\sim 1\ km$ depths (Bense et al., 2013). Fractures generally have limited thickness, but their length ranges from a few millimeters to kilometers. They have a major control on :

— water flow and transfer properties (Tsang & Neretnieks, 1998),
— elastic properties of rock masses (Kachanov, 1992).

Fractures shape connected fractured networks having scale-dependent properties (Davy et al., 2010). The growing societal needs for freshwater, energy extraction/storage and waste management imply that geological fractured reservoirs are increasingly subject to multiple (competing) pressures. Considering the scarcity of appropriate data, they present unique and well identified challenges for (1) the evaluation and monitoring of their structure and properties (NRC, 1996; Cornet, 2016) and (2) the modeling of flow and transport (e.g. De Dreuzy et al., 2012).

2.3 Experimenting the Critical Zone

2.3.1 Modeling water flow in the CZ

Models can be seen as a synthesis of the current knowledge. Understanding the mechanisms of water flow and storage, and their response to anthropogenic and climatic destabilization, remains as a major scientific challenge and an open question that had and will focus important research efforts (e.g. Montanari et al., 2013; Sivapalan, 2017).

The mining of groundwater resources is a good global-scale example of the current challenge to model the CZ. In several regions, water pumping in groundwater systems is accelerating the water cycle. Unsustainable water management is one contributor to sea level rise (Cazenave et al., 2014). Yet, the estimation of the impact of water management at global scale is complex and controversial (Pokhrel et al., 2012; Döll et al., 2014; Wada, 2016; Konikow, 2011), and hydrological models suffer from limited predictive abilities (Schewe et al., 2014). Wada et al. (2013) show that the uncertainties associated with the modeling of water flows in the subsurface largely exceed the uncertainties associated with atmospheric circulation models and the greenhouse gas emission scenarios. Finally, unlike model predictions, recent observations have shown that continents have been acting as water sinks over the last 10 years, offsetting the background increase of sea level rise (Reager et al., 2016).

Recent shifts in model implementation propose to meet this challenge with hyper-resolution (Wood et al., 2011), hypothesizing that all heterogeneities will disappear and that the governing equations used will match the spatial scales of the processes one is trying to model (Clark et al., 2017). Yet, it is expected that the poor model predictability is mainly linked to (1) a limited representation of subsurface heterogeneity, which is not stopping at a specific scale ; and (2) the poor understanding of processes at the scale of interest (Beven, 2006). A new paradigm is now rising in modeling within the Earth System approach : considering the functional role of one phenomenon, in opposition to the mechanist approach (Sivapalan, 2017). For example, groundwater irrigation modules in global hydrological models do not explicitly represent groundwater systems, but rather estimate crop requirements, with potential water stress (Muller Schmied et al., 2016).

A descriptive challenge. The mechanist modeling approach, originating from the compelling need to describe soil-atmosphere interactions, has been developing quickly over the last years with the sharp increase of computing power and the availability of global descriptive datasets (e.g. topography (Jarvis et al., 2008), vegetation and land cover (Global Land Cover Characterization (GLCC)), soil parameters (Hengl et al., 2017)). Recent studies have tried to estimate hydrodynamical properties from main geological structures (Gleeson et al., 2014; Fan et al., 2016), yet, the multi-scale heterogeneity of geological layers (Figure 2.3) is still not captured and described, although localized structure can significantly control water flow (De Marsily et al., 2005). Lack of knowledge also remains in boundary conditions. At short time scales, one of the first source of uncertainty is linked to forcings datasets and mainly precipitation. Several works underlined the large variability among different state-of-the-art precipitation datasets (Beck et al., 2017) with large impact on model results at seasonal (Schellekens et al., 2017) and long-term time scales (Felfelani et al., 2017). Uncertainties in forcing dataset might be as high as the differences among an ensemble of models in a few regions (especially in monsoonal and semi-arid regions). Further, evapotranspiration is still poorly constrained (Long et al., 2014a; Jung et al., 2010), while representing 50% of global fluxes.

A representation challenge. Beyond the scale-dependence of process representation, the strong non-linearity of low processes emerges as a general pattern : flow processes are storage dependent (van Genuchten, 1980), flux dependent (Taylor et al., 2012), temperature dependent (Walvoord & Kurylyk, 2016), and pressure dependent (Rutqvist & Stephansson, 2003). The effective way to represent such processes is still not fully clear, and may be thought as geology/climate driven. Indeed, non-linearities appear with the inter-relationship of the different compartments, either groundwater - and connectivity to surface (Goderniaux et al., 2013), or vegetation - redistributing rainfall between storage, runoff and infiltration (e.g. Favreau et al., 2009). One more time, this underlines the need to explicitely represent all compartment functions to model the CZ.

A complexity challenge. The inter-relationship among the different compartments is even more critical when studying the trajectory of the Earth's system, as a coupled atmosphere-ocean-cryosphere-continent object. The questions of (1) the impact of interannual climate variability ; and (2) the response to the intensification of the water cycle ; are focusing a lot of attention, considering both the source of variability that arises through internal and external mechanisms (Figure 2.7, Mitchell, 1976; Mitchell et al., 2015), and the range of response time for each of these compartments (Pail et al., 2015). It is expected than interannual climate variability (Sutton & Dong, 2012; Le Treut et al., 2007) drives to more frequent extreme events and extended droughts (Green et al., 2011; de Marsily & Abarca-del Rio, 2015) and can impact the course of history (Turner & Sabloff, 2012). In a modelling study, Ngo-Duc et al. (2005) detected a strong decadal variability and critical interactions between continents and oceans. At such time scales, "inertial" compartments, such as GW and oceanic systems, are expected to play a significant role. As underlined, aquifers have large storage capacity, but are yet under-represented.

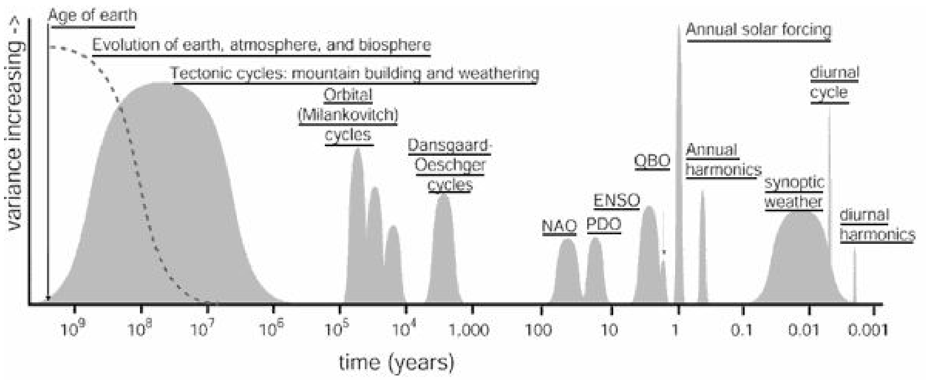

FIGURE 2.7 – *Internal and external processes defining the evolution of the CZ. Adapted from Mitchell (1976).*

The observational challenge emerges from the last 3 challenges : the critical need to define structures, processes and linkages at useful scales. It is now accepted that the information content of the available observations might be weak to further improve models. Flow measurements integrate in time and space, well data are sparse (relative to heterogeneity) and represent the local state of intercepted structures. According to Beven (2006), significant advances can only be made with new observational techniques, which provide integrated flow and inventory information at useful scales. A last issue is linked to the length of observations, which are certainly limited with respect to known sources of variability. Any trend or acceleration over a limited time range can be the expression of a longer-term cycle (Eicker et al., 2016).

2.3.2 Seizing on the observation challenge

Observation is one of the three pillars of science, with processes representation and modeling, and creates the link from basic knowledge to decision making and management. Observations have therefore many objectives, including (1) answer scientific questions, test hypothesis and understand processes (2) feed conceptual/predictive models with highly informative data and (3) monitor system evolution and generate early warnings. Many different observation types would be required to capture all processes within the CZ, we will focus on a general strategy to capture the dynamic nature of the CZ.

How does flow in heterogeneous media translates in the observation challenge ? As highlighted in the previous sections (Figures 2.2 and 2.3), one of the main challenge is associated with the multi-scale heterogeneity of the CZ, in which water flows. High resolution observations seems essential (figure 2.8) to advance on process understanding and pattern extraction. The main difficulty consists in defining the right scale of heterogeneity, which is a concept relative to the process media and a time scale under consideration.

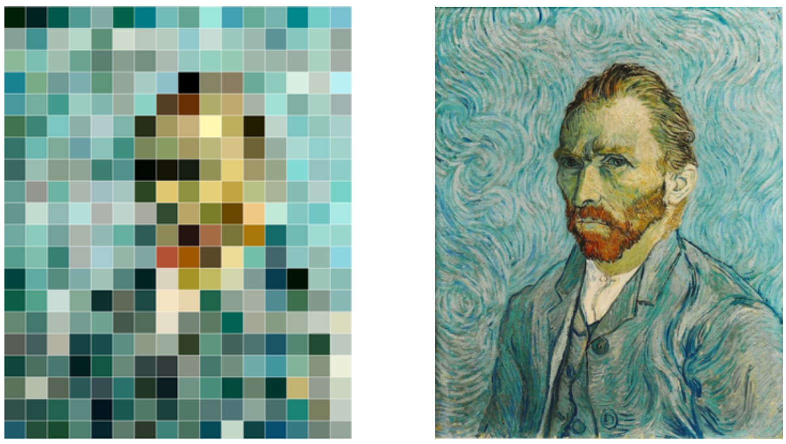

FIGURE 2.8 – *The critical need for high resolution observations over extended scales*

When considering water diffusion, both space and time are interrelated (Figure 2.9, which is roughly ranging between $[\,0.1 - 10\,]\; m^2.s^{-1}$. This might be understood in several ways. First, as a blindness issue (or an opportunity for simplification), flow erases heterogeneities and little information can be extracted on sub scale heteorogeneities, although they are important for transport processes (solute, energy transfer). Secondly, as a description issue, this sets the size of the domain to be described for a specific time scale (e.g. $5 - km$ domains at annual time scales).

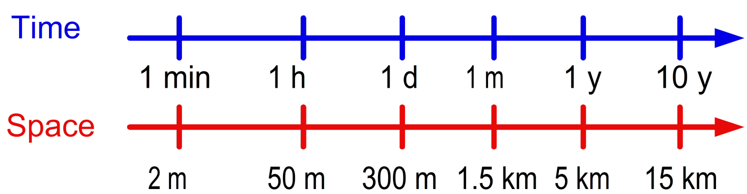

FIGURE 2.9 – *Interrelation between spatial and temporal scales for diffusion processes, considering diffusivity* $D = 1\; m^2.s^{-1}$

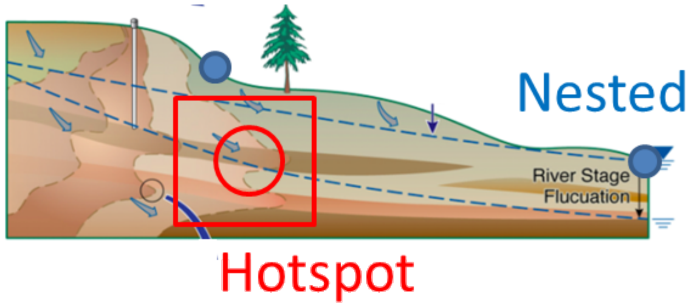

Figure 2.10 – *The complementarity between experimental and monitoring approaches. Blue points represent the location, at the surface, of integrative monitoring capturing some flow lines (or none). The red square highlights the active hotspot (at one specific moment).*

What observation strategies should be applied on the CZ ? Our knowledge of the CZ is often based on "tiny data" to answer both the structure and dynamics questions. Direct observations are available at the surface or in boreholes, both representing a limited fraction of the "volume" of the CZ. Transforming information into knowledge relies on process-based models to compensate for the sparse nature of direct observations. Both modeling and observation approaches are bi-directional (set context, improve predictive ability) and inseparable (e.g. Kikuchi et al., 2015). The complexity of flow and transport processes requires to tackle the question of the impact of heterogeneity with 2 main approaches :

— adopt an integrative approach to define the emergent properties (response/residence time, ...) at catchment scale and resolve the energy and mass balance

— identify hotspots, i.e. define the heterogeneity and its consequences on various processes. Further, the experimental approach can mitigate the space-time blindness to reach high resolution, by generating flow variability at much smaller time scales than natural flow.

In such a context, monitoring and experimental approaches fully complement each other (figure 2.10).

How could different observation types be combined to better capture CZ processes ? The CZ scientists have access to 2 different types of data (Grayson & Blöschl, 2001) :

— integrative information having a larger support than a defined heterogeneity scale - over a defined region (geophysics), along the flow path (geochemistry, temperature) or a set of flow lines (discharge)

— point information with limited representativity, but able to capture the steep gradients in space and time - soil moisture, well level, etc ...

Both observation types are generally used in common, with the holly wish to have a convergence between both points of view, either by spatial integration - requires high coverage (Longuevergne et al., 2007), or temporal deconvolution - requires high frequency observations (Floury et al., 2017). One more time, process understanding and their implementation in models is a privileged frame to perform both operations.

2.3.3 Geophysics to investigate hotspots within the CZ volume

Boreholes can be drilled to access the subsurface and focus on a specific zone. Granting a direct access to the subsurface is important to for various reasons : (1) physically describe the storage and permeable structures crossed by the borehole (Davy et al., 2010). Yet, it is representative for a $\sim 10\ cm$ domain over limited depth. This method leaves blind scales and under-constrained zones. The investigated volume is still limited with respect to the hotspot size and the hydrological system. (2) Perform experiments do define how these structures participate to flow, such as sinusoidal tests (Becker & Guiltinan, 2010), hydraulic tomography (Illman et al., 2009), dilution test (Jamin et al., 2015). Finally, boreholes might be an issue : they create flow shortcuts between permeable structures, and modify the natural processes to be imaged.

Geophysical methods have been developed for more than a century to complement or spatialize our limited knowledge of the subsurface. Geophysics relies on quantitative methods to explore how physical properties of the subsurface evolves in space and time. While these methods are generally used for characterization purposes (Parsekian et al., 2015), current research is moving towards their implementation to track dynamic processes (Binley et al., 2015). For the specific case of time-lapse or continuous investigations, different passive and active approaches have been developed to sense :

— the fluid, its saturation (storage structures), electrochemical interaction at grain interfaces (Singha et al., 2015), including biological processes (Atekwana & Slater, 2009), fluid velocity (Jougnot & Linde, 2013), as well as transport processes (Dorn et al., 2011; Robinson et al., 2016). Mapping methods, such as electromagnetic methods (Robinson et al., 2012) or gravity variations (Jacob et al., 2010), have also proven to be powerful to capture spatial patterns, continuity and lateral flow, which are also important characteristics (Jayawickreme et al., 2014)
— the rock response to fluid pressure changes, mainly sensitive to permeable structures (e.g. Hisz et al., 2013; Schuite et al., 2015).
— the mixed fluid-rock response such as temperature (e.g. Bense et al., 2016; Klepikova et al., 2014) or seismic (Pasquet et al., 2015b)

Geophysical tools offer undeniable advantages, able to identify subsurface spatial variability with minimally invasive methods and high resolution, complementing classical observations. Active methods generally rely on surface sources with limited energy and penetrating depth, impacting resolution at depth. In general, such methods (in environmental sciences) areapplied at scales below $\sim 100\ m$ (i.e. day scale flow). Passive methods (e.g. seismic methods (Lecocq et al., 2017)) are now developing quickly, offering larger investigation scales at the expense of lower resolution. The main limitation of geophysical methods lies in their indirect nature (Day-Lewis et al., 2017) requiring petrophysical models for quantitative interpretation (Linde, 2014).

2.3.4 My favorite CZO playground : Ploemeur Observatory

The Ploemeur site (figure 2.11)is part of the Research Infrastructure OZCAR dedicated to the observation of the Critical Zone. It is located near the south coast of Brittany (France), a region shaped by a large granitic pluton intruded during the Hercynian orogeny (325 Myrs). The contact zone between the granitic body and the schist has been described as a major permeable structure along which regional groundwater flow is upwelling (Touchard, 1999). The fractured crystalline aquifer emerges from the intersection of this contact zone, gently-dipping to the North (Ruelleu et al., 2010) and dextral-slip normal fault zone striking $N20\deg E$ (figure 2.12). Both constitutes the main transmissive structures of the aquifer, allowing distant water transfer beyond the topographic catchment. At the surface, crystalline rocks are partly weathered as a result of favorable climate during the Eocene period, with variable thickness generally ranging from 0 to 30 m. The site is highly monitored since 1991 (figure 2.11).

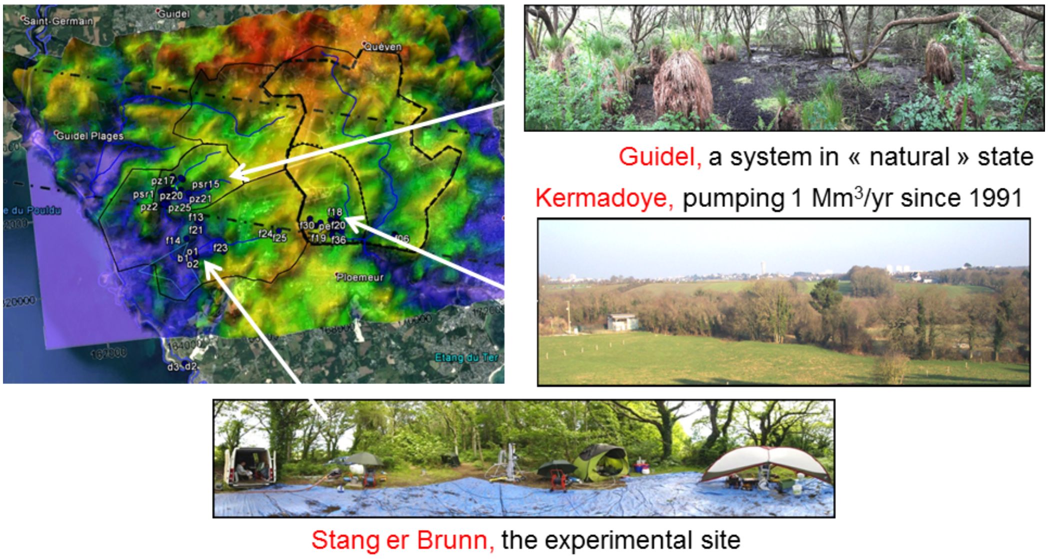

Figure 2.11 – *Localization of the Ploemeur Observatory (IR OZCAR) and the 3 sub-sites of interest : Kermadoye, the original site exploited for water resources, and monitored since 1991, providing* 1 $Mm^3.yr^{-1}$ *water per year ; Guidel, the same system in "natural" state ; Stang Er Bunn, the experimental site*

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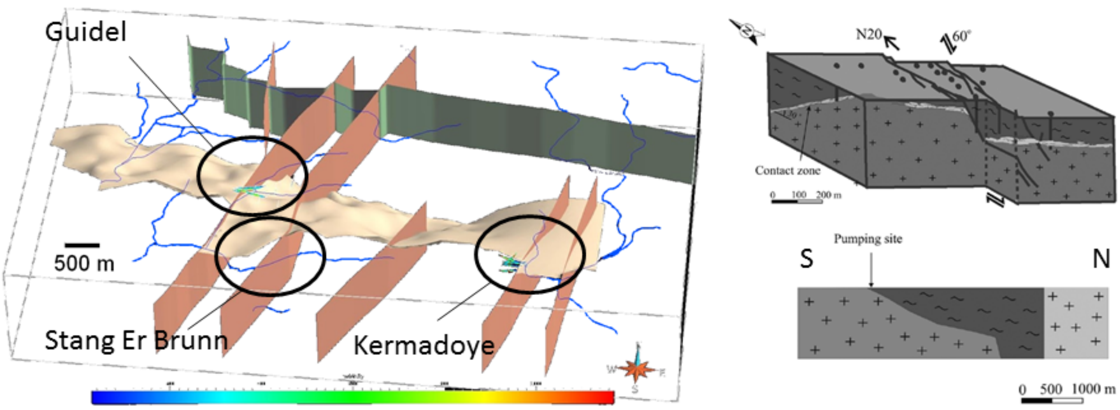

Figure 2.12 – *Geological context of the Ploemeur Region. Two main conductive structures shape the reservoir : the contact zone between the Ploemeur granite and mica-schist, and subvertical normal fault zones oriented* N20 deg *E with dextral strike-slip component.(Left) GoCAD geomodel higlighting these main structures at regional scale, superimposed with rivers at the surface : vertical fractures, the gently-dipping contact between Ploemeur granite (South) and micaschists shown as the pink surface, and the East-West vertical contact between micaschists and the Guidel granite (North). (Right) Structural sketches of the Ploemeur aquifer system from Ruelleu et al. (2010) : the contact zone between granite (cross) and mica-schist (tilde) getting sub-horizontal towards North, and a subvertical normal fault zone with dextral strike-slip component.*

The Ploemeur/Kermadoye site is exploited since 1991 for human water consumption, providing 1 $Mm^3.yr^{-1}$ of high quality fresh water per year to the community. This singularly high productivity - considering the geological context - is thought to be intimately linked to the large-scale structures and their capacity to drain large reservoirs (Roques et al., 2016). Indeed, the sub-horizontal contact zone can drain a large volume of overlying micaschists from a far-end recharge zone to the vertical fault, that allows for the vertical ascension of ground water fluxes towards the pumping site (Leray et al., 2013; Jiménez-

Martínez et al., 2013). Hydrodynamic properties depends on the scale of investigation (Jiménez-Martínez et al., 2013). Locally (i.e. at small time scales), the system needs to be seen as a connected fractured network with highly variable properties, while at larger scales (i.e. monthly time scales and beyond), properties are quite equivalent among wells. Despite the apparent complexity, few information is lost when considering the system as an homogeneous aquifer bounded by the defined permeable structures (Jiménez-Martínez et al., 2013).

Ploemeur/Kermadoye is surely the hydrogeological observatory gathering the most extended geodetic monitoring : 4 long-base tiltmeters (including 2 orthogonal tiltmeters to capture the orientation of the tilt vector), 4 Blum tiltmeters, 2 GPS stations. Most of these instruments were set in 2006 for a large-scale experiment. All pumps were stopped, the recovery of the aquifer was monitored by the latter instruments, plus gravimetric and leveling observations. Gravity variations showed no significant variations, setting a maximum value for the storage coefficient (below 0.05), confirming the confined nature of the aquifer. On contrary, tilt and leveling showed a very nice response that are presented later.

The site is also made of 2 complementary sub-sites, which are in the same geological (and climatic) context. The Guidel site is an equivalent to the Ploemeur/Kermadoye site, but in natural state. The site is also monitored by 25 wells and discharge stations (figure 2.11). GW resurgence is creating an extended humid-zone, providing insights on how was the Kermadoye site before the start of the large-scale pumping. Finally, Stang Er Brunn is an experimental site. Three 80-m wells have been drilled, separated by a few meters, and crossing the contact zone (Le Borgne et al., 2007). Considering the knowledge accumulated during numerous experiments, the site is a perfect tool to validate new methodological and instrumental developments (e.g. Dorn et al., 2011; 2012; Shakas et al., 2016; Jamin et al., 2015; Schuite et al., 2015; Klepikova et al., 2014).

2.4 Linking the Critical Zone to the Solid Earth

2.4.1 Aquifers : Albeit they do deform

Among the different geophysical methods highlighted in the previous section, the "rock response" tools has been developed for reservoir operations monitoring (Verdon et al., 2013; Lecampion et al., 2016; Vasco et al., 2008), aquifer subsidence monitoring (Burbey, 2003; Hernandez-Marin & Burbey, 2009; Galloway & Burbey, 2011) and volcanic applications (e.g. Solaro et al., 2010). In these applications, observed surface deformations where large enough and could be easily related to pressure changes and fluid transfer in predefined structures. Addressing the question of natural processes is more complex.

Hydrogeologists do not consider aquifers as deformable structures. Surprisingly, they are handling everyday an important parameter, specific storage. By definition, specific storage is the ability of the media to store water in the elasticity of the rock (volume change) by unit pressure change. The consequences are important for confined aquifers : by essence, the structure of the rock is modified with pressure changes, so that hydrodynamical parameters are pressure dependent. Such behavior is more obvious in the rock mechanics and reservoir communities (Rutqvist & Stephansson, 2003; Chin et al., 2000), as stress-dependent permeability is affecting the access to fluid resources or wastes.

2.4.2 Aquifers are constantly deforming

Poroelasticity is the core principle here : water is in direct contact with the hosting aquifer rock, where both interact physically by a 2-way fluid-solid coupling (Wang, 2000) :

- solid to fluid coupling that occurs when a change in applied stress produces a change in fluid pressure or fluid mass (e.g. tide-induced water level variations)
- fluid to solid coupling that occurs when a change in fluid pressure or fluid mass produces a change in the volume of the porous material (e.g. subsidence related to groundwater mining).

In other words, aquifer structure, mechanics, flow and storage are intimately related. This opens new potentials to represent the internal structure and behavior of heterogeneous aquifers. Interestingly, both fluid pressure variation sources and deformation sources can become tools to inform on the subsurface structure and behavior, providing many opportunities to answer the multi-scale challenge of water flow in the CZ (Figure 2.13). The challenge, however, lies on the limited amplitude of such pressure changes.

Stresses	Sinusoidal testing		Seismicity	Rainfall	Atmospheric pressure			Seasonal cycle
					Tides	Pumping test		
Stress period	10 s	1 min	10 min	1 h	12 h	3 days	30 days	1 year
Pressure changes [kPa]	1 - 10		0.1 - 100	0.1	1	1	10 - 100	1 - 10
Estimated averaged effective volume	3 m	5 m	25 m	50 m	200 m	500 m	1.5 km	5 km

Figure 2.13 – *Typical temporal support of pressure/deformation amplitude of various stresses applied on the Earth. An estimate of the averaged volume is also provided (Diffusivity = 1 $m^2.s^{-1}$).*

For example, tides and atmospheric pressure variations, as external solicitations generating stress variations in the Earth, have provided important information on the confinement of aquifers and their properties (Burbey, 2010; Hussein et al., 2013). The principle is simple : stress variations deform the elastic aquifer, while water is (nearly) incompressible,

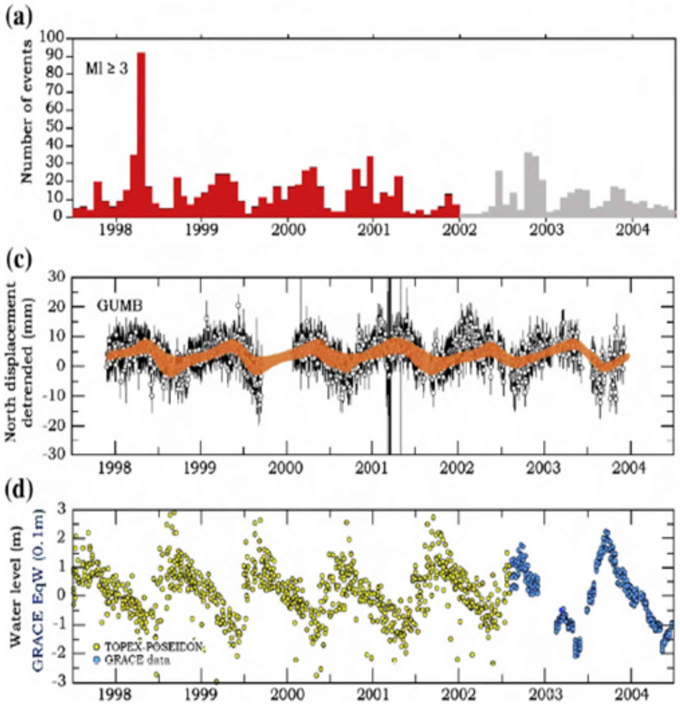

FIGURE 2.14 – *Impact of continental water storage variations on "Solid Earth" observables. From bottom to top (d) water storage changes in the northern Indian monsoon zone are significant and induce surface displacement (c) observed by GPS. As water storage increases, the GPS on the Himalayan front moves south towards the additional mass. This change in stock also modulates the seismicity (a) despite the small pressure variations applied on the surface* $2kPa$*.*

generating water level changes in wells. The amplitude of the response can be linked to aquifer elastic parameters (storage) and the phase lag inform on the ability of water to flow (permeability). Tidal-induced deformation has revealed powerful to estimate aquifer evolution over time, such as permeability increase associated to remote seismic activity (**?**) or fluid type modification in CO2 storing facilities (Sato, 2006).

In both cases, the aquifer, itself, acts as a volumetric strainmeter, with a double value. The impact of tides are superimposing to other deformation processes and offer a constantly repeating auscultation tool to characterize its own properties and track changes. When elastic properties are known and constant, the aquifer can be used to estimate surface pressure changes, for example, weighing surface water storage variations (Marin et al., 2010; Burgess et al., 2017).

When the CZ impacts the Solid Earth's behavior

The perpetual redistribution of fluid at the Earth's surface generate pressure changes on the Earth's crust (figure 2.13). Increase number of work underline the strong interactions between the CZ and the "Solid Earth". A first meaningful evidence was published by Bettinelli et al. (2008), see figure (see figure 2.14]), showing that surface water storage in the Indian region at seasonal time scales (1) was inducing displacements of the Earth's surface ; and (2) was modulating seismicity in this active region.

This example was followed by several others. Successive droughts in the Western United States have "lightened" the earth's crust by a waterlayer $\sim 10\ cm$ over large areas (i.e. $1\ kPa$ stress decrease), leading to a $15\ mm$ vertical uplift. The question was raised whether water storage changes and flow in the subsurface could trigger Earthquakes in this region, which is already in a critical context (Borsa et al., 2014; Amos et al., 2014). Indeed, groundwater mining was pointed as a potential driver for the Mw=5.1 earthquake in Spain (González et al., 2012). In this region, groundwater pumping since the 1960s have lowered head pressure by $\sim 300\ m$, changing the Coulomb stress on the by several $10s$ of kPa.

As rock failure is linked to changes in applied stresses (pore pressure, normal stress) and fault strength (Calais et al., 2016), several processes were proposed (1) synchronous with pressure variations, water loads increase confinement at depth and increase shear stress at the edge of the loaded surface (2) requiring pressure transfer from pressure source to seismogenic area (delayed, see figure 2.13), pore pressure changes and indirect impact on a fault's shear resistance ... Obviously, all these processes could play together.

At smaller scales, the direct impact of human activities is already clearly identified : large-scale waste water injection have significantly increased the number of seismic events in the USA (Ellsworth, 2013). Rock failure can in turn impact the subsurface permeability : the Pawnee earthquake (Oklahoma, magnitude 5.8 in September 2016), certainly induced by the injection of wastewater, has increased natural flow measured in a river by an order of magnitude during several days (Manga et al., 2016).

It does not take much to trigger an earthquake (Avouac, 2012). Deep water injection projects showed that permeable fractures tend to be critically stresses and in a state of incipient failure, so that pressures required to trigger earthquakes are not significantly larger than the hydrostatic pressure (Townend & Zoback, 2000). Talwani et al. (2007) concluded that most of fractures that had triggered earthquakes by pore pressure changes have diffusivity lying between $0.1 - 10\ m^2.s^{-1}$, i.e. the same range observed in shallow layers !

2.4.3 When Solid Earth phenomenon modulate water fluxes

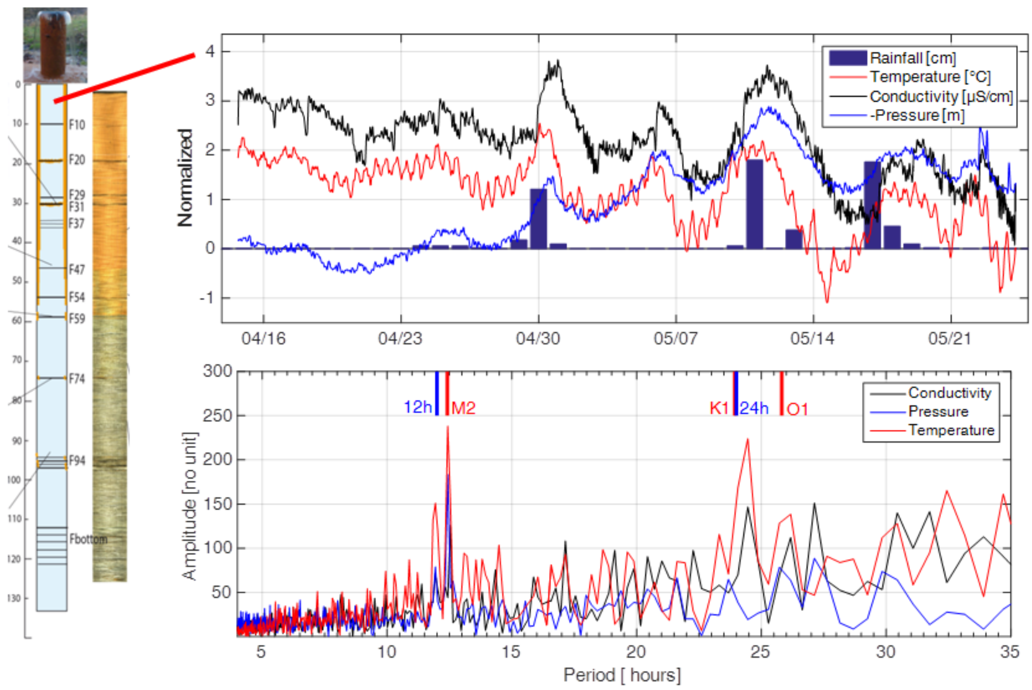

FIGURE 2.15 – *Left : schematic showing PZ26 artesian well in Ploemeur observatory, with the main fractures intersecting the well. Top right panel shows evolution in time of temperature, conductivity and pressure measured 2 meters below surface. As the borehole is closed, pressure variations are linked to the well upward fluxes. Note the oscillation in temperature. Lower right panel shows the spectrum of the different observations on a longer time range, with indication of main modes of variability, semi-diurnal and diurnal periods, as well as the most energetic tidal components (M2, K1, O1). Note the main signal on temperature, whose period (12 hours and 25 minutes) is exactly the period of the main tidal component M2.*

It is clear, from the previous examples, that water flow and pressure changes have a impact of lithospheric processes. Yet, little is known on the effective transfer of pressure and the process for rupture. New insights would certainly pop up from the study of fractured rock flow, as underlined in the example below. This last example should be set to perspectives, but these recent results are really promising and support the strong interrelation between Solid Earth and CZ processes. A multi-parameter probe was set up in an artesian well in Ploemeur Observatory. Water is naturally flowing upwards as water head imposed by deep fractures is above the surface. The borehole image shows significant fracturation, among which 5-6 are significantly flowing. The overall water temperature, conductivity and pressure variations are measured (figure 2.15), so that the behavior of a single fracture cannot be separated. As it can be expected, temperature and conductivity increase quickly after rainfall, surely by piston effect (pressure increase pushes older water). More interestingly, a continuous oscillation linked to tidal wave M2 is clearly visible on temperature data. On contrary to previous tidal examples where the tide was impacting the state of the aquifer, tide is here impacting temperature, a proxy for fluxes. Intuitively, we can hypothesize that the inflow of water having a different temperature is modulated by tides. There are therefore 2 potential processes :

- the reservoir having a different temperature is compressed, releasing more/less water
- the diffusivity of the fracture connecting the reservoir and the artesian well is impacted, by hydro-mechanical coupling.

Such observations are unique (to my knowledge) and underline the interactions between the Solid Earth and the Critical Zone much beyond what is currently expected.

Conclusion

The role of groundwater in shaping surface and subsurface ecosystems is undeniable. Rephrasing Llyel - as water velocity in groundwater systems can be equivalent to the velocity of tectonic plates - the complexity of water flow through heterogeneous aquifers and the depth of time explains how trivial events, such as the mixing of different waters, carve ecosystems. The challenge is also equivalent : to which extent are we able to observe, interpret and represent groundwater flow ?

In order to answer this challenge, I propose to dive down the basic physical interactions between fluid and solid. Pressure gradients power water flow in aquifers, but also deforms the rock body. Therefore, deformation bear a critical information on the path of water (i.e. the reservoir). If measurable, this deformation would bring much insights into groundwater flow and its role in shaping ecosystems.

Hydrogeodesy of heterogeneous systems 3

La simplicité est la sophistication suprême

Léonard de Vinci

La lune est, à bon droit, regardée comme l'astre du souffle vital ; c'est elle qui sature les terres ; elle est pour les corps cause de réplétion par son approche, d'inanition par son éloignement : ainsi, quand elle croît, les coquillages croissent ; et les êtres qui ressentent le plus l'action de son souffle sont ceux qui n'ont pas de sang.

Pline l'Ancien. *Histoire Naturelle. Livre II : Cosmologies*

Sommaire

Geodesy appears as a perfect framework to investigate the low-amplitude deformation betraying fluid-rock interactions in aquifers. Both gravity - sensitive to water masses, and deformation - sensitive to water pressure, are remote effects that penetrate the Earth's, highlighting subsurface processes from surface or space observations. In this chapter, I present the instrumental and methodological developments I lead to adapt and qualify geodetic instruments as tools for hydrology, and , therefore, better capture the rôle of groundwater systems within the Critical Zone.

Behind these developments lies the basic question of the sensitivity of subsurface layers to deformation, and the underlying equivalent behavior of rock-fluid structures.

3.1 Hydrogeodesy : principle and opportunities

3.1.1 The principle of hydrogeodesy

Geodesy is the scientific discipline that deals with the measurement and representation of the Earth, including its gravitational field, in a three-dimensional time-varying space. As geodesists were initially responsible for drawing maps - the shape of the Earth, they relied on global and national networks to set datums and coordinate systems. As the Earth is also a visco- plasto- poro- elastic body (all but rigid), geodesists also study geodynamical phenomenon, such as crustal motion, co- and post-seismic activity, tides. [1]

The impact of mass redistribution on geodetic instruments is weak. As an example, the gravity value measured near Rennes was 9.808748309 $nm.s^{-2}$ in 2005. The third digit "0" is linked to the ellipsoidal shape of the Earth [2], the fifth digit "7" depends on topography and mass distribution within the Earth [3], the seventh digit "8" corresponds to the first time-variable contribution, i.e. tides [4]. In the end, the typical amplitude of mass redistribution is the eighth digit "3" [5], while the instrument precision is approximatively the ninth digit [6].

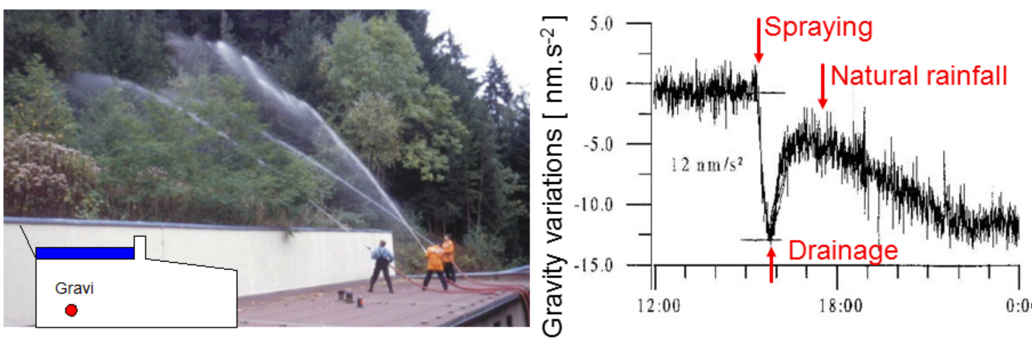

Figure 3.1 – *Spraying test experiment in Moxa Observatory (Germany). (Left) A $4-cm$ equivalent water layer was sprayed on the roof of the building hosting the superconducting gravimeter. (Right) associated gravity variations : gravity is decreasing right at the beginning of the test - decreasing because masses are added above the gravimeter. The impact of water storage on the roof is measurable, a $4-cm$ water layer is equivalent to a gravity change of $12nm.s^{-2}$, i.e. a billionth of the gravity value at the Earth's surface ! The most interesting part is next, gravity is going back to its initial value as water is flowing away from the roof. This response time is linked to hydrodynamical parameters. Rain is also falling for real, the gravity value is, one more time, decreasing.*

As underlined in figure 3.1, spatio-temporal variations in gravity can be interpreted

1. Interestingly, the son of Charles Darwin, George H. (1845-1912) was the first to prove the elastic nature of the Earth observing the "smaller than expected" amplitude of monthly oceanic tides in India. He then started a systematic theory of Earth tides. In Britanny, the amplitude of the oceanic tide is $\sim 10\ m$, the elastic response reaches $\sim 10\ cm$ (Llubes et al., 2008).

2. Jean Richer (1630-1696) realized that a pendulum beating the second is 2.8 mm shorter in Cayenne (French Guyanna) than in Paris. He estimated the Earth's ellipticity based on the Centrifugal force theory by Christian Huygens (1929-1965)

3. Significant developments by Pierre Bouguer (1698-1758) during a 10-year scientific mission to Peru with Charles Marie de La Condamine to measure the length of a meridian arc near the Equator.

4. The first observations of Earth tides by a gravimeter dates back to 1914 thanks to Wihlem Schweydar (1877-1959)

5. The first references to hydrological *interferences* is found in H. Lettau (1937) followed by Melchior (1978) : *Hydrological disturbances are probably the major long-period disturbances experienced in tidal measurements. Changes in the level of nearby rivers or of underground waters may produce strong deformations of the galeries where the instruments are installed*

6. Along the path of Science, all the following ingredients are required : instrumental developments, theory elaboration, conceptual models framing and sound observation strategies.

in terms water storage changes within a hydrological system. Indeed, a $\sim 1 - cm$ water layer modifies the gravity amplitude by $\sim 4\ nm.s^{-2}$, i.e. one billionth of the value of the Earth's gravity field at surface. At this level, Water masses redistribution is one contributor having the same amplitude as atmosphere. Therefore, doing hydrology with geodetic instruments requires (1) highly sensitivity instruments (2) robust observations strategies and (3) adequate modeling tools to extract the hydrological contribution of interest.

Though, the high value of gravity is set : a volume of water results in a mass that modifies gravity field at distance according to the Newtonian attraction principle. Gravimetric methods are direct and independent of the environment. The remote effect "penetrates" subsurface systems, with limited issue of resolution loss with depth, but imposing vertical intergration.

3.1.2 Processes linking geodesy and water storage - pressure

To better understand the full potential of all geodetic observations, it is important to better understand the various processes linking water to geodetic observables (figure 3.2).

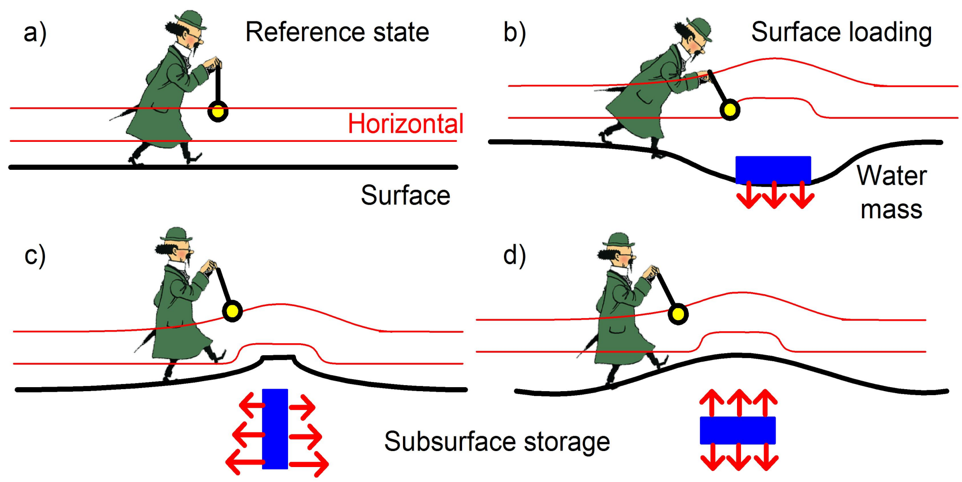

FIGURE 3.2 – *Processes linking the redistribution of subsurface water masses to geodetic observables. The Earth creates its own field of gravity, represented here by the equipotentials (horizontals). The pendulum shows the orthogonal direction, the vertical or direction of gravity. (b) An additional water mass modifies the horizontals (changes gravity) according to Newtonian Attraction. Further, masses (and generally observations) are linked to the Earth's surface. Therefore, the bending of the Earth's surface, due to elastic deformation, need also to be considered (water applies a pressure vertically on the crust). This same mass can be stored in underground reservoirs, where the pressure can be applied horizontally if the subsurface reservoir is vertical (c) or vertically if the reservoir is horizontal (d). The deformation is determined by the reservoir bearing water. If all masses are identical in the 3 differences cases, then gravity variations will be identical. Hence, both gravity and deformation provide complementary information.*

Loading : The impact of mass redistribution at the Earth's surface, implying that the weight of water is exerting a vertical pressure on the crust has been unified under the "loading theory" (figure 3.2 case b,) Farrell, 1972). This theory is powerful as it provides tools to adequately relate any surface mass distribution to any geodetic observable (gravity and deformation), hypothesizing a 1-D distribution of the Earth's elastic properties.

Poroelastic deformation : As higlighted in the previous chapter, any fluid pressure change generate some deformation at distance. Surface deformation includes a sensitivity to the distribution of fluid pressure in the subsurface, i.e. the reservoir. As an example, vertical surface displacement can be upward or downward if pressure is applied at the surface or in a confined aquifer (figure 3.2, panel b and d).

As a synthesis : geodesy contributes to answer the following questions at both local and large scales :
— How much water is stored ?
— where is water stored at the surface - subsurface ?

The combination of different observations is much informative to define the reservoir or extract the information of interest. For example, gravity is mainly sensitive to total mass changes, defining the reservoir bearing these mass changes will required deformation. Further, water redistribution generally occurs continuously at the surface and the subsurface, so that their impact mix in the data. In this case, different observation types with different sensitivities, jointly interpreted, would help to focus on the reservoir.

3.1.3 The opportunity provided by Solid Earth tools

Geodesists have invented several ways to observe the Earth from both ground-based or space-born instruments : gravity variations, deformation as surface displacement, tilt (angle), strain in all directions (figure 3.3). Each of these observables propose either (1) a different vision of the mass variation (Agnew, 2001) and (2) different instrumental opportunities (field instrument, reference instruments) to optimize an observation strategy.

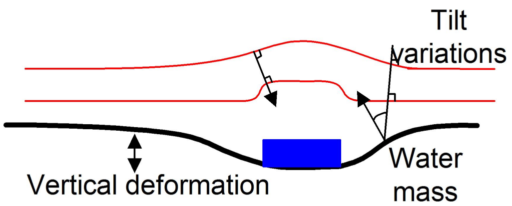

Figure 3.3 – *Various methods to capture the impact of water pressure/storage changes in the subsurface from ground-based or space-born observations : gravity changes, surface displacement (vertical, horizontal), deformation (tilt, strain).*

Indeed, each observable has a specific sensitivity. For example, tilt deformation is negligible if measured far from the mass, or located right at the center. Therefore, tilt is best suited to capture local to regional masses, and is maximum near the edge of the mass. On contrary, vertical displacement is maximum in the center of the mass and keeps increasing when it is extending laterally. Vertical displacement is best suited to study large-scale water storage processes. The typical support of each observable has been defined for the loading process by Llubes et al. (2004). They cover a large continuum of spatio-temporal scales, in accordance to the wide range of spatio-temporal scale associated with CZ processes (figure 3.4). The complementarity of the observables can be also seen as the opportunity to transfer information from one scale to another.

On an instrumental point of view, the same observable can be captured by various instruments. For example, 3 different types of tiltmeters can be applied, all having similar resolution (table 3.1), but different usage. Long base tiltmeters are composed of 2 vessels, separated by several 10*s* of meters, connected by a pipe. The water level defines the horizontal, so that any relative displacement between the vessels lead to water level re-equilibration. The difference between the water levels defines the tilt. They offer very high accuracy, low drift (i.e. high stability), however, they can only be installed in specific conditions (in observatories). On contrary, Blum tiltmeters are horizontal pendulum of reduced size and inexpensive. As they are also sensitive to very local deformations, e.g.

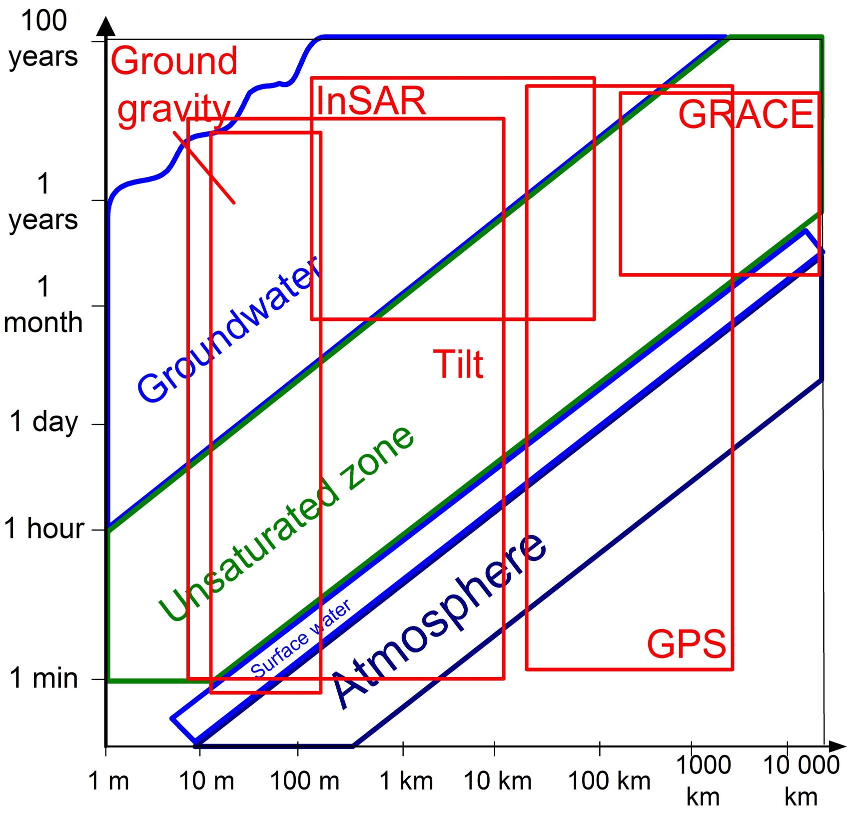

FIGURE 3.4 – *Main spatial and temporal scales associated with different water redistribution processes in different storage compartments of the CZ, adapted from Sivapalan (2005). The typical spatial and temporal support of geodetic observations is superimposed in red, adapted from (Llubes et al., 2004).*

TABLE 3.1 – *Different geodetic tools used in this work, focusing on their resolution (raw unit and a first order interpretation in terms of equivalent water layer (EWH) considering the loading process), their typical integration and major value.*

Instrument	Resolution	Integration	Value
Superconducting gravimeter	$< 1nm.s^{-2}$ i.e. $< 2mm$ EWH	$\sim 100m$	Observatory instrument, stable
Absolute gravimeter	$\sim 10nm.s^{-2}$ i.e. $\sim 20mm$ EWH	$\sim 100m$	Reference station
Field gravimeter	$\sim 50nm.s^{-2}$ i.e. $\sim 100mm$ EWH	$\sim 100m$	Field tool, mapping @1km network scales
Satellite gravimetry (GRACE)	$\sim 10mm$ EWH	$\sim 400km$	Global, mapping @400km scales
Long base tiltmeter	$< 1nrad$ i.e. $< 10mm$ EWH	$\sim 10m - 10km$	Observatory instrument, stable
Blum tiltmeter	$\sim 1nrad$ i.e. $\sim 10mm$ EWH	$\sim 10m - 10km$	Field, easy to setup
Borehole tiltmeter	$\sim 1nrad$ i.e. $\sim 10mm$ EWH	$\sim 10m - 10km$	Intermediate
Strainmeter	$\sim 1nstrain$ i.e. $\sim 1mm$ EWH	$\sim 1km$	High resolution, borehole or horizontal
GPS	$\sim 1mm$ i.e. $\sim 20mm$ EWH	$\sim 100km$	Quasi-global, reference
optical methods	$\sim 1mm$	$\sim 10m$	Mapping @100m scales
InSAR	$\sim 1mm.yr^{-1}$	$\sim 100m$	Mapping @10km scales

those induced by thermal stress, and will be best suited for short-term studies. Borehole tiltmeters are intermediates between both Blum and long-base tiltmeters. All three types of tiltmeters would enter in a observation strategy, benefiting from their complementaries.

For more details on instrumental questions, the interested reader could refer to Crossley et al. (2013) for gravimeters, Pail et al. (2015) for GRACE, Agnew (1986); Schuite et al. (2016) for strainmeters and tiltmeters, Bock & Melgar (2016) for GPS, Crosetto et al. (2016) for InSAR.

Geodetic observables and instrumental types (figure 3.4 and 3.1) offer distinctive advantages to study the CZ with respect to classical methods :

1. gravity is directly sensitive to a volume of water, i.e. well-calibrated requiring no petrophysical relationship ;
2. gravity and deformation are remote effect, therefore non-invasive tools, able to monitor the spatio-temporal behavior of the subsurface (including spatial patterns) from surface observations ;
3. they are sensitive to storage and/or pressure changes, i.e. sensing active structures and subsequent heterogeneity ;
4. as passive methods, they are not limited by some penetration depth, but constrained by the spatial integration ;
5. a few geodetic instruments are absolute and/or stable, granting applicability in various application such as reservoir monitoring, hazard monitoring and early-warning systems.

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Among the different tools, tiltmeters are very specific instruments, and tilt deformation seems to be perfectly suited to study the CZ : **(1)** their sensitivity covers large range of spatial and temporal scales, with no sensitivity to large-scale mass redistribution. Indeed, the Green Function, describing the tilt of a point mass at the surface is a r^{-2} function, where r represents the distance between the instrument and the point mass. This drives to a scale-invariant sensitivity up to a distance of $\sim 10\ km$ (while the induced stress is focused in the crust). As a consequence, the same instrument can be used to study a fracture, a catchment or a regional aquifer (see Longuevergne, 2008, figure 6.30) ; **(2)** tilt, as the horizontal gradient of vertical displacement, is an directional information, sensitive to the imbalance between both sides of the instrument. It seems fairly well suited to study the natural heterogeneities and localized active structures within the CZ. Further, tilt, as a rotation, has a double sensitivity : the amplitude of the pressure change, but also the area on which the pressure is applied, acting as a lever arm, providing to tilt a specific value in fractured context ; **(3)** tiltmeters are generally sensitive instruments, able to observed a tilt equivalent to a vertical displacement of $\sim 1\ mm$ located at a distance of $\sim 1000\ km$! This high sensitivity is a real opportunity to capture small-amplitude phenomenon.

3.1.4 Hydrogeodesy : Current challenges

As highlighted in the previous figures (3.1, 3.5), the impact of water redistribution on geodetic fields is generally limited in amplitude and many different sources can mix in data. The main challenges of hydrogeodesy can be synthesize into the following questions :(1) How to set a geodetic monitoring strategy on the field (and complementary observations) to separate the different sources, extract the meaningful signal linked to the reservoir under study ? and (2) How to quantitatively interpret such indirect observations to answer CZ challenges ? These intricate questions were systematically borne in mind when granting a hydrological meaning to geodetic data, or implementing an experience

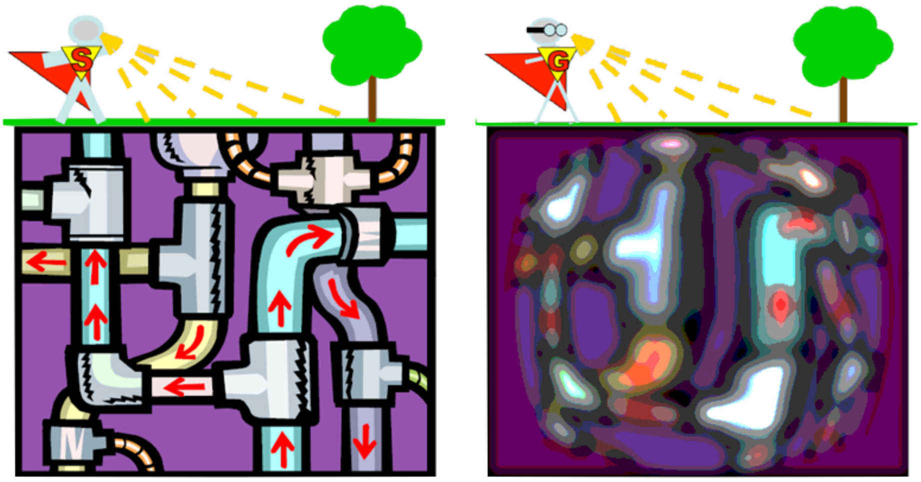

FIGURE 3.5 – *(Left) The subsurface as we wish to capture it. (Right) the same as it could be interpreted through the indirect sensivity of geodetic instruments : blurred image, structures moving laterally, focusing on specific orientations (here, vertical). Adapted from Day-Lewis.*

with geodetic tools. I have split them into sub-challenges to highlight the main development and present the main directions for future developments :

An instrumental challenge : it is necessary to "take out" geodetic instruments from their observatories and adapt them to fields of CZ value - while preserving (at best) similar accuracy and stability (for example, figure 3.6). The actual leap into unknowns is the coupling issue between the instrument and the object to be measured to ensure meaningful and high quality data. This focuses practical, logistical and conceptual issues :

— the need to set stable observation points and repeatable networks (all ground instruments) without relying systematically on concrete pillars or affecting the subsurface to be measured ;
— the difficulty to apply InSAR and leveling in the natural environment, with growing vegetation
— the need to set up a monitoring network able to represent the spatial variability to avoir mis-interpretation.

A strategic challenge : Accounting for the low amplitude of hydrological effects, close to the instrumental sensitivity, is a constant question. The expected signal (in space and time) is furthermore often unknown. Relative deformation measurements are particularly sensitive to short wavelength heterogeneities (media and mass distribution), so that they become a real opportunity to maximize amplitudes. Another strategy is to focus on a known structure and create a measurement network where the gradients are easier to interpret (Kennedy et al., 2014; Jacob et al., 2009).

A methodological challenge : disaggregation of various contributions to observed data remain as a thorny issue. The CZ is beating at the rate of the day and the year, so that observations can be the result of constructive or destructive interferences of different processes (temperature, water storage, number of fish in the pond, ...) Longuevergne et al. (2009). The experimental approach, classically implemented in hydrogeology, is a real opportunity to shorten the observation time focused on controlled behaviors

An interpretation challenge : the obligation to go beyond the loading theory. It is necessary to develop tools that are not based on some "homogeneity" assumption. Water distribution cannot be considered as homogeneous, while impacting geodetic observations even within their integration scale, and is by essence a dynamical notion that evolves quickly in time. The following issues should be resolved :

1. the deviation of the Earth's elastic properties to the reference elastic model (Chanard et al., 2014; Wang et al., 2012) ;
2. the relative position of the geodetic observation with respect to the water (instruments could be below surface), requiring to process differently the asymptotic behavior at local scale (Kamigaichi, 1998; Okubo, 1988) ;
3. the relative distribution of water masses at and below surface (Llubes et al., 2004; Longuevergne et al., 2009) and the various processes linking pressure changes (figure 3.2)
4. the rapid movement of water at and below surface (Mouyen et al., 2017), water flow and diffusion should not assimilated as some viscous behavior of the rock.

In the next sections, three examples will provide clues to answer them.

FIGURE 3.6 – *Peut-on mesurer précisément les déformations sur le terrain pendant un essai de pompage sans modifier le milieu ?*

3.2 A focus on gravity from GRACE satellite

3.2.1 The value of GRACE

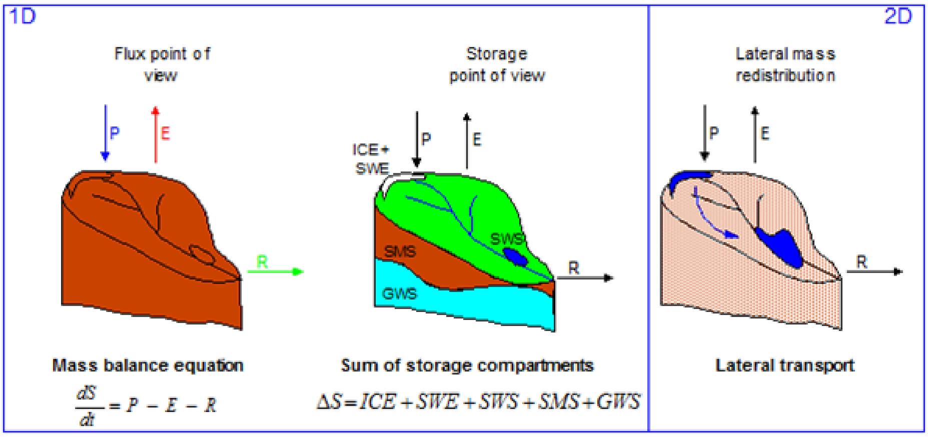

Figure 3.7 – *Various applications of gravity variations at catchment/basin scale, interpreted as water storage variations (S or ΔS). (Left) GRACE is considered as a flux information to resolve the mass balance equation. P, E and R stand for precipitations, actual evapotranspiration and runoff. (Center) GRACE, as total storage changes, can be rewritten as the sum of storage compartments integrated vertically. ICE, SWE, SWS, SMS and GWS stand for ice, snowpack, surface water, soil moisture and groundwater storage changes. (Right) Tracking lateral mass transfer*

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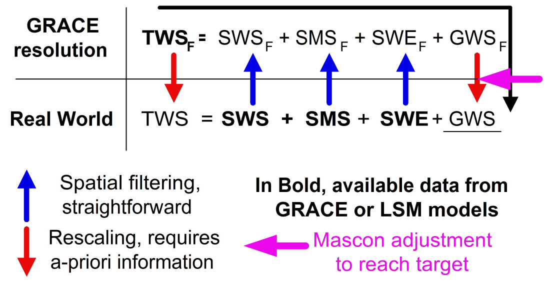
The GRACE satellite mission was launched in 2002. It was the first satellite of its generation with sufficient accuracy to measure changes in water storage changes on the Earth's surface, with a spatial integration of $\sim 400\ km$ (Tapley et al., 2004; Schmidt et al., 2008; Cazenave & Chen, 2010). Gravity measurements are provided by 2 chasing satellites, they do not carry remote sensing tools. The satellites are $220km$ apart, range-rate (relative velocity) variations are measured with high accuracy ($\sim 0.1\ \mu m.s^{-1}$ over a satellite separation) and can be directly linked to surface gravity.

Over the first 10 years, the scientific community was mainly interested in understanding the data itself, and how it could be applied for various challenges in Earth Science (figure 3.7). Following a first phase to improve signal to noise ratio and spatial resolution (Swenson & Milly, 2006; Wahr et al., 2004; Bruinsma & Lemoine, 2010; Ramillien et al., 2011), GRACE proved to be successful in quantifying mass changes linked to various processes, including ice cap and glacier melting (Jacob et al., 2012; Shepherd et al., 2012; Horwath & Dietrich, 2009; Chen et al., 2006), water storage variations on the continents (Reager et al., 2016; Rodell et al., 2009; Feng et al., 2013) or solid Earth mass redistributions resulting from earthquakes (Han et al., 2006; De Linage et al., 2009). In all cases, the mass/volume resolution was of the order $\sim 1\ km^3$ or $\sim 1\ Gt$ at annual to interannual time scales.

The global nature of GRACE data is a real opportunity, to impact the community and expand collaborations. I have benefited from important opportunities that stimulated many methodological developments for new challenges, including :

1. the validation of GRACE processing approaches and value on highly monitored hydrological systems (Longuevergne et al., 2010; Scanlon et al., 2012; Shamsudduha et al., 2012);

Figure 3.8 – *Updated GRACE processing strategy developed to best extract water storage in a single component (here groundwater storage changes - GWS) from available a-priori data (SWE, SMS, SWS stand respectively for snow water equivalent, soil moisture and reservoir mass changes). Subscript F represents spatial filtering, applied equivalently to GRACE or a-priori information. While filtering "as GRACE" is a straightforward mathematical operation, "rescaling" require a-priori information and generates uncertainties. From Scanlon et al. (2012); Farinotti et al. (2015).*



2. the constrained estimation of water fluxes such as evapotranspiration (Springer et al., 2014; Long et al., 2014a)
3. the understanding of climate-related long-term and extreme events (Kusche et al., 2016; Eicker et al., 2016) ;
4. the monitoring of small-scale aquifers (Castellazzi et al., 2016) and mountain glaciers (Farinotti et al., 2015) ;
5. the validation and calibration of hydrological models (Xie et al., 2012; Yang et al., 2011; Felfelani et al., 2017; Pokhrel et al., 2015) ;
6. the design of future gravimetric space missions (Pail et al., 2015).

An important lesson from my studies is the dependence of GRACE interpretation to hydrologic, oceanic and atmospheric models. While a goal of the GRACE mission is to provide independent measures of the water cycle, it is clear that an iterative analysis is the most effective. In all future gravity measurements from space, it is anticipated that land surface models will continue to guide the formulation of GRACE water storage variation estimates as, in turn, GRACE or other gravity satellite estimates contribute global hydrological modeling, whichever approach is considered (land surface models, global hydrological models, Earth science models).

3.2.2 GRACE is sensitive to masses, not spatial scales

My main contribution is relying on a simple fact : the high heterogeneity of landscapes and behaviors over the integration scale. Indeed, GRACE can only provide a spatially filtered image of reality at scales $\sim 400\ km$, small-scale gravity variations are damped by the altitude of the satellite (figure 3.3). This integration scale is physically driven, due linked to the altitude of the satellites $\sim 400\ km$. This corresponds, for example, to the distance between Dijon and Milan or between the Ganges and the Tibetan plateau : from aquifers to high mountains, the heterogeneity of landscapes and behavior is dazzling. Therefore, an accurate estimate of mass variations requires to take into account mass distribution within the integration scale (Longuevergne et al., 2010; Scanlon et al., 2012; Longuevergne et al., 2013).

Basically, the application of GRACE data at regional scales calls for 3 challenges to be resolved :

The large-scale sensitivity, leading to damping of signal amplitude within the area of interest, and sensitivity to surrounding masses and their distribution. Filtering true mass variations "as GRACE" is a straightforward mathematical operation, but the inverse, called "rescaling", is much more complex (figure 3.8 and Longuevergne et al., 2010), requiring

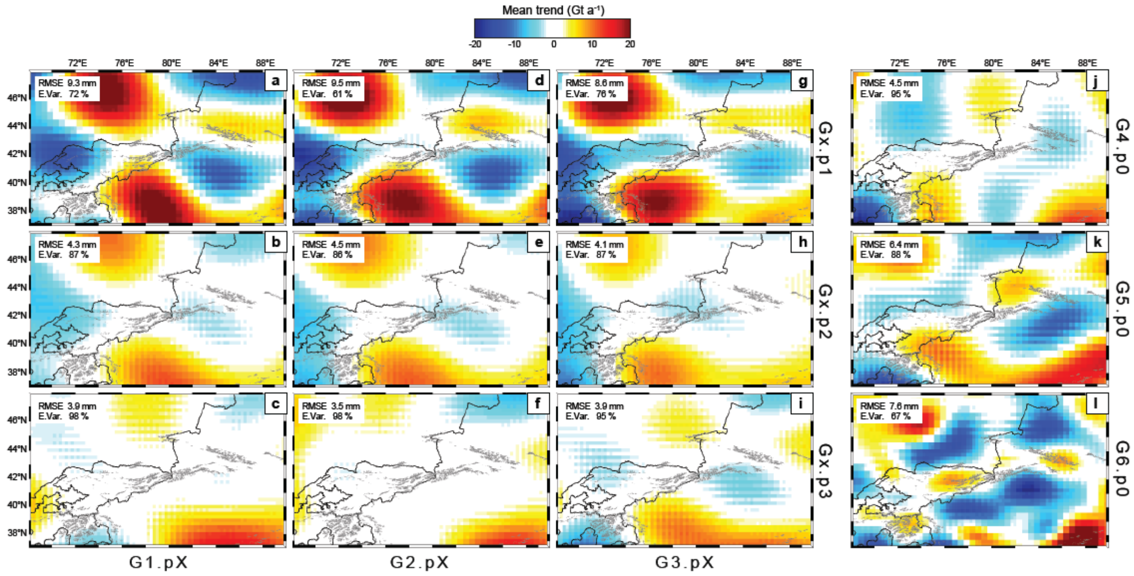


FIGURE 3.9 – *The quest for the information content of GRACE data Farinotti et al. (2015). Several post-processing strategies can be implemented to filter noise - affecting spatial resolution. Glaciers are shown as the gray structures in the center of the images. The maps show the residuals, for each processing strategy, after removing all known contributions (storage changes, snow, glaciers), evaluating the quality of the whole processing chain. When close to 0, all contributions to GRACE gravity are understood, while non-zeros reflect GRACE noise, model errors, and/or the quality of the glacier estimate. On the 3 first column, official solutions are shown (CSR, GFZ, JPL, see Bettadpur, 2012), with 3 different post-processing strategies as lines. These solutions are mainly subjected to noise, but one filtering option drive to meaningful results (DDK filter, see Kusche et al., 2009), indicating a good estimate of the different components. The right most column higlights a different story : these "constrained solutions" (GRGS, regularized CSR Bruinsma & Lemoine, 2010; Save et al., 2012) do not require further post-processing and offer higher spatial resolution. Residuals are focused above/close to glaciers, so that the main limitation is not the GRACE data itself, but the spatial resolution of the glacier model. The lower right solution is provided up to a resolution of* $\sim$ 170 *km, which clearly indicates spatially variable glacier melting rates within the different Tienshan mountain ranges*
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a-priori information. The optimal use of GRACE and a-priori data would suggest to limit and delay, as much as possible, the usage of a-priori data. As an example, in the quest to extract groundwater storage variations from GRACE, the updated method (figure 3.8) makes best use of available spatially-distributed models by working essentially in the filtered domain. The a-priori information required could limited to (1) the position of GW masses, i.e. the extend of the aquifer system (Scanlon et al., 2012).

The limited signal to noise ratio, which is partially linked to the previous point. At regional scale, the variability among different processing GRACE products and post-processing strategies is still important. As GRACE is the first satellite of its generation, solutions have been improving continuously since 2002 - the signal-to-noise ratio has been enhanced by a factor of 10. The understanding of GRACE information content and limitations necessarily require to consider different products. As an example, I worked on glacier mass changes in the Tienshan region (figure 3.9 from Farinotti et al., 2015), with the will to forward model all known contributions, including the glacier melting. Residuals showed the high dependence of results to the post-processing strategy (i.e. signal to noise ratio) as well as sub-scale mass distribution. The differences among GRACE products and processing strategies are still important, but a thorough evaluation of the different products and processing strategies clearly highlights the wide potential and limitations of

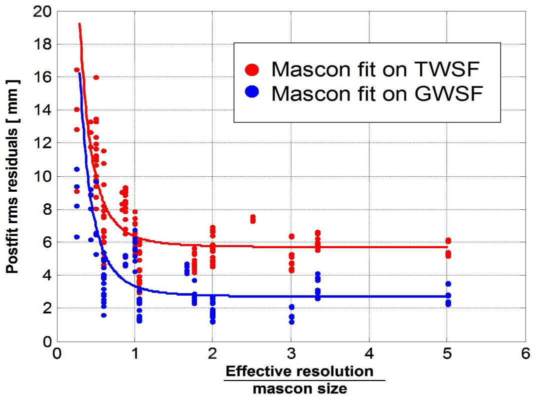

Figure 3.10 – *Link between post-fit residuals after mascon fit and the ratio between the effective GRACE resolution and mascon size from an extensive fitting experiment on the Tienshan region. Post-fit residuals are always smaller when the contribution of other compartments is removed, meaning that the specific mass distribution of glaciers has a defined signature in GRACE data. Post-fit residuals also decrease rapidly from coarse resolution to high resolution, with an optimum for mascon sizes equivalent to the effective resolution.*

GRACE. It is important to realize that although GRACE provides large-scale information, the sub-scale mass distribution is partially contained in GRACE spatial patterns.

Consequently, the inversion strategy, to recover surface masses is still questioned considering the last 2 points. The use of mascons to fit surface mass distribution directly on spherical harmonics is growing in interest for its explanation power (Tiwari et al., 2009; Chen et al., 2009; Long et al., 2016; Schrama et al., 2014). Though, there are 2 main questions : (1) what is the optimal mascon size, explaining GRACE data without having too many tunable parameters and (2) how to represent the sub scale spatial variability. These questions were hardly raised although they conditioned the result (Horwath & Dietrich, 2009; Farinotti et al., 2015). I defined effective resolution with the spatial scale (spherical harmonic) at which the original amplitude of the Stockes Coefficients is divided by 0.5. The effective resolution of GRACE is a good order of magnitude of the typical mascon size on which masses can be actually estimated (figure 3.10).

Considering these three points, I developed approaches for direct modeling and inversion accounting for the spatial variability. To my mind, the full information content of GRACE data is not yet fully understood. As a sticking example, GRACE is fundamentally sensitive to masses, with no minimum threshold of spatial extension (Longuevergne et al., 2013). This opens new potentials to re-investigate classical challenges in Earth Sciences, such as tracking sediment mass accumulations in the ocean (Mouyen et al., submitted). This will be further developed in perspectives.

3.2.3 Hotspots of non-understanding

Our understanding of future climate relies on the predictive ability of an ensemble of models (e.g. Bates et al., 2008). These models are based on our current understanding of the different processes composing the water cycle and interactions among its different components (ocean, cryosphere, continents). As underlined by Wada et al. (2013), the current divergence among predictions is mainly explained by the large variability among hydrological models.

The understanding of GRACE data goes along some knowledge of the water cycle from models. I am regularly working with 14 model outputs, based on different concepts (global hydrological models, land surface models), representation of processes, inclusion of storage compartments, forcings dataset (including anthrogenic pressure). While a single model can be biased, we generally rely on the ensemble to better describe the actual water cycle. See table Annex A for more details. Along with an ensemble of GRACE solutions, such datasets allow extraction of common features and highlight systematic differences between models and GRACE (figure 3.11). The main discrepancies in long-term storage changes are focused in the three following regions :

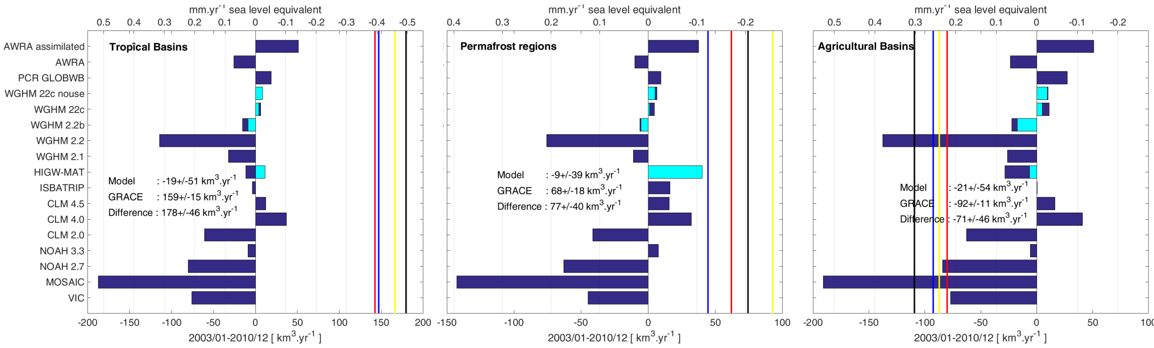

FIGURE 3.11 – *10-year total water storage variations from GRACE (different processing strategies, vertical colored lines) and 17 hydrological models (horizontal bars, total storage in dark blue, groundwater storage in light blue, when available, models are named on the left) for 3 major regions on Earth (tropical basins, permafrost regions, agricultural regions). Storage changes are provided as a volume (lower x axis) in $km^3.yr^{-1}$ or equivalent sea level rise $mm.yr^{-1}$ (upper x axis). Mean long-term storage changes are provided for GRACE and models.*

Tropical regions. The largest discrepancy between GRACE and global models is located in tropical regions (figure 3.11). In these regions, vegetation, high temperatures and permanent high humidity are engines for rock weathering. Therefore, soil and weathered layers have high thicknesses (Pelletier et al., 2016), providing large storage capacities in both soil and groundwater layers. In such contexts, GW plays the role of a large buffer (Pokhrel et al., 2014) with significant contribution to other compartments (inundation areas) and water cycle (river baseflow). The representation of such large storage capacities is critical (Swenson & Lawrence, 2015) and might explain the large differences between model and GRACE storage changes (resp. $-19\ km^3.yr^{-1}$ and $159\ km^3.yr^{-1}$).

Permafrost regions. Permafrost is a typical example on how climate change shapes the structure of continental water storage compartments. As frozen layers have a low permeability, temperature increase above the melting point in the subsurface significantly modifies the hydrologically-active storage compartments, modifying fluxes and internal storage distribution. Several works noted increasing storage in such regions (Velicogna et al., 2012). Several processes can have a significant role, including the thickening of the shallow active layer or the increasing connection with deep GW layers (Walvoord & Kurylyk, 2016). Such soil temperature-dependent processes are generally not represented in models, while they are expected to play a major role on long-term water storage changes (resp $-9\ km^3.yr^{-1}$ and $68\ km^3.yr^{-1}$ for hydrological models and GRACE, see figure 3.11).

Agricultural regions. The estimation of the direct human contribution to water cycle have focused a lot of attention over the past years with the development of dedicated modules in large-scale modeling. Indeed, the phenomenal growth of the human footprint has significantly modified hydrological processes in various ways (e.g. irrigation, artificial dams, and water diversion) and at various scales (Wada et al., 2017). The main difficulty lies in the representation of the boundary condition imposed by humans, with limited knowledge of water volume at stake. Most of the time, irrigation modules in global hydrological models are based on rules and statistics, including crop requirements with some water stress (Muller Schmied et al., 2016). Water storage depletion is generally underestimated, the difference between models and GRACE reach $70km^3.yr^{-1}$ (resp -21 $km^3.yr^{-1}$ and -92 $km^3.yr^{-1}$, see figure 3.11)

3.3 The value of deformation

As highlighted in the previous chapter, the physical interaction between fluid and solid need to be seen as a new opportunity to define the behavior of the reservoir in response to pressure changes. The deformation can be measured over a wide range of spatial scales 3.4, and already applied to monitor reservoir operations from the surface (Vasco et al., 2000; Verdon et al., 2013). The development of deformation to study natural processes is more recent, considering the small amplitude of expected signals (Van Dam et al., 2001; Chaussard et al., 2014).

My main contributions are mainly instrumental and methodological, with (1) the development of numerical tools to link water flow in heterogeneous media and deformation and (2) the development of observation strategies to measure tiny deformation with tiltmeters, and the validation of designed numerical tools. Most of developments were carried out during the PhD thesis of Jonathan Schuite on the Ploemeur observatory.

3.3.1 Constraining deep fractures from surface observations

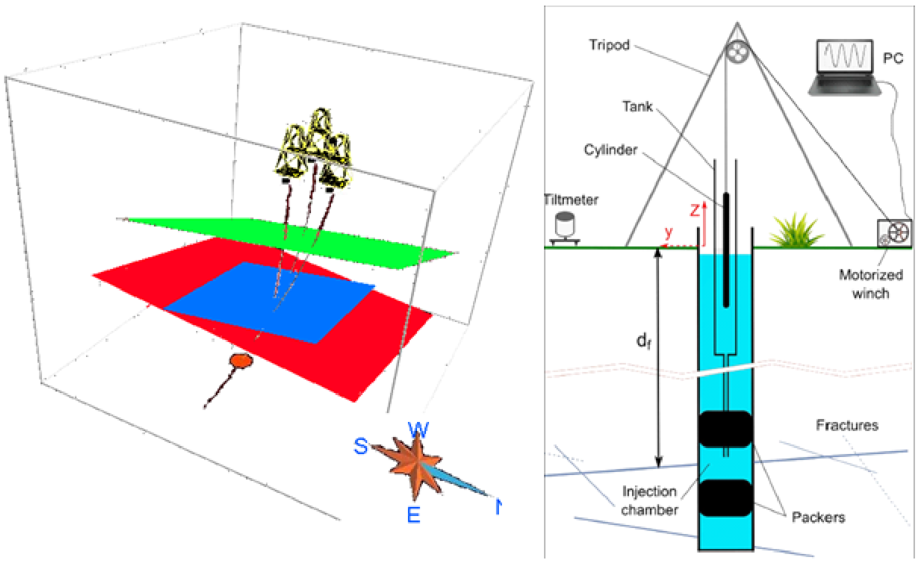

Figure 3.12 – *(Left) Gocad geomodel of the 3 main permeable fractures on the Stang Er Brunn experimental site. (Right) Sketch showing the setup of the hydro-mechanical experiment involving the injection of sinusoidal pressure variations in a single fracture, and the surface monitoring of deformation using a Blum tiltmeter (Schuite et al., 2015)*

The *in situ* hydromechanical behavior of fractures (i.e. the stress-permeability relationships) is fairly under-constrained, while it has wide implications on flow (Witherspoon et al., 1980) and controls structure stability Cornet (2016). Typically, pressure variations modifies fracture aperture and hydrodymanic parameters. Fracture stiffness, linked to the storage coefficient, controls such non-linear behavior (Bandis et al., 1983). Laboratory and numerical experiments have brought considerable insights on such processes, though, *in situ* hydromechanical experiments are relatively uncommon, mainly because of technical and instrumental limitations. Generally, such experiments consists in setting downhole tiltmeters or strainmeters to monitor the fracture behavior to hydraulic solicitations (Guglielmi et al., 2015; Burbey et al., 2012; Hisz et al., 2013; Schweisinger et al., 2011).

We developed an original methodology, based on surface instruments, extending the sensitivity to hydro-dynamical parameters at $\sim 10\ m$ scales, in-between boreholes. Blum tiltmeters were installed at the surface on the borehole rim. While such instruments are relatively unstable (table 3.1), the idea was to impose sinusoidal pressure variations in a single fracture (figure 3.12). This methodology offers 2 main advantages : (1) le period of the sinusoid modulates the pressure diffusion length within the fracture / fractured network ; and (2) the sinusoidal nature of the signal, orthogonal to the signature of natural phenomenon, facilitates the signal recognition in tilt measurements and increase the signal to noise ratio by stacking sinusoids with known period. More details can be found in Schuite et al. (2015). The methodology was successful, we obtained fracture stiffnesses consistent with published data.

The ability to observe 80-m deep fracture behavior from surface observations is promising. However, tilt is sensitive to an alternate information beside fracture mechanics : the extent of the same fracture on which pressure is applied. In the analysis, we used *a priori* estimation of the pressure penetration depth from well data, hypothesizing a 2D radial flow. The observation of local fracture deformation in the borehole would partly clear up this ambiguity. Future improvements will be detailed in the perspective section.

Finally, it is important to note the high sensitivity of Stang Er Brunn fractured networks to low-amplitude pressure changes. Estimated stiffnesses are in the lower bounds of laboratory and field data gathered in the review by Zangerl et al. (2008).

3.3.2 Estimating fracture geometry and relationship with the reservoir

Despite the apparent complexity, monthly-scale flow in crystalline aquifers might be by a simple homogeneous media (the reservoir) bounded by specific permeable structures (fractures). Little information would be lost on water level data (Leray et al., 2013; Jiménez-Martínez et al., 2013). Though, two important issues arise, where the permeable structures, and their relationship with the reservoir, should be clearly defined (Bense et al., 2013). On the one hand, the identification of productive zones might be challenging, as it is controlled by the connectivity with the most permeable structures. On the other hand, transport properties - and reactivity, is defined by water pathways though the main permeable structures.

Deformation has proven to be useful for imaging the geometry of active fractures and flow structure, based on the careful re-interpretation of tilt and leveling data from the 2006 pumping stop experiment (figure 3.13). Both geodetic observations largely complement each other : tilt offers high resolution time variations, integrated at $\sim 100\ m$ scales, while vertical displacements from leveling captured the time lapse spatial variations (two surveys were performed, one before the pumping stop, another one just before restarting the pumps. each leveling map takes ~ 4 hours). The vertical displacement, reaching 3 mm can be measured with usual topometry tools. The elongated shape of the vertical displacement is striking, as it reflects the the focused deformation induced by pressure buildup in the known vertical fracture. The storage coefficient can be also quickly estimated as the simply ratio between vertical displacement and pressure head changes, here $\sim 3.10^{-4}$, coherent with published values. Tilt deformation also followed closely pressure variations, and was oriented towards the main active fracture.

Assuming a pure elastic behavior during the first hour, Schuite et al. (2015) built up a simple analytical modeling framework to quantitatively use these observations and recover the geometry of the active part of the subvertical fault zone and its storage properties. Note that these results have been obtained from a short-scale experiment.

The analysis of the whole time series by a fully coupled poro-elastic model allowed to dig deeper the information content of deformation. The ratio between tilt deforma-

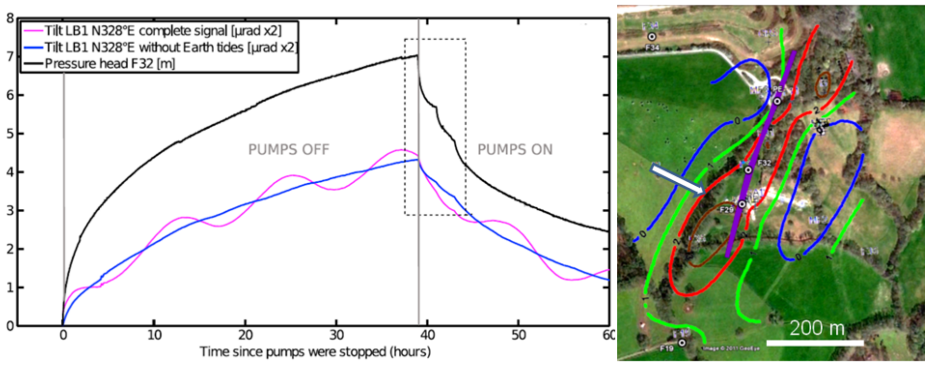

Figure 3.13 – *Pumping stop in Ploemeur/Kermadoye as imaged by tilt monitoring and vertical displacement mapping. (Left) Tilt time series, with (magenta) and without Earth tides (blue), compared to pressure head variations in well F32 in between the pumping stations. Both show the same evolution, from the pump stop (time=0) to the restart of the pumps (time=39h). (Right) map of the pumping site, with the 3 pumping wells (PE, F31, F29) and F32 observation well. Superimposed, the vertical displacement from leveling, blue is 0 mm, green 1, red 2 and brown 3 mm). The white arrow shows the direction of the maximum tilt deformation, orthogonal to the active fracture.*

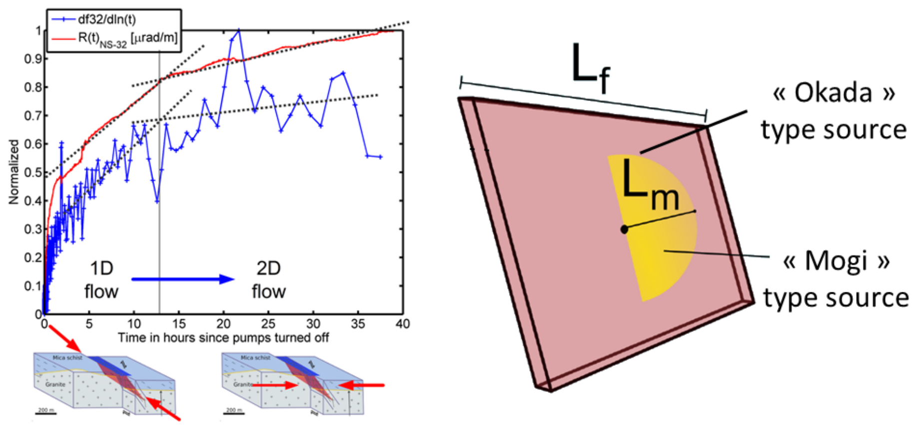

Figure 3.14 – *Temporal evolution of the equivalent "elastic parameter" defined as the ratio between tilt deformation and fluid pressure and its interpretation. (Left) A hydrogeological point of view : time series showing the ratio between tilt and pressure (red) and the logarithmic derivative of F32 well evolution to define the dimensionality of the flow (Renard et al., 2009) (blue). (Right) A hydromechanical point of view : the phases (2) and (3) can be described by asymptotic behaviors, where deforming structures are static (**?**). In our context, the complex poroelastic behavior can be split into 2 simpler problems : the definition of the deforming/flowing structure and water flow within them.*

tion and fluid pressure can be assimilated as an equivalent "elastic parameter". This ratio was evolving following 3 distinct phases, clearly defined : (1) a setup phase, as defined previously, where tilt is growing quickly for geometric reasons, the extension of the pressurized zone is growing within the sensitivity zone of the tiltmeter (Schuite et al., 2015) ; (2) an second phase, where the ratio tilt/pressure is growing steadily, coherent with a mono-dimensional flow within the fracture (3) a third phase in late time, where the ratio tilt/pressure is slowing down, and coherent with a 2D flow structures where the less transmissive micaschist is contributing to the flow. The equivalent elastic parameter is large when deformation is focused in the fracture, and smaller when the rock volume is solicited. Indeed, deforming a focused 2D structure is more efficient than spreading the deformation in a volume. A similar behavior has also been found in (Zhou & Burbey, 2014).

Interestingly, the transition time between fracture flow and matrix flow is equivalent for both well and tilt data, but the tilt to pressure ratio is less affected by noise and better defines the different flow structures.

Surprisingly, tiltmeters are noninvasive tools that seem even more suited to fractured hydrogeology than fault hydromechanics at the $\sim 100\ m$ scale and beyond, because they display stronger sensitivity to hydrodynamical properties than poroelastic properties. This is in line with results obtained with strainmeters, another relative deformation tool, by Barbour & Wyatt (2014).

3.3.3 Tilt as a flux information

The previous section highlighted to high sensitivity of tilt observation to water flow and the different structures bearing the pressure changes. When the deforming structure is constant in time, tilt can be further simplified. Intuitively, the vertical displacement u is related to pressure head h via the storage coefficient S so that $u \propto Sh$. Darcy law further states that pressure head gradient $\frac{\partial h}{\partial x}$ is linked to water fluxes Q. Tilt, as the horizontal gradient of vertical deformation can be rewritten

$$tilt = \frac{\partial u}{\partial x} \propto \frac{\partial h}{\partial x} \propto Q \tag{3.1}$$

Therefore, tilt is directly sensitive to water flux over the integration scale of the tiltmeter ($100s\ m$ in the direction of the tiltmeter). This peculiar feature was higlighted on the tiltmeters installed on the LSBB site, a karstic aquifer (Vaucluse, South of France) (Lesparre et al., 2017). The outlet of the karst drains a $1130\ km^2$ area, and is located $30\ km$ further west of the tiltmeter, in its orthogonal direction. The correlation coefficient between tilt time series and water discharge at the outlet of the karst reached 0.95! Further, the tilt amplitude was large, suggesting that the tilt deformation was induced by a $\sim 350\ m$ deep, partially flooded facture located $\sim 1\ km$ south of the instrument. It is probable that large and highly permeable tectonic structures drains the karst massif towards the resurgence.

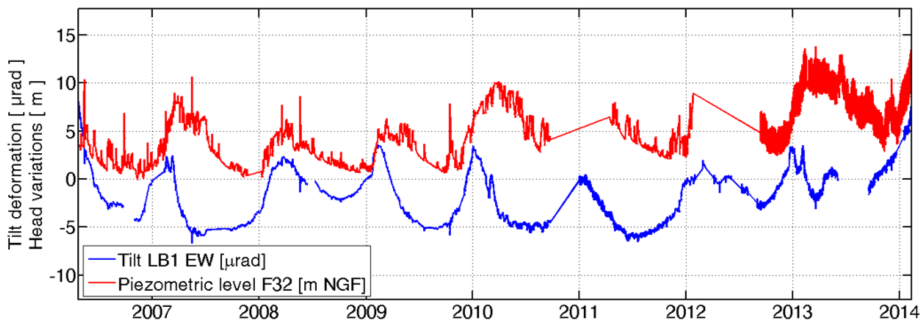

FIGURE 3.15 – *Tilt and F32 pressure head variations over the 2006-2014 period observed in Ploemeur. F32 is located within the pumping wells, therefore, the "noise" is linked to pumping operations. The seasonal variations are clearly visible on both time series. The tilt time series, though, is in advance, in the way that tilt maximum seems to be located at the maximal temporal derivative of well head time series. May tilt predict seasonal recharge ?*

.

Long-term observations on the Ploemeur site (figure 3.15) higlights a similar behavior : long-term tilt is linked to the temporal derivative of well data. As tilt is in advance to well data, it could become a tool to (1) capture deep water transfers in fractures and (2) predict recharge in crystalline aquifers. We are currently working on the interpretation of such data, together with GPS deformation.

3.4 Joining forces of gravity and deformation observations

Surprisingly, very few papers exist combining deformation and gravity methods, mostly focusing on the loading theory. Though, a few exciting works have been published, where the combined use of GRACE and GPS displacements questions the rheology of the crust, and its lateral variability (Chanard et al., 2014). The combined use of various geodetic observations is highly valuable :

- to separate signal and noise and better extract processes ;
- to explore the complexity of water flow and storage (spatial variations due to water redistribution processes) ;
- to explore the complexity of the crust (lateral variation in elastic parameters) ;
- to validate a conceptual/numerical model using complementary data.

Two examples are developed below.

3.4.1 Resolving shallow and deep aquifer behavior

Agricultural regions, whose irrigation is mainly based on groundwater pumping, are facing water management challenges. Therefore, groundwater observation networks are generally carried out to monitor aquifer state and answer the sustainability issue. However, in thick and complex aquifer systems, monitoring networks can not be sufficient, considering their sensitivity to close-by pumping stations. Furthermore, wells are representative for intercepted structures, so the meaning of the data itself is questioned in the case of complex aquifer structures made from a succession of aquifers and aquitards.

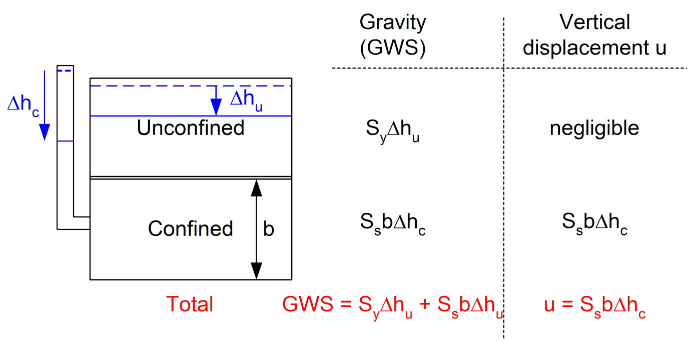

Figure 3.16 – *Sketch showing the impact on gravity change and vertical displacement of a dual unconfined/confined aquifer with head changes Δh_u and Δh_c respectively. S_y, S_s and b stand respectively for the specific yield in the unconfined aquifer, specific storage and thickness of the confined aquifer.*

As shown on figure 3.16, gravity integrates vertically all aquifers, while vertical displacement sensitivity is limited to pore pressure changes in the confined aquifers. Mass changes in the unconfined aquifer can be written as $GWS_u = S_y \Delta h_u$, where S_y and Δh_u represent specific yield and head (water level) change in the unconfined aquifer. When considering that the confined aquifer is at equilibrium, vertical displacement can be assimilated as the cumulative volume of water extracted over the time period (as gravity changes). Thereby, vertical displacement and gravity changes share the same contribution for the confined aquifer $GWS_c = S_s b \Delta h_c$, where S_s, b and Δh_c represent respectively specific storage, confined aquifer thickness and head change.

We worked with Feng Wei and colleagues on the North China Plains, a 250000 km^2 region which is one of the main grain basket for China. Groundwater irrigation contributes to $\sim 70\%$ of total water supply. We benefited from the unique geodetic network in China (GPS, InSAR, ground gravity) and GRACE satellite and propose a coherent conceptual model to interpret all data (now shown). The joint interpretation of GRACE gravity data and land surface displacement from GPS and InSAR provides access to both storage and pressure state changes in the complex North China Plain aquifer. We estimate a total groundwater volume loss of $8.0 \pm 1.5\ km^3.yr^{-1}$ over the 2002-2014 period, which has been largely underestimated by ground-based monitoring wells. Indeed, $\sim$ 80% of the depletion takes place in deep confined aquifer layers as inelastic storage, resulting in widespread land subsidence.

Interestingly, the ratio between gravity and vertical displacement $\frac{GWS}{u} = 1 + \frac{S_y \Delta h_u}{S_s b \Delta hc}$. When considering that head change in both unconfined and confined aquifers are similar the ratio simplifies to $1 + \frac{S_y}{S_s b}$, a constant value linking specific yield in the unconfined aquifer and storage coefficient in the confined aquifer. Under this hypothesis, when applied to the North China Plains, geodetic observations estimate that $S_s b \approx 4 S_y$, meaning that the deep confined aquifers can provide 4 times more water than shallow unconfined aquifers, for the same pressure change.

Gravity and vertical displacement can be used as a diagnostic tool to infer storage parameters and response of complex aquifer systems to boundary conditions.

3.4.2 Transferring information from one scale to another

In the following example from Castellazzi et al. (2018), we propose to transfer aquifer-scale information obtained from high-resolution InSAR to feed the inference of GRACE-based water storage changes at $\sim 500\ km^2$ scales. Indeed, GRACE provide the information required to resolve water budgets and contribute to water management, but the large-scale sensitivity limits its application to the largest aquifer systems (around 3 or 4 on Earth).

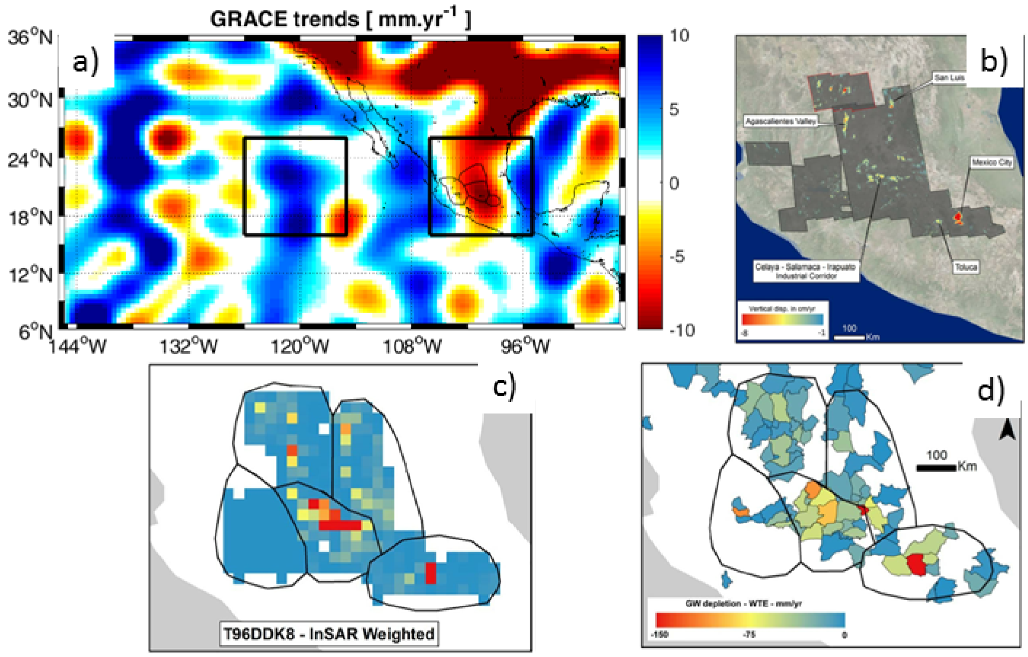

Figure 3.17 – *The high value of combining gravity and deformation. (a) GRACE trends over Mexico and surrounding oceans from CSR product with DDK-8 anisotropic filter. The large declining trends in California and Texas are coherent with previous studies (Long et al., 2013; Scanlon et al., 2012). Some depletion is seen in Mexico (back box), but difficult to separate from noise (see black box in the ocean, West of Mexico, GRACE signal in the ocean can be typically interpret as uncertainties (Longuevergne et al., 2010). (b) InSAR map in Mexico, highlighting hotspots of GW depletion in focused aquifer system in valley bottoms, with typical size $\sim$ 10 km. (c) GW depletion rate defined from the combination of both InSAR spatial patterns and GRACE volume information, to be compared with (d) cachment-scale official water budgets used for GW governance.*

Both gravity variations and subsidence are (or equivalent to) water volumes, so can be used together for groundwater management questions. Following the Tienshan example (figure 3.9), we proposed to inverse GRACE mass storage on a finer scale, based on the knowledge of groundwater masses brought by InSAR. The method was quite successful (figure 3.17), as GRACE data had been downscaled on a $\sim 25\ km$ grid, with good correspondance to available water budgets published by the state of Mexico. The value of InSAR is twofold : (1) localize subsurface water masses with high resolution and (2) provide a spatial structure to be recognize in GRACE data, allowing for a better separation between signal and noise.

However, we also showed that the defined spatial patterns were depending on the GRACE product. The method was working well for CSR product with DDK filter and GRGS data, but not testable with recent mascon products (Save et al., 2016), that were showing no mass loss in this region.

Conclusion

Geodesy offers a range of instruments and methods to auscultate the Earth's and study water transfer and storage change in the CZ on a wide range of spatial scales. They grant access to unprecedented information, which are key to resolve basic scientific questions (e.g. understand fracture flow at network scale), represent the heterogeneity of the CZ and its impact on flow, and inform water management. It is clear that the combination of different tools is much informative fully decipher complex behavior.

4 Scientific challenges and perspectives

L'objectif de l'art n'est pas le déclenchement d'une sécrétion momentanée d'adrénaline, mais la construction, sur la durée d'une vie, d'un état d'émerveillement et de sérénité

Glenn Gould

Sommaire

Hydrogeodesy is a promising approach to study the Critical Zone, and the specific role of the hidden groundwater. On the one hand, deformation is both an intrinsic process when water flows, and a distant action betraying subsurface pressure changes. On the second hand, gravity variations are directly sensitive to storage, an essential variable to understand available water for ecosystems and resolve water budgets. Both combined provide critical insights into the active structures bearing water flow in the heterogeneous subsurface, and how they shape exchanges between surface and depth.

The last 10 years have been dedicated to the development of instrumental and methodological approaches to qualify geodetic instruments as tools to better understand flow and storage in the heterogeneous subsurface. In the next 10 years, I would like rely on these developments and contribute to a better understanding of aquifer systems and their critical role in shaping ecosystems and the water cycle at different scales (figure 4.1) : (1) at $\sim 10\ m$ scales, investigating the basic processes linking transient pressure, flow and deformation in compressible aquifers ; (2) at $\sim 1\ km$ scales, imaging the internal architecture of the CZ and its impact on water storage and flow ; (3) at $\sim 100\ km$ scales, understanding the fundamental role of groundwater in the climatic system. A major experiment will refocus the work on ecosystems, and define how geodetic observations can decipher internal

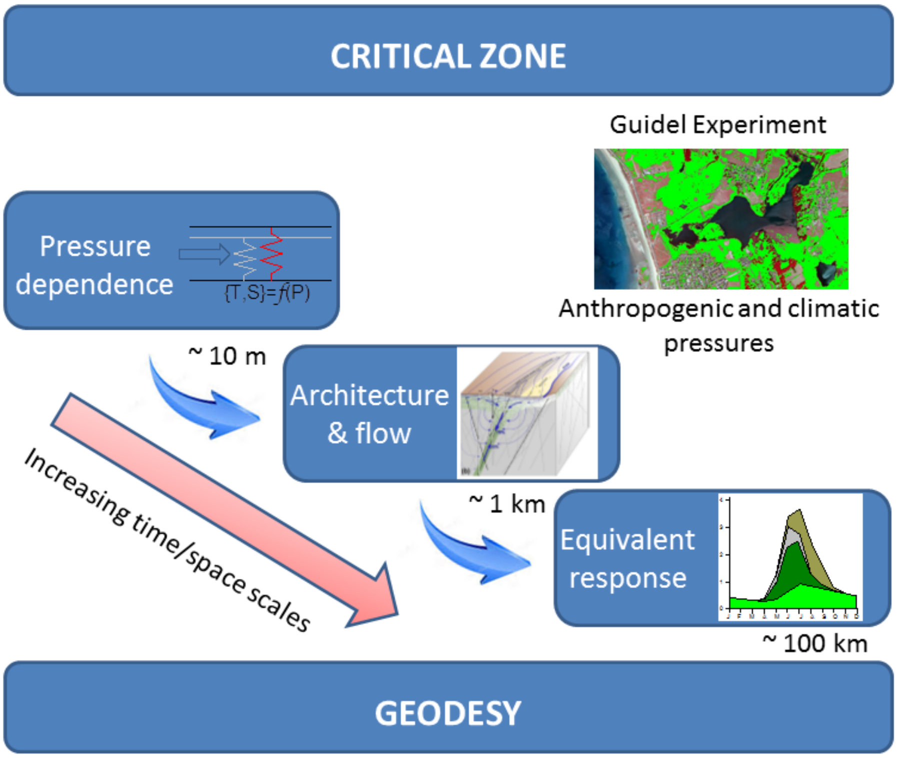

FIGURE 4.1 – *A synthesis of the different research axis I want to lead in the next 10 years, and their relation.*
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4.1 Hydro-mechanical interactions

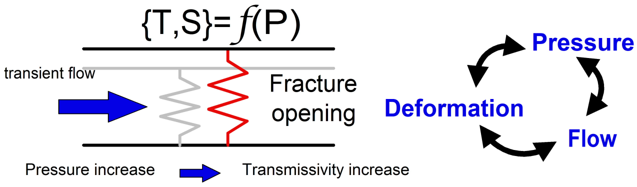

Figure 4.2 – *Sketch describing the basic hydro-mechanical process : transient pressure increase generates transient flow, but also opens the fracture. On the right, the essential interrelated variables*

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Staff	Maxime Mouyen (post-doc Région Bretagne, 2017 - 2019) Behzad Pouladi (PhD ITN ENIGMA, 2017 - 2020)
Collaboration	Experimental (laboratory) : civil engineering plateform @ INSA Rennes Website Experimental (flow, *in-situ*) : Matthew Becker, Univ. California (flow) Experimental (deformation, *in-situ*) : Larry Murdoch, Clemson Univ. (deformation)
Funding	Equipment : EQUIPEX CRITEX, Rennes Metropole, Pre-proposal submitted to ANR : ROCK'n ROLLS
Outcome	Developing tilt and Fiber-optic based strains for *in-situ* experiments Explore hydro-mechanical coupling in single fractures and connected networks Representation of pressure-dependent hydrodynamical parameters in flow models
Impact	Flow and mechanics in fractured rocks Subsurface ecosystems at $\sim 100\ m$ depths (O_2 transfers) Pore pressure transfers towards seismogenic depths

Table 4.1 – *Synthesis of the axis "Hydro-mechanical interactions"*

Fractures exist on a wide range of spatial scales and form connected fractured networks. Both have a major control on fluid transfer (Tsang & Witherspoon, 1981), and on the mechanical properties of rock masses (Kachanov, 1992). The representation of a fracture network remain as a daunting challenge considering the scarcity of appropriate data with respect to the volume of rock (Davy et al., 2010).

As a consequence, little is known on flow and transport in fractured networks. Fluid flow through a single fracture has been linked to the cube of the fracture aperture (Witherspoon et al., 1980) during experiments are core scale. Yet, at largest scales, longer (so thicker) fractures are expected to be more sensitive to aperture (Klimczak et al., 2010), so that flow at fractured network scale would biased by the (less numerous) longest fractures. There is a clear lack of understanding of flow processes at scales above 1 m and *in-situ* conditions (Rutqvist, 2015).

As underlined by Manga et al. (2012), shallow fractured rock are more sensitive to pressure changes than expected. Deformation is a dedicated tool to explore flow/pressure/deformation relationships (Guglielmi et al., 2015), but also contain an information on the pressure distribution, and therefore, how fractured network shape flow beyond the fracture scale. For example, hydro-mechanical interactions have been clearly highlighted in Stang er Brunn on deformation observations (Schuite et al., 2017). With technological advances, deformation is growing as a major tool to track localized active structures (Becker et al., 2017).

The development of surface tilt to track deep fractures is a major originality of the Rennes team. Tilt grants access to the fractured network behavior from surface observations. Though, tilt is sensitive to both fracture extent and hydro-mechanical behavior, and strain observations in boreholes would bring a complementary information.

4.1.1 Developing distributed strain observations in boreholes.

Strain observations in boreholes are now common tools (Guglielmi et al., 2015; Cappa et al., 2006; Burbey, 2010; Jeanne et al., 2017), they are generally meter-scale tools focusing with limited resolution, and therefore require high pressure testing. New developments in shallow fractured rock would need to answer 2 constrains : (1) first, high spatial resolution, this is required to capture the high strains focused in front of fractures. High resolution can answer the small amplitude problem and also decipher the respective contribution of different fractures within the typical length of a strainmeter. (2) second, strain observations over extended lengths to have access to the behavior of the connected fractured-network. Even if experiments are carried out by injecting in a single fracture, flow quickly reaches the network scale and occurs in a set of fractures (Dorn et al., 2012).

We have recently purchased a fiber-optic (FO) based system to measure distributed strains with high resolution (~ 1 *cm*). First results obtained during a hydraulic test in Ploemeur/Stang Er Brunn experimental site are promising (figure 4.3), giving a new vision of active structures in fractured network. Actually, we highlighted that (1) a limited number ($\sim$ 25%) of fractured mapped by classical optical tools can be considered as active, (2) classical tools, such as GPR and hydraulic tests are unable to capture all the active structures.

Instrumental adaptation and experimentations. As first results are promising, several key points should be carefully evaluated : (1) The Fiber-Rock coupling, is a key issue to ensure the robustness of the observations. This need to be answered over the length of the optic fiber. In the experimental setup, we used a "light" coupling method on contrary to classical (destructive) methods based on anchors : an over-pressured flexible liner pressing the fiber on the borehole walls. Alternate coupling strategies should be tested.(2) The position of the fiber was not ensured. One solution consists in taking full advantage of the fiber versatility and flexibility and defining its vertical path along 4 orthogonal directions in the borehole. This question should be answered at the same time as the coupling issue. (3) The meaning of longitudinal strains should be strengthened. FO-based observations do not separate different deformation orientation, such as shear and normal stresses. A better understanding of the FO data is required. This will be answered in the next years with more *in-situ* and laboratory tests, in collaboration with INSA mecanical plateform.

4.1.2 Consequences on flow

From fracture to network scale. Both hydraulic and deformation datasets are expected to provide critical information to feed and condition discrete fracture network models (DFN, e.g. (Davy et al., 2013)). Local strain will provide orientation of the fracture and its opening with respect to pressure variations, while tilt will be sensitive on how pressure redistributed in the fracture network. A clear interpretation framework should be shaped on a single fracture, based on numerical analyses and application on the field. (1) at fracture scale, the main The link between pressure, flow, and fracture opening should be defined to understand how to decipher such processes from localized and indirect observations. (2) at fracture network scale, it is also important to understand potential interactions among fractures.

Aquifer systems are deformable structures, and the defined stress-permeability relationship should be scaled up to re-investigate classical hydraulic methods. Currently, hydrogeologists do not consider aquifers as deformable, although there are clear evidences of such hydro-mechanical coupling on pressure observations (figure 4.4). For example,

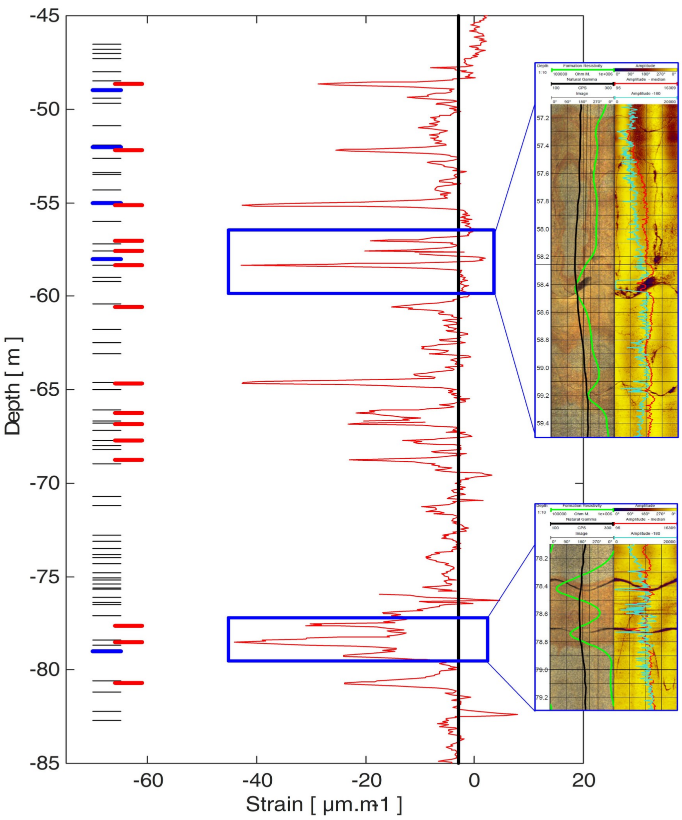

FIGURE 4.3 – *(Left) Longitudinal strain measured by high-resolution FO based strain sensing in a borehole during a hydraulic test in a neighboring well in Ploemeur observatory (Right) optical, acoustic and geophysical diagraphy for 2 specific zones. The borehole hosting the FO is sealed (no flow). In this experiment, gauge length is* $\sim$ 2 *cm, highlighting active fractures contributing to flow. On this* $40 - m$ *section,* 64 *fractures have been mapped on logs (black dash, one each* 60 *cm), on which* 16 *are active (red dash, one each* 2.5 *m). Note that only 3 actives fractures were detected during flow inference test (Le Borgne et al., 2007) and 5 during tracing tests interpreted with geological penetrating radar (GPR, blue dash) (Dorn et al., 2012). Note the high spatial resolution* $\sim$ 2 *cm and high sensitivity* $\sim$ 10 $\mu m.m^{-1}$ *over the* 100 *m total length of the optic fiber.*
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during a pumping test in a fault zone, a scale-dependent decrease in transmissivity can be inferred, hiding a local stress-dependent behavior. Further specific behavior are also valuable to explore : rock mechanical fatigue due repeated hydrological cycles and solicitations, increasing permeability, ...

Linking fracture behavior to lithospheric and ecosystemic processes. Following Guglielmi et al. (2015), I speculate that transient fluid pressure perturbations are amplified through the transmissivity increase (non-linear response). This work will have several impacts beside a better understanding of flow in fractured rock :

— How can small fluid pressure changes modulate natural seismicity, or trigger earthquakes (Calais et al., 2016) ?
— How is O_2 transfered at depth to create microbial ecosystems at the base of the biogeochemical cycles (Bochet et al., submitted) ?
— Does the amplitude of the hydrological cycle control the permeability of the shallow crust, as suggested by (Rojstaczer et al., 2008) ?

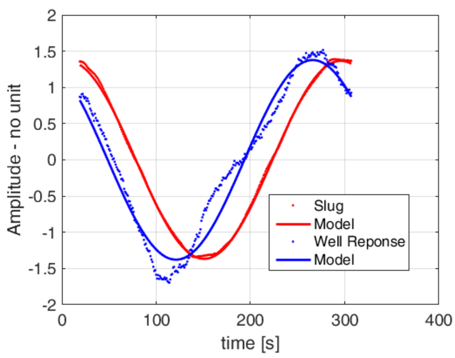

FIGURE 4.4 – *Field evidence of the dependence of hydrodynamical parameters to pressure during a sinusoidal test in Stang Er Brunn. Pressure changes imposed in a fracture (red curve), observation and sinusoidal model, reduced to a single period (290 sec), and the response of the media measured in a borehole 6m away (blue curve), observations as dots and sinusoidal model. Note the "deformation" of the sinusoid, head changes (i.e. flow) are quicker when pressure is more important, and slows down when pressure is close to zero.*

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4.2 Imaging dynamical processes in heterogeneous media

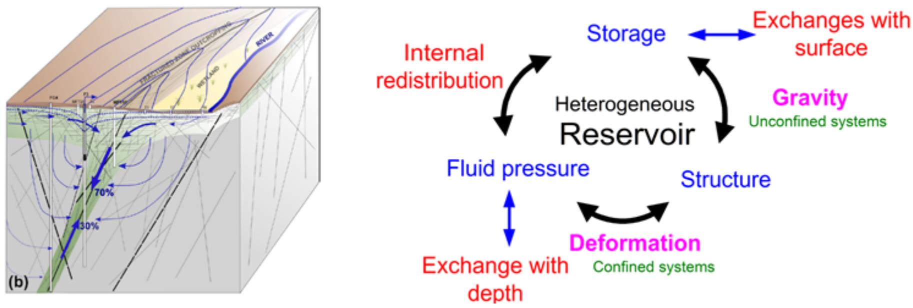

Figure 4.5 – *(Left) Sketch describing the structural control on water flow, from Roques et al. (2014). (Right) conceptualization of the links between depth and surface, and how geodetic observations can bring new insights*

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Staff	Luca Guillaumot (PhD, 2016 - 2018) Maxime Mouyen (post-doc Région Bretagne, 2017 - 2019) Lara Antonia Blazevic (PhD ITN ENIGMA, 2017 - 2020)
Collaboration	Seismic methods : Ludovic Bodet et Damien Jougnot (UPMC) Gravimetry : Jacques Hinderer (IPGS), Cédric Champollion (Univ. Montpellier) Deformation : Frédéric Boudin (ENS, Paris), Stéphane Durand (ESGT Le Mans) Hydrological modeling : Konstantinos Chalikakis (INRA Avignon)
Funding	Equipment : EQUIPEX CRITEX, RESIF and MIGA Equipment : CNRS-INSU shared equipment pool ITN ENIGMA (2017-2020)
Outcome	Petrophysical relationships between seismic velocities, water content/pressure Geodetic data information content for distributed modeling
Impact	Active/passive seismic to track water storage changes at various scales Identification of storage and permeable structures within hydrological systems

Table 4.2 – *Synthesis of the axis "Imaging dynamical processes in heterogeneous media"*

This axis consists in diving in the internal processes of hydrological systems, relying on the complementarity among surface geodetic and seismological observations. Hydrological and hydrogeological approaches are generally disconnected, while both CZ and GW are intrinsically connected. The equivalent response of a hydrological system is generally interpreted as complex, non-linear and hysteretic (Andermann et al., 2012). Another point of view would consider the current response as the superposition of numerous transient events in an heterogeneous medium (De Marsily et al., 2005), which necessarily depends on the past trajectory of the reservoir and boundary conditions. The complexity of flow cannot be captured by integrative observations (e.g. river discharge), while understanding water pathways is critical to work on transport, mixing and reactivity (Binley et al., 2015) and understand how interfaces shape ecosystems. Therefore, imaging of subsurface processes should be achieve by non-invasive methods covering scales left blind by other methods (Beven, 2006, typically, 100 m and beyond, see).
This axis is dedicated to the characterization and monitoring of storage structures, and the was they are drained by main permeable structures. The approach consists in translating gravity, deformation and seismic data as a hydrological information to track internal water redistribution.

4.2.1 Characterization and monitoring of active structures by seismic methods

In the context of the rapid evolution of seismic-derived methods for study the subsurface Earth's dynamics (surface wave analysis (Pasquet et al., 2015a;b), seismic noise monitoring (Shapiro & Campillo, 2004)), and their wide potential to provide high resolution on subsurface systems, the transformation of seismic methods into a tool for hydrology require to base the link between the mechanical state and hydrological variables on strong physical basis. The challenge is to define quantitatively how estimation of mechanical parameters inferred from seismic methods could contribute to a better understanding of mechanical and hydrological subsurface processes. Lara Antonia Blazevic, within the ITN ENIGMA project, will work on the qualification of seismic methods as tools to capture temporal evolution of the subsurface water content/pressure.

In an initial study, Lecocq et al. (2017) showed long-term records in seismic observatories could bridge both a spatial and temporal gap to sense deep subsurface storage : (1) the gap between the climatic time scales and the Earth's observation scale, as seismic networks were setting up globally 40 years ago ; (2) the gap between the instrumental network (generally at $\sim 10\ km$ scales) and the large integration of GRACE gravity observations. Further, they show that the equivalent elastic parameter linking pore pressure to seismic velocity is ten times larger than usual elastic processes. This underlines the critical need to refine petrophysical relationships to translate seismic velocities into an useful information.

The full wealth of seismic signals to study the CZ is not yet fully exploited. Pasquet et al. (2015b; 2016) already progressed on both laboratory and field experiments to develop a time-lapse application of active seismic methods in hydrogeophysics. Several other studies noticed that seismic velocity variations measured on the field are highly correlated to hydrological observations, though, that petrophysical relationships generally underestimate the observed seismic velocity changes. Two contributions should be investigated : the localization of changes and the petrophysical relationships themselves. The latter impact should be tackled through the systematic and thorough exploration of existing petrophysical models. It is critical to finding appropriate links between porosity/fracture density, saturation/pressure states, hydrodynamic parameters and seismic properties. Finally, it is important to obtain reference datasets during reference hydrological tests (e.g. infiltration test) to test the developments.

4.2.2 Coupling ground geodetic methods

The coupling of gravity (sensitive to total storage changes) and deformation (sensitive to pressure variations in confined aquifers) have shown powerful to complement each other and resolve the other's blindness (e.g. Castellazzi et al., 2018). This remote sensitivity to subsurface flow is inestimable, and should be used in combination to regular methods (e.g. set in an hydrological observatory) to fully investigate the exchanges between surface and depth.

A massively collocated monitoring system is being designed on the LSBB/Fontaine de Vaucluse observatory, IR OZCAR, providing very interesting opportunities to further develop geodetic methods. The "Fontaine de Vaucluse" is draining one of the largest karst system in Europe (1130 km^2, Vaucluse, South of France), and will be the theater for a unique multi-technique monitoring system at mesoscale. Several large equipment projects in France (EQUIPEX RESIF, MIGA, CRITEX) have setup challenging equipments. One core idea was to study how water is stored and redistributed in the karst system. Several tools are planned :

1. Monitoring storage in the thick unsaturated zone. Two superconducting gravimeters have been setup, one in galleries ($\sim 400\ m$ deep), another one on top of the karst. The vertical gravity gradients will allow access to storage variations in-between the 2 instruments (Jacob et al., 2009; Kennedy et al., 2014), while avoiding the processing of large-scale contributions to gravity ;
2. Monitoring deformation, as already started in (Lesparre et al., 2017), with the setup of a new quasi-orthogonal tiltmeter and extended GPS monitoring ;
3. time-lapse geophysical methods (seismic, nuclear magnetic sounding) will be applied to investigate spatial variability at the surface.

This experiment requires a necessary modeling component. First, it is important to fully understand the full information content of these indirect observations, and their complementarity with respect to classical observations. Geodetic observations should benefit to a better understanding of sub-scale water redistribution within hydrological systems. Luca Guillaumot, PhD student, is working on the information content of various indirect observations, including tilt and surface displacement (as well as dissolved gases and temperature). The availability of several independent observations should improve the descriptive and predictive abilities of models through the development of specific calibration/assimilation methods (e.g. Gupta et al., 2008).

4.3 The Role of Groundwater within the Critical Zone

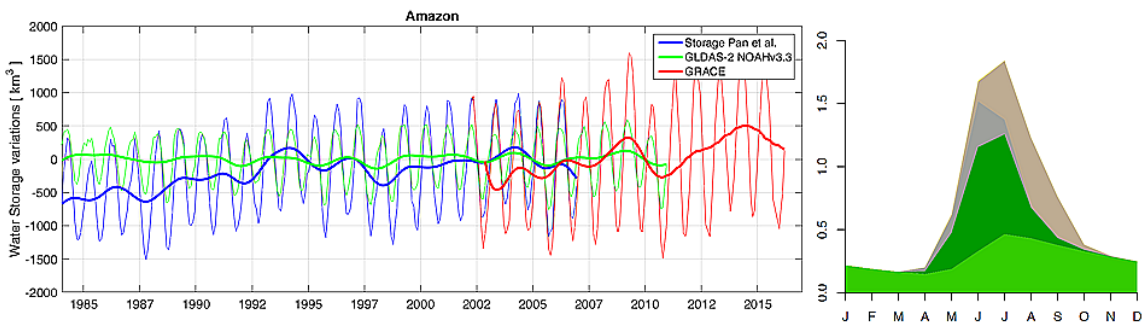

Figure 4.6 – *(Left) A comparison between different storage variation estimates over the Amazon basin : (blue) Pan et al. (2012) reanalysis data satisfying the mass balance constrain ; (green) NOAHv3.3 model forced with homogeneous data ; (red) GRACE data. The reanalysis product shows large interannual variability, including a long-term trend, on contrary to NOAH model. Compared to GRACE, the reanalysis model captures the seasonal variations, while model outputs are twice smaller. In the end, GRACE highlights large interannual variability. NOAH model lacks representation of both surface water and groundwater compartments. (Right) Sketch showing the contribution of different compartments to monthly river discharge data. River baseflow during dry months is sustained by the groundwater contribution (light green). This slow store*

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Staff	Luca Guillaumot (PhD, 2016 - 2018) PhD student (Research unit, 2018 - 2020)
Collaboration	Modeling : Yoshihide Wada, (IIASA) C/DA Research Unit (Germany) UNESCO
Funding	DFG Research unit (2018-2020)
Outcome	"Extended" GRACE time range product Ground-based validation datasets Global hydrological models with improved GW description
Impact	Improvement of global model predictability skills Contribution of GW to long-term continental-scale mass balance

Table 4.3 – *Synthesis of the axis "The role of Groundwater within the Critical Zone"*

In the time/space scales diagram (figure 3.4), GRACE is falling in the "Unsaturated Zone" compartment. As shown in the last chapters, new challenges with GRACE consists in (1) improving spatial resolution to work at water management scale, e.g. by combining to high resolution information (Castellazzi et al., 2018) ; and (2) extending time series to approach the climatic time scales. In both case, groundwater is a major contributor to total storage variations and cannot be neglected. The importance to include groundwater systems within global modeling is undeniable, and necessary to predict the evolution of the CZ in response to boundary conditions, which are non-stationary (Milly et al., 2008) (figure 4.6 and 3.11).

However, as underlined in figure 3.11, the representation of groundwater in global models is highly simplified - both structure and processes- when existing. By essence, the main difficulties are linked to their hidden nature, large heterogeneity and long response time. Recent global efforts are seeking for defining hydrodynamical properties from main geological structures (Gleeson et al., 2014; Fan et al., 2016). Such data have the virtue of existing, but questions are raised on their ability to define localized structures and represent effective parameters at useful scales. Finally, the processes, themselves, are not known or considered as secondary processes, even if they can be important at long-term time scales (pressure and temperature dependence of hydrodynamic parameters).

4.3.1 Exploring climatic time scales

Water flows slowly in geological layers over depths up to kilometers, locally intercepting the surface where it interacts with rivers or wetlands, and therefore atmosphere and ocean (Alley, 2002). The typical time response of groundwater systems typically range from months to millions of years (Rousseau-Gueutin et al., 2013; Brutsaert, 2008). In essence, groundwater conserves the memory of past events, much beyond the typical length of modern Earth Observation Systems. It is clear that long-term homogeneous and informative datasets representing the response of groundwater systems should be developed for 2 main applications : (1) exploring processes and how they shape the response of hydrological systems to interannual climate variability and the intensification of the water cycle (Green et al., 2011; Huntington, 2006) and (2) future data and model validation.

Putting GRACE in the perspective of climatic time scales. Considering the high value of GRACE data, extending GRACE time series in time would be much valuable for various applications, mainly to set GRACE time series in the context of interannual climate variability impacting long-response time hydrological systems (Eicker et al., 2016). There have been several attempts with interesting results, including the wide potential to explore the succession of droughts and floods (Long et al., 2014b; Becker et al., 2011), explore linkages between continental storage and oceanic modes of variability (Forootan et al., 2014). However, evaluating the performance of the extended GRACE dataset remain as a tricky issue. In any case, a data-driven approach is required, to avoid founding the analysis on strong hypotheses that would corrupt the results.

4.3.2 Implementing and validating global models

The regional drying and wetting patterns can be only insufficiently explained by direct anthropogenic effects such as global warming, groundwater and surface water withdrawals,irrigation, reservoir building (Wada et al., 2017). Such land models lack groundwater systems. In such a context, the full representation of groundwater systems within land models cannot be overlooked. As underlined in figures 3.11 and 4.6, current modeling platforms do not allow the representation of interannual variabilities and long-term variations, even at $\sim 15\ yr$ time scales. I hypothesize that groundwater has a significant role to play, considering its large storage capacity, long-time response and non-linear behavior (coupling with surface, pressure-dependent hydrodynamical parameters). Previous works by Vergnes et al. (2012) and Niu et al. (2007) have shown how the inclusion of groundwater in global models could impact modeled fluxes. However, their approach was based either on a coarse resolution or limited to a shallow structure. By essence Groundwater fluxes are strongly influenced by topography, creating shallow (local) to deep (regional) circulation loops towards minimum topography, so that the adequate approach should consider high resolution and deep structures (e.g. Maxwell & Condon, 2016). Luca Guillaumot spent a month in IIASA with Yoshihide Wada, coupling MODFLOW model to CWAT hydrological model. This first stay was already highly productive with a functional model over the Rhine aquifer, and raised further question on the full coupling of both models (recharge and capillary rise, baseflow generation, ...). Finally, it highlighted the requirement to evaluate model improvement on a set of observables (river discharge, GRACE storage, evapotranspiration), as several model structures and process representations can lead to similar responses.

Finally, I am participating to the "Research Unit" called Global CDA : Understanding the global freshwater system by combining geodetic and remote sensing information with modelling using a calibration/data assimilation approach, funded by DFG, as a Mercator fellow. The idea is to improve the representation of several processes within WGHM global hydrological model (Döll et al., 2003; Muller Schmied et al., 2016), and develop tools to perform calibration/assimilation on a range of global observations. I share a work package with Annette Eicker (Hamburg University), exploring the way GRACE can be used to inform models, and developing an independent ground-based dataset for validation purpose. Overall, this project should highlight the extended value of complementary geodetic observations (gravity variations, surface displacements, e.g. Castellazzi et al., 2016)) for the representation of the water cycle and the role of groundwater systems.

4.4 The GUIDEL experiment

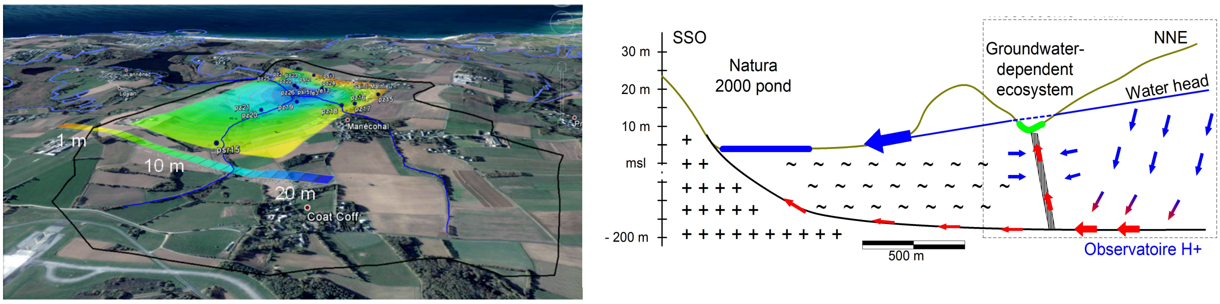

Figure 4.7 – *(Left) Perspective of the Guidel site, a geological and climatic equivalent to the Ploemeur site, but in "natural" state. Downstream to upstream : the ocean, the Natura 2000 Lannenec pond, fed by a the* $3 - km^2$ *catchment in which large scale pumping will be set up. The two rivers converge towards a local topographic minimum hosting an extended groundwater-dependent ecosystem. The blue dots are the well monitoring system. The colormap corresponds to head spatialized head drawdown generated by a 2-month pumping in 2009. Pressure changes are important below the wetland and diffuse mainly towards the East direction. (Right) Conceptual model of the Guidel site, showing the role of the main heterogeneities in connecting the different compartments of the CZ, favouring the mixing of deep and shallow water.*

Staff	The Guidel group within OSUR, 17 researchers, 5 engineers/techniciens 4 laboratories 2 PhD students
Collaboration	To be determined.
Funding	RISC-E structure - collaborative and interdisciplinary aspects OSUR - OSUNA (2017) - deformation component SNO H+ - Maintenance, equipment CNRS/INSU - EC2CO project submitted (wetland ecosystem)
Outcome	A controlled experiment increasing water scarcity on a $\sim 1\ km^3$ mesocosm The definition of physical proxies to define habitat complexity, interactions An image on how physical forcings shape ecosystems
Impact	Ecosystem functioning, degree of interdependence and resilience A collaborative large-scale experiment pushing for disciplinary developments An original dataset relevant for Earth System Science

Table 4.4 – *Synthesis of the axis "Guidel experiment"*

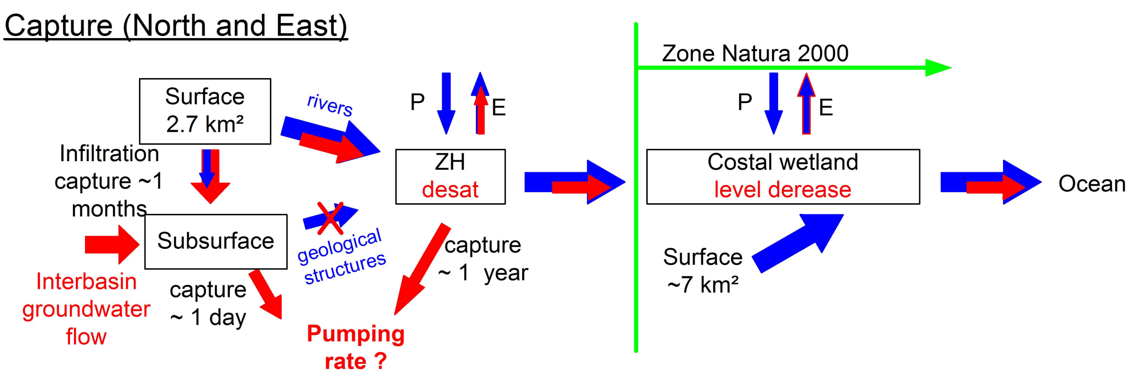

Figure 4.8 – *Impact of pumping on the evolution of water flow among the different storage compartments (i.e. capture process, red arrows) with respect to the initial condition (blue arrows). This sketch sets the challenge in monitoring the evolution of a* $\sim 1\ km^3$ *mesocosm (from tree top to deepest groundwater !).*

The ambition of this axis is to dig into the concept of ecosystem, considering the definition of Tansley as a starting point : an ecosystem is defined in the sense of physics, as the indivisible system of biota and environment, where both organic-inorganic cycles are completely integrated. The different compartments (litho-, hydro-, atmo-, bio- spheres) are constantly interacting and participate to the functioning of ecosystems 2.1. This implies the need to gather beyond the classical disciplinary dichotomies to identify the actual dynamics of ecosystems and predict their future evolution under climatic pressure. There is still an important need to understand the processes regulating the inter-related components of ecosystems

The GUIDEL project consists in working on the deep interactions that connect the different components of a 1 km^3 ecosystem (4 km^2 at the surface) and understand the processes that regulate them, through an experimental approach. The Guidel Observatory (SNO-SOERE H + Ploemeur) will be destabilized by a large-scale AEP pumping. This physical action will increase water stress and profoundly destabilize the ecosystem.

The Guidel site offers a favorable context to work on these questions (figure 4.7). The granite and micaschist contact zone has been identified as the main permeable structure, allowing large volume of water to be drained. Water is upwelling due with the presence of vertical fractures, feeding an extended groundwater dependent ecosystem with warm, anoxic and iron rich water. The river draining the wetland was measured at several locations in September, following a 3 months period with very low rainfall. Between the last 2 downstream stations, 250m apart, discharge doubles thanks to the groundwater contribution. Between the 2 upstream stations, discharge remained constant, suggesting an almost complete consumption of the groundwater upflows by the vegetation. It should be noted that the baseflow rate of this stream is 10 times larger than the typical baseflow for a catchment of this size.

4.4.1 A long-term experiment

A large scale pumping will be started in 2018 for community water supply, at a yearly rate planned $\sim 1\ M^3.yr^{-1}$. This will completely reorganize flow structures, at depth and surface, stimulate water mixing ... and generate large transient signals describing the convergence towards a new equilibrium - surely equivalent to the Ploemeur/Kermadoye site - over a wide range of time scales. The impacts on the ecosystem are difficult to predict, some might be counter-intuitive, for example :

- the potential improvement of the ecological quality of the rivers (pumping will capture upwelling anoxic water), or deterioration if the water stress becomes too severe ;
- the transfer of the reactive zones, e.g. the denitrifying functions, from the wetland down to the deep systems thanks to water mixing, stimulating reactivity (Roques et al., 2018) ;
- the transformation of habitats, evolution of biodiversity and landscapes.

The idea is to monitor the evolution of the mesocosm with classical and innovative methods (geophysics, geochemistry, ecology), with a focus on 3 complementary scales : (1) The process scale, where a set of direct and indirect methods connect ecosystem function evolution and the local physico-chemical conditions ; (2) A spatialization scale, relying mainly on geophysics and other indirect methods to capture the variability/extension of local processes ; and (3) An integration scale to monitor the equivalent response of the ecosystem. We want to answer to the following question :

1. How do physical forcings shape habitats and ecosystems ? What are the relationships between surface and depth ?

2. Can we define proxies to characterize the complexity of habitats, interactions, and upscaling ?

This "controlled experiment" is a natural incubator for extensive interdisciplinary research on systemic approaches. Further, the large amplitude of transient signals is a real opportunity for the disciplinary-interdisciplinary balance, encouraging disciplinary developments, but also benefiting other disciplines for the global interpretation.

Curriculum Vitae

5

J'entretiens l'inconfort
À l'allure qui dort
Grace à lui contractant
Chaque muscle de mon corps
Je tiens encore un peu
Ce cul entre deux sorts
Mon embarras, c'est moi

Charlotte Gainsbourg, *I'm a lie, Rest*

Sommaire

Ce

Parcours

Laurent Longuevergne
Né le 21/05/1978, marié, 3 enfants
CR CNRS, matricule 87434

Cursus

Avril 2008	Thèse de Doctorat de l'Université PIERRE ET MARIE CURIE, PARIS VI, spécialité "Géosciences et Ressources Naturelles", sous la direction de Nicolas Florsch. Jury : Philippe Ackerer (rapporteur), David Crossley, Philippe Davy, Philippe Elsass, Jacques Hinderer (rapporteur), André Mariotti (Président), Walter Zürn. Manuscript. Prix de la thèse du CNFGG (2009)
Septembre 2002	Diplôme d'ingénieur en Géophysique – Géotechniques Polytech'Paris – Université PIERRE ET MARIE CURIE, PARIS VI

Carrière

2010-	Chargé de recherche CNRS, section 30
Ete 2013	Professeur invité à l'Institute for Geodesy and Geoinformation, Université de Bonn
2008-2010	Post-doctorant à l'Université du Texas à Austin (financement NASA)
2004-2008	Doctorant à l'Université Pierre et Marie Curie, Paris VI.
2002-2004	Volontaire Civil à l'Institut Paul Emile Victor, responsable scientifique de l'observatoire des Kerguelen

Formation

2017	Formation avancée Python
2015	Ecole d'été "Écoulements et Transport en Milieux Poreux et Fracturés : Développement, Protection, Gestion et Sequestration des Fluides Souterrains", Site web
2007	Ecole d'été en hydro-météorologie, Université de l'Aquila
1997-1999	Classes de mathématiques supérieures et spéciales MP* L.E.G.T. Albert Schweitzer de MULHOUSE (Maths - Physique – option Informatique)

5.1 Projets

5.1.1 Projets financés

2018-2021 **Global CDA : Understanding the global freshwater system by combining geodetic and remote sensing information with modelling using a calibration/data assimilation approach**. DFG Research Unit, PI : Petra Döll, participe à une thèse en tant que "Mercator Fellow", Site web
Amélioration des capacités descriptives et prédictives des modèles globaux, validation, 12 laboratoires allemands (+Luxembourg, Suisse, France), 15 thèses.

2017-2020 **ENIGMA : European training Network for In situ imaGing of dynaMical processes in heterogeneous subsurfAce environments**. Projet européen ITN, PI Philippe Davy, participe à 2 ESR (thèses), Site web
Développement des méthodes d'imagerie des processus dynamiques s'appuyant sur le réseau d'observatoires $\mathcal{H}+$ international, 11 partenaires européens, 15 thèses

2017 **FOREVER : Fibre optique : un outil révolutionnaire et versatile pour le suivi des processus environnementaux et l'auscultation des infrastructures**. PI Laurent Longuevergne, Rennes Métropole, Soutien à l'acquisition d'équipements scientifiques. 48 k€
Co-financement (avec l'Equipex CRITEX) des outils de déformation par fibre optique

2017-2018 **FRACFLOW : Caractérisation dynamique des réseaux de fracture par des mesures distribuées de déformation par fibre optique**. PI Laurent Longuevergne, Région Bretagne, stratégie d'attractivité durable. 75 k€
Post-doctorat de 2 ans pour développer les outils de déformation par fibre optique

2016-2017 **Quantification des flux sédimentaires par gravimétrie spatiale** : CNES - postdoctorat. PI Maxime Mouyen, 100 k€
Une nouvelle application pour le satellite GRACE : le transport de masses solides

2012-2019 **CRITEX, Parc national d'équipements innovants pour l'étude spatiale et temporelle de la Zone Critique des Bassins Versants**. ANR-EQUIPEX, PI Jérôme Gaillardet, direction adjointe. 7 M€, Site web
22 partenaires, 5 instituts de recherche, 15 universités
S'appuie sur les réseaux d'observatoires SOERE $\mathcal{RBV}$ et $\mathcal{H}+$
A permis de structurer la communauté nationale autour de la Zone Critique, et a abouti à l'Infrastructure de recherche $\mathcal{OZCAR}$

2012-2013 **Description et mise en œuvre de méthodes de caractérisation des débits d'étiage à l'échelle d'un bassin versant**. Région Bretagne - CRESEB - Centre de Ressources et d'Expertise Scientifique sur l'Eau de Bretagne, PI Laurent Longuevergne, 4 k€, Rapport
Formalisation des approches quantitatives pour la gestion des ressources et l'estimation des débits minimum biologiques avec les acteurs breton de l'eau

2012 **GEOFRAC, l'hydrogéodésie appliquée aux systèmes fracturés**. CNRS INSU EC2CO, PI Laurent Longuevergne, 11 k€
Développement des méthodes de déformation pour l'hydrogéologie

5.2 Communication scientifique

5.2.1 Conférences invités

Longuevergne L., Gaillardet, J., Pannard A., Dufrenes A., Bour, O., Chatton E.,Labasque T., Aquilina, L., Le Borgne, T.,Bochet, O., Guillaumot L., Lavenant, N.,Petton C. : The Water Age Vertigo, **eLTER Conderence a LTER-Europe annual meeting**, Malaga, November 2017,

Scanlon, B.R., Zhang, Z., Save, H., Sun, A., Müller Schmied H., van Beek, L.P.H., Wiese, D.N., Wada, Y., Long, D., Reedy, R.C., Döll, P., Longuevergne, L. : Comparison of Decadal Water Storage Trends from Global Models and GRACE Satellite Data, **AGU Fall meeting**, San Francisco, December 2017

Longuevergne, L. : A few notes on GRACE information content for ESM improvement, **Impact of Groundwater in Earth system Models workshop**, Paris, October 2016

Longuevergne, L. : GRACE information content for hydrological studies, challenges and opportunities, **First workshop on Satellite Gravity and Hydrology**, Beijing, June 2016

Scanlon, B.R., Long, D., Longuevergne, L. : Use of GRACE Satellites to Assess Trends in Groundwater Storage Globally, **AGU fall meeting**, San Francisco, December 2014

Bour, O., Le Borgne, T., Longuevergne, L., Lavenant, N., Jimenez-Martinez, J., Dreuzy, J.R., Schuite, J., Boudin, F., Labasque, T., Aquilina, L. : Innovative field methods for characterizing the hydraulic properties of a complex fractured rock aquifer (Ploemeur, Brittany), **AGU fall meeting**, San Francisco, December 2014

Gaillardet, J., Longuevergne, L., Nord, G., André, F. : Critical Zone Science : a new scientific paradigm ? **AGU fall meeting**, San Francisco, December 2014

Gaillardet, J., Longuevergne L. : The CRITEX project, challing equipments for the temporal and spatial exploration of the Critical Zone at the catchment scale, **TERENO international conference**, Bonn, October 2014

Longuevergne L. : Geodesy for Hydrology, **Summer school "GRACE/GRACE-FO applications for the terrestrial water cycle"**, Mayschoss, Germnay

Longuevergne, L. : Hydrological contribution to geodetic observations, **RESIF projet technical and scientific meeting**, Yenne, October 14-16 2013

Longuevergne, L. : Information content of GRACE. **DFG roundtable discussions**, Frankfurt, 15-16 November 2012

Longuevergne, L. : GRACE : Monitoring River Basins in Africa, tutorial session of the **Joint AfricaArray and IGCP 565 Sessions**, Johannesburg, Afrique du Sud slides

Longuevergne, L., Scanlon, B.R., Wilson, C.R. : New GRACE hydrology products, **IGCP 565 workshop 4** : Integration of geodetic observations and products in models of the hydrological cycle, Support for water management through hydrological models and data assimilation, Johannesburg, November 2011

Longuevergne, L. : Extracting the local hydrological contribution from gravity measurements for model assessment : case study of Strasbourg observatory, **USGS workshop on superconducting gravimeters** Arizona Water Science Center, May 2011.

Longuevergne, L., Scanlon, B.R., Wilson, C.R. Turning GRACE as a tool for hydrological monitoring. **EGU meeting**, Vienna, 3-8 April 2011

Scanlon, B.R., Longuevergne,L., Favreau, G., Zheng, C., Gao, G, Shen, Y. Water Scarcity within the Context of Climate Change and Land Use Change and Linkages to Food Production in Semiarid Regions. **AGU Fall meeting**, San Francisco, 14-18 décembre 2010

Longuevergne, L., Boy, J.P. Gascoin, S. Florsch N., Viville, D. Ferhat, G., Ulrich, P. Luck, B., Hinderer, J. Constructive and destructive hydrological effects on gravity at the

Strasbourg station, **COST Workshop on hydrological and other local effects in gravity measurements**, mars 2009, Bruxelles.

Longuevergne, L., Wilson, C., Scanlon, B., Wu, H., Sharp, J. : Turning a superconducting gravimeter into a field tool for hydrological studies. **Colloque du CNFG2** – eau continentale, 17-19 novembre 2008, UNESCO, Paris

5.2.2 Séminaires invités

ESGT, Le Mans (2017). La géodésie peut-elle contribuer aux grands défis environnementaux ?

ENS, Paris (2017). Sur l'interface entre Terre Solide et Zone Critique.

ETH Zürich, Zürich, Suisse (2017). Weighing the value of gravity and deformation observations in groundwater studies.

Chinese Academy of Sciences, Institute of Geodesy and Geophysics, Wuhan, Chine (2016). Hydrogeodesy : can geodetic tools meet hydrologists' expectations.

ISTERRE, Grenoble (2016). Sur l'intérêt des méthodes gravimétriques et mécaniques pour mieux contraindre la dynamique des systèmes hydrologiques.

METIS, Paris (2016). Variations de gravité et déformation : des outils non-invasifs pour capturer la dynamique des systèmes hydrologiques.

Virgina Tech, Blacksburg, USA (2014). Surface geodetic tools to characterize underground active structures.

GFZ, Potsdam, Allemagne (2013). Weighing the value of geodetic instruments for hydrological studies.

Bonn University, Institute of Geodesy and Geoinformation, Bonn, Allemagne (2013). Weighing the value of geodetic instruments for hydrological studies.

International Water Management Institute, Accra, Ghana (2011). Using GRACE satellite for hydrological studies in Africa.

CUAHSI cyberseminar, USA (2010). Advances in Ground-based Gravity for Hydrologic Studies Slides.

Columbia University, New York, USA (2010). Use of GRACE Satellite and Subsurface Tracers to Assess Groundwater Resources in Semiarid Regions.

Géosciences Montpellier, Montpellier (2009). Sur l'intérêt des méthodes de gravimétrie au sol et spatiale en hydrologie.

Géoazur, Nice (2009). L'inclinomètre et ses capacités d'observation des systèmes hydrologiques, à l'échelle de la fracture, du bassin versant et de la nappe alluviale.

University of Texas at Austin, Austin, USA (2009). Using ground geodetic instruments as a tool for hydrology ? Gravimeters, a case study.

University of Texas at Austin, Austin, USA (2009). Using ground geodetic instruments as a tool for hydrology ? Tiltmeters, a case study.

EOST, Strasbourg (2008). Contribution à l'Hydrogéodésie.

5.3 Liens avec l'enseignement et la vulgarisation

5.3.1 Participation à l'enseignement

3h ETD introduction à l'hydrogéodésie, M2 H3 (Hydrogéologie - Hydrobiogéochimie - Hydro-pédologie - Université Rennes 1)

35h ETD Encadrement de stages M1/M2 sur le terrain à Ploemeur/Guidel.

15h ETD cours de gravimétrie (2011 - 2015), M2 GARE (Géophysique Appliquée, Ressources, Environnement - Université Paris 6)

6h ETD Gravity tools for hydrology (2013), M.Sc. Université de Bonn, Allemagne

10h ETD Processing GRACE data for water storage estimation, application to Africa (2011), doctorants et chercheurs associés à International Water Management Institute - Université d'Accra, Ghana

5.3.2 Encadrement d'étudiants en Master

Yinghao Li (M2 Université Rennes 1) - 2011 - Impact du changement climatique sur les basins versants de montagne. Thèse à l'établissement public Paris - Saclay

Amandine Kehil (M2 Université Rennes 1) - 2012 - Contraindre les systèmes aquifères fracturés et leur comportement par la géophysique appliquée, site de Saint Brice en Coglès. Thèse à l'Université de Bordeaux

Julien Assemat (Ingénieur INSA Strasbourg) - 2015 - Evaluation des performances de capteurs topographiques pour la mesure de déformation, en collaboration avec Stéphane Durand, ESGT, Le Mans. En poste dans un bureau d'étude.

Lucia Salguero Puerta (Ingénieur INSA Strasbourg) - 2015 - Caractérisation des Réserves Hydrologiques à partir de Données Sismologiques.

Tales Carvalho Resende (M2 Université Paris 6) - 2015 - L'évaluation de l'impact de la variabilité climatique sur les ressources en eau souterraine dans les grands aquifères. Consultant à l'UNESCO

Quentin Courtois (M2 Université de Poitiers) - 2016 - Apport des mesures de déformation de surface pour caractériser les aquifères de socle, leurs flux et leur recharge. En thèse à l'Université rennes 1 (co-encadrement)

Solenne Schneider (M1 Université Rennes 1) - 2016 - L'évaluation de l'impact de la variabilité climatique sur les ressources en eau souterraine dans les grands aquifères. M2 à l'université Rennes 1

Angela Maria Nieto Parra (M1 INP Grenoble) - 2017 - Understanding shallow and deep groundwater flow on the Guidel site. M2 à l'INP Grenoble

Kevin Gobron (Ingénieur ENSG) - 2017 - Etude de la correction des effets de la réfraction atmosphérique sur les mesures tachéométriques, collaboration avec Stéphane Durand. En thèse à l'Université de La Rochelle

Michael Pons (M2 Université Rennes 1) - 2017 - Impact des séismes sur le signal gravimétrique GRACE, en collaboration avec Philippe Steer

Alexandra Kaelin (M2 ETH Zürich) - 2017 - Modelling the hydrological regime of Lake Turkana by combining spatially distributed hydrological modelling and remote sensing datasets, en collaboration avec Peter Molnar et Clément Roques

5.3.3 Encadrement d'étudiants en Doctorat

Charlotte Therion (Université Paris 6 - Ecole des Mines, implication 10%) - 2010-2011 - Modélisation du fonctionnement de l'aquifère alluvial du fossé rhénan supérieur, vulnérabilité sous l'impact du changement climatique (pdf), 1 article. Actuellement chez ANTEA group

Christophe Andermann (Université de Rennes 1 - Université de Freiberg, implication 20%) - 2010-2012 - Climate, topography and erosion in the Nepal Himalayas (`https://hal.archives-ouvertes.fr/tel-00674919`), 2 articles, actuellement au GFZ Potsdam

Clément Roques (Université Rennes 1, implication 20%) - 2011-2013 - Hydrogéologie des zones de faille du socle cristallin : implications en terme de ressources en eau pour le massif Armoricain (`https://hal.archives-ouvertes.fr/tel-00967360`), 1 article, actuellement à l'ETH Zürich

Anne Springer (Université de Bonn, superviseur externe) - 2013 - - Assimilation des données satellite (GRACE, altimetrie) dans un modèle hydrologique , 2 article, toujours en thèse

*__Jonathan Schuite__ (Université Rennes 1, co-directeur) - 2014-2016 - Apports des mesures de déformation de surface et de l'inclinométrie pour la caractérisation pluri-échelle des réservoirs géologiques fracturés (`https://hal.archives-ouvertes.fr/tel-01486125v1`) , 3 articles, en post-doctorat à l'école des Mines de Paris.

Pascal Castellazzi (INRS Québec, Canada, implication 25%) - 2014-2017 - Water deficit and land subsidence in Central Mexico using GRACE and InSAR, 2 articles. En post-doctorat au CSIRO

*__Luca Guillaumot__ (Université Rennes 1, co-directeur) - 2016-2018 - Déstabilisation anthropique des systèmes naturels, contenu informatif de différents observables pour la modélisation hydrologique.

*__Quentin Courtois__ (Université Rennes 1, co-directeur) - 2017-2019 - AquiFR - Développement d'une modélisation régionale des systèmes aquifères

*__Lara-Antonia Blazevic__ (Université Rennes 1 - UPMC, co-directeur avec L. Bodet et D. Jougnot) - 2018-2020 - Monitoring spatio-temporal water redistribution in the subsurface with seismic methods

*__Behzad Pouladi Borj__ (Université Rennes 1 co-directeur avec O. Bour) - 2018-2020 - Active Fiber Optic methods to quantify subsurface flow distribution and dynamics

5.3.4 Encadrement d'étudiants en post-doctorat

Di Long (Université du Texas, implication 30%) - 2011-2013 - Contraindre les différents termes du bilan hydrologique avec GRACE, 4 articles, actuellement professeur associé à Tsinghua University, Chine

Maxime Mouyen (Université de Rennes 1) - 2015-2017 - Apport des données satellite GRACE pour le suivi des transferts sédimentaires, actuellement post-doctorant au laboratoire.

5.3.5 Participation à des jurys de thèse

Pierre Valty (2013), IPGP/Université Paris 7, Apport de la géodésie à l'étude des transferts de masse d'origine climatique. Application au Sud de l'Europe, examinateur

Feng Wei (2014), CNES/Université Toulouse 3, Regional Terrestrial Water Storage and Sea Level Variations Inferred from Satellite Gravimetry, examinateur

Basile Hector (2014), EOST/Université de Strasbourg, Caractérisation hydrogéophysique multi-échelle et dynamique des stocks d'eau souterrains d'un bassin versant en zone soudanienne de socle : apport de la gravimétrie, examinateur

Ehsan Forootan (2014), Institute for Geodesy and Geoinformation. Statistical Signal Decomposition Techniques for Analyzing Time-Variable Satellite Gravimetry Data, examinateur

Benjamin Fores (2016), Université de Montpellier 2, Gravimétrie et surveillance sismique pour la modélisation hydrologique : application au bassin karstique du Durzon (Larzac,France), examinateur

5.3.6 Articles de vulgarisation

- 2012 **Newsletter INSU**. Un nouveau regard sur le cycle de l'eau dans l'Himalaya, Site web
- 2012 **Sciences Ouest**. L'Himalaya est une véritable éponge ! Site web
- 2012 **Time Science**. Can Anything Save the Drying Southwest ? Site web
- 2012 **Planet**. Groundwater depletion from irrigation, Site web
- 2012 **Science daily**. Groundwater depletion in semiarid regions of Texas and California threatens US food security, Site web
- 2012 **Science Ouest**. L'irrigation assèche les Etats-Unis, Site web
- 2013 **Sciences Ouest**. L'eau potable, une ressource fragile, Site web
- 2013 **Sciences Ouest**. Quand l'eau trouve la faille, Site web
- 2014 **Le Monde**. En sous-sol, la sécheresse invisible, prochaine menace, Site web
- 2015 **Eurekalert**. Substantial glacier ice loss in Central Asia's largest mountain range, Site web
- 2015 **Sciences Ouest**. Le climat lu dans l'eau, Site web
- 2017 **Sciences Ouest**. Avec les chercheurs d'eau, Site web
- 2017 **NASA Sensing our Planet**. Closed Season, Site web
- 2017 **Newsletter INSU**. Quand les océans chuchotent aux aquifères, Site web
- 2017 **Newsletter INSU**. Comment les cyclones tropicaux déforment la croûte terrestre, Site web

5.4 Responsabilités collectives

5.4.1 Responsabilités locales

2017 - Responsable de l'observatoire de Ploemeur (SNO/SOERE $\mathcal{H}+$, IR $\mathcal{O}$ZCAR)
Gestion de l'observatoire, organisation des expériences, prospective
Animation d'une équipe pluri-disciplinaire au sein de l'OSUR pour mettre en place une expérience interdisciplinaire sur les interactions lithosphere-hydrosphere-biosphere

2017 - Animateur de l'atelier "Hydrologie de Terrain Imagerie Géophysique"
Gestion des moyens instrumentaux de terrain

2013 - 2017 Membre de la Commission Recherche de l'OSUR
2018 - Co-président de la Commission Recherche de l'OSUR
Direction : Vincent Bernard (CREAAH). Missions de stimulation des synergies entre les UMR de l'OSUR, développement des recherches aux interfaces entre les disciplines

2017- Responsable hiérarchique Nicolas Lavenant (AI CNRS)
Responsable hiérarchique de 2 CDD IE

5.4.2 Responsabilités nationales

2012 - 2019 Directeur adjoint du projet EQUIPEX CRITEX SiteWeb
22 partenaires, 15 universités, 5 instituts de recherche, 7 M€
Coordonné par Jérôme Gaillardet (IPGP), a permis de structurer la communauté nationale autour de la Zone Critique, et abouti à l'Infrastructure de recherche $\mathcal{O}$ZCAR
Gestion, animation et participation au projet
2017 - Animateur du volet "Instrumentation" au sein d'$\mathcal{O}$ZCAR

5.4.3 Responsabilités internationales

2012 - 2013 IAH – CGCC : Commission on Groundwater and Climate Change Site web. Preparation of a review paper on Groundwater and Climate change, published in Nature Climate Change
2012 - 2015 Co-chair of IAG working group "Land hydrology from gravity" Site web. Following a joint initiative of IUGG, GGOS and IAG, A. Eicker and me coordinated the hydrological chapter on consolidated science and user needs for future satellite gravimetry missions. Final report is available here : pdf
2017 - Member of the "Grand Challenge" on regional sea level WCRP, with a focus on "Land waters"

5.4.4 Activité éditoriale

Reviewer pour Nature Geoscience, Scientific Reports, Geophysical Research Letters, Earth and Planetary Science Letters, Scientific Reports, IEEE selected topics in Earth Sciences, Survey in Geophysics, Remote Sensing, Geophysical Journal International, Journal of Geodynamics, Journal of Geodesy. Hydrogeology Journal, Journal of Hydrology, Water Resources Research, C.R.A.S., Climatic Change.

Editeur invité pour une édition spéciale intitulée "GRACE and the extreme scales" dans la revue "Remote Sensing", Website

5.4.5 Organisation de conférences

2012 **AGU**. Organisateur et chairman de la session G33A : Decade-Long Mass Flux Measurements From GRACE, status and Future Prospects

2013 **G2**. Organisateur du colloque national du G2 Site web

2015 **Our Common Future Under Climate Change**, organisateur de session « Climate Change and Freshwater »

2016 3ème école d'été **Flow and transport in porous and fractured media** à Cargèse, membre du comité d'organisation

5.5 Liste complète des publications

56 publications h=21 (ISI WEB) 1600+ citations, 250+ co-authors Starred : supervised student as first author

5.5.1 Travaux soumis

Xie, H., **Longuevergne, L.**, Ringler, C., Scanlon, B.R. (2017) : Integrating anthropogenic impact of groundwater irrigation into hydrological simulation in India — with a model application to projecting groundwater storage variation in the northwest under climate change, submitted to HESS

*Carvalho-Resende, T., **Longuevergne, L.**, Gurdak, J.J., Leblanc, M., Favreau, G., Ansems, N., Van der Gun, J., Gaye, C.B., Aureli, A. (2017) : Assessment of climate variability impacts on groundwater resources for improved water management and policy in Africa, submitted to Hydrogeology Journal.

5.5.2 Travaux publiés

2018

56. Scanlon, B.R., Zhang., Z., Save, H., Sun, A.Y., Schmied, H.M., van Beek, L.P.H, Wiese, D.N., Wada, Y., Long, D., Reedy, R.C.,**Longuevergne, L.**, Döll, P., Bierkens, M.F.P.(2018) : Global Models Underestimate Large Decadal Declining and Rising Water Storage Trends Relative to GRACE Satellite Data, Proc. Nat. Academy of Science. Site web

*55. Castellazzi, P., **Longuevergne, L.**, Martel, R., Rivera, A., Brouard, C., Chaussard, E. (2018) : Quantitative mapping of groundwater depletion at the water management scale using a combined GRACE/InSAR approach, Remote Sensing of the Env., 205, 408-418, doi :10.1016/j.rse.2017.11.025 Site web

54. Roques, C., Aquilina, L., Boisson, A., Vergnaud-Ayraud, V., Labasque, T., **Longuevergne, L.**, Laurencelle, M., Dufresne, A., de Dreuzy, J.R., Pauwels, H., Bour, O. (2018) : Autotrophic denitrification supported by biotite dissolution in crystalline aquifers, 619-620, 491-503, doi :10.1016/j.scitotenv.2017.11.104 Site web

53. Khaki, M., Forootan, E., Kuhn, M., Awange, J., **Longuevergne, L.**, Wada, Y. (2017) : Efficient Basin Scale Filtering of GRACE Satellite Products, Remote Sensing Env., doi : 10.1016/j.rse.2017.10.040 Site web

2017

*52. Schuite, J., **Longuevergne, L.**, Bour, O., Burbey, T.J., Boudin, F., Lavenant, N., Davy, P. (2017) : Understanding the hydromechanical behavior of a fault zone from transient surface tilt and fluid pressure observations at hourly timescales, Wat. Res. Res. doi :10.1002/2017WR020588 Site web

*51. Mouyen, M., Canitano, A., Chao, B.F., Hsu, Y.J., Steer, P., **Longuevergne, L.**, Boy, J.P. (2017) : Typhoon-induced ground deformation, Geophys. Res. Let, doi : 10.1002/2017GL075615 Site web

50. Lecocq, T., **Longuevergne, L.**, Pedersen, H.A., Brenguier, F., Stammler, K. (2017) : Long-term monitoring of subsurface water storage at basin scale : 30 years continuous observation with seismic noise, Nature Scientific Reports, 7, 14241, doi :10.1038/s41598-017-14468-9 Site web

49. Shamsuddha, M., Taylor, R.G., Jones, D., **Longuevergne, L.**, Owor, M, Tindimugaya, C. (2017) : Recent changes in terrestrial water storage in the Upper Nile basin : an evaluation of commonly used gridded GRACE products, HESS, 21, 4533-4549, doi :10.5194/hess-21-4533-2017 Site web

48. Felfelani, F., Wada, Y., **Longuevergne, L.**, Pokhrel, Y.N. (2017) : Natural and human-induced terrestrial water storage change : A global analysis using hydrological models and GRACE, J. Hydrol., 553, 105–118, Site web

*47. Schuite, J., **Longuevergne, L.**, Bour, O., Guihéneuf, N., Becker, M.W., Cole, M., Burbey, T.J., Lavenant, N., Boudin, F. (2017) : Combining periodic hydraulic tests and surface tilt measurements to explore in situ fracture hydromechanics, J. Geophys. Res., doi :10.1002/2017JB014045 Site web

*46. Long, D., Pan, Y., Zhou, J., Chen, Y., Hou, X., Hong, Y., Scanlon, B.R., **Longuevergne, L.** (2017) : Global analysis of spatiotemporal variability in merged total water storage changes using multiple GRACE products and global hydrological models, Remote Sensing Env., doi :10.1016/j.rse.2017.02.011 Site web

45. Scanlon, B.R. Zhang, Z., Save, H., Wiese, D.N., Landerer, F.W., Long, D., **Longuevergne, L.**, Chen, J.(2017) : Global Evaluation of New GRACE Mascon Products for Hydrologic Applications, Water Res. Res., doi : 10.1002/2016WR019494 Site web

44. Lesparre, N., Boudin, F., Champollion, C., Chéry, J., Danquigny, C., Seat, H. C., **Longuevergne, L.** (2017). New insights on fractures deformation from tiltmeter data measured inside the Fontaine de Vaucluse karst system. Geophysical Journal International, doi : 10.1093/gji/ggw446 Site web

2016

*43. Castellazi, P., Martel, R., Galloway, D., **Longuevergne, L.**, Riviera, A. (2016) : Assessing groundwater depletion and dynamics using GRACE and InSAR : potential and limitations, Groundwater, doi : 10.1111/gwat.12453

42. Kusche, J., Eicker, A., Forootan, E., Springer, A., **Longuevergne, L.** (2016) : Mapping probabilities of extreme continental water storage changes from space gravimetry, Geophys. Res.Let. doi :10.1002/2016GL069538

41. Eicker, A., Forootan, E., Springer, A., **Longuevergne, L.**, Kusche, J. (2016) : Does GRACE see the terrestrial water cycle ‘intensifying’ ?, J. Geophys Res, doi :10.1002/2015JD023808

*40. Schuite, J., **Longuevergne, L.**, Bour, O., Boudin F., Durand, S., Lavenant, N. (2015) : Inferring field-scale properties of a fractured aquifer from ground surface deformation during a well test, Geophys.Res. Letters, doi : 10.1002/2015GL066387

39. Pail, R., Bingham, R., Braitenberg, C., Dobslaw, H., Eicker, A., Güntner, A., Horwarth, M., Ivins, E., **Longuevergne, L.**, Panet, I., Wouters, B. IUGG Expert panel (2015) : Science and User Needs for Observing Global Mass Transport to Understand Global Change and to Benefit Society, Survey in Geophysics, doi : 10.1007/s10712-015-9348-9

38. Jamin, P., Goderniaux, P., Bour, O., Le Borgne, T., Englert, A., **Longuevergne, L.**, Brouyère S. (2015) : Contribution of the Finite Volume Point Dilution Method for measurement of groundwater fluxes in a fractured aquifer, J. contaminant Hydrology, 182, 244-255, doi :10.1016/j.jconhyd.2015.09.002

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37. Pasquet, S., Bodet, L., **Longuevergne, L.**, Dhemaied, A., Camerlynck, C., Rejiba, F., Guérin, R. (2015) : 2D characterization of near-surface Vp/Vs : surface-wave dispersion inversion versus refraction tomography, Near Surface Geophysics 13(4), 315 – 331, doi : 10.3997/1873-0604.2015028

36. Farinotti, D., **Longuevergne, L.**, Moholdt, G., Duethmann, D., Bolch, T., Vorogushyn, S., Güntner, A. (2015) : Substantial glacier mass loss in the Tien Shan over the past 50 years, Nature Geosciences, doi :10.1038/ngeo2513

*35. Long, D., **Longuevergne, L.**, Scanlon, B. (2015) : Global analysis of approaches of deriving total water storage changes from GRACE satellites, Water Res.Res. 51(4), 2574 – 2594, doi : 10.1002/2014WR016853

34. Pokhrel, Y.N., Koirala, S., Yeh P.J.F., Hanasaki, N., **Longuevergne, L.**, Kanae, S., Oki, T. (2015) : Incorporation of groundwater pumping in a global Land Surface Model with the representation of human impacts, Water Res. Res., 51(1), 78-96, doi : 10.1002/2014WR015602

*33. Springer, A., Kusche, J., Hartung, K., Ohlwein, C. **Longuevergne, L.** (2014) : New estimates of variations in water flux and storage over Europe, based upon regional reanalyses and multi-sensor observations, J. of Hydrometeorology, 15(6), 2397–2417, doi : 10.1175/JHM-D-14-0050.1

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31. Forootan, E., Kusche, J., Krasbutter, I., Schuh, W.D., Eicker, A., Awange, J., **Longuevergne, L.**, Diekkrüger, B., Schmidt, M., Schum, C.K. (2014) : Multivariate prediction of total water storage changes over West Africa from Multi-satellite data, Surv. Geophys., 35 (4), 913-940, doi :10.1007/s10712-014-9292-0

2014 *30. Long, D., **Longuevergne, L.**, Scanlon, B.R. (2014) : Uncertainty in evapotranspiration from Land Surface Modeling and Remote Sensing using Water Budget Closure and GRACE satellites, Water Res.Res, doi : 10.1002/2013WR014581

*29. Armandine les Landes, A., Aquilina, L., De Ridder, J., **Longuevergne, L.**, Pagé, C., Goderniaux, P.(2014) : : Investigating the respective impacts of groundwater exploitation and climate change on wetland extension over 150 years, J. Hydrol., 509, 367-378, doi :10.1016/j.jhydrol.2013.11.039

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2013 and lake storage, HESS, 17, 4817-4830, doi : 10.5194/hess-17-4817-2013

*25. Jimenez-Martinez, J., **Longuevergne, L.**, Le Borgne, T., Davy, P., Russian, A., Bour, O. (2013) : Temporal and spatial scaling of hydraulic response to recharge in fractured aquifers : insights from a frequency domain analysis, Water Res. Res, doi : 10.1002/wrcr.20260

*24. Long, Di, Scanlon, B.R., **Longuevergne, L.**, Sun, A.Y., Nelun, F., Himanshu, S. (2013) : GRACE satellites monitor large depletion in water storage in response to the 2011 drought in Texas, Geophys. Res. Lett, doi : 10.1002/grl.50655

*23. Andermann, C. **Longuevergne, L.**, Bonnet, S., Crave, A., Davy, P., Gloaguen, R. (2012) : Impact of transient groundwater storage on the discharge of Himalayan rivers, Nature Geosciences, doi : 10.1038/NGEO1356

22. Scanlon, B.R., Faunt, C.C., **Longuevergne, L.**, Reedy, R., Alley, B., McGuire, V. L., McMahon, P.B. (2012) : Groundwater Depletion and Sustainability of Irrigation in the US High Plains and Central Valley, Proc. Nat. Acad. Sciences 109, 9320-9325 ; doi :10.1073/pnas.1200311109

*21. Andermann, C., Bonnet, S., Crave, A., Davy, P., **Longuevergne, L.**, Gloaguen, R. (2012) : Sediment transfer and the hydrological cycle of Himalayan rivers in Nepal, CR. Géosciences, doi :10.1016/j.crte.2012.10.009

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19. Aquilina, L., Vergnaud-Ayraud, V., Labasque T., Bour, O., Molénat, J., Ruiz, L., De Montety, V., De Ridder, J., Roques, C., **Longuevergne, L.** (2012) : Nitrate dynamics in agricultural catchments deduced from groundwater dating and long-term nitrate monitoring in surface and ground waters, Science of the Total Environment, 435-436, 167-178, doi :10.1016/j.scitotenv.2012.06.028

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This document was prepared with the typographic composition software LaTeX 2ε on the overleaf.com plateform. Overleaf is an online LaTeX and Rich Text collaborative writing and publishing tool that makes the whole process of writing, editing and publishing scientific documents much quicker and easier.
I deeply thank Ludovico Einaudi, Hans Zimmer, Max Richter, Mogwai, Mono, ... for assisting me during the long nights of writing

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Résumé Le résumé en français (≈ 1000 caractères)

Mots-clés Les mots-clés en français

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Keywords Les mots-clés en anglais