Toward a water cycle approach for flood risk assessment …

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Abstract: Floods were long believed to be epi-phenomena, involving schemes based on rainfall–runoff principles or equivalent. The unusual flood event which affected the Somme river in France in 2001, clearly showed that this was not always the case as suspected already by several hydrogeologists. Indeed, the high waters seen during the winter 2000-2001 in the Somme river valley highlighted the contribution of groundwater to river floods.

Flooding event in rivers in fact often result from the integration of several phenomena, including rainfall, surface runoff, infiltration, shallow and deep groundwater flow, as well as exchange fluxes mechanisms between groundwater and surface water. Besides, the state or the conditions of the soils and the subsurface –i.e. the moisture content in the soils and in the unsaturated zone, the water levels in the aquifers, …- may play an important role in flood generation during a wet episode; it is even believed that in some cases, the unsaturated zone may become the seat for a secondary flood triggering mechanism.

A new type of flood risk assessment model which is now operating on a routine basis in the Somme river valley was developed in the early 2000. It takes into consideration the entire water cycle. It helps improving assessing the risk of flooding episodes in the Somme river, but it also extends the forecasting period way beyond the rainfall event scale, thereby allowing for better management of floods and more generally high water episodes. The Somme river catchment is not a unique case and a full water cycle approach to flood risk assessment could often bring significant benefits in flood risk assessment.

Keywords: Floods, risk assessment, groundwater, water cycle, hydro-system, modelling

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Riassunto: *Per lungo tempo si è creduto che le inondazioni fossero fenomeni secondari, che coinvolgevano schemi basati sui principi di precitazione-deflusso superficiale o equivalenti. Gli eventi alluvionali insoliti che hanno interessato il fiume Somme in Francia nel 2001, hanno chiaramente mostrato che questo non era sempre il motivo come peraltro sospettato da diversi idrogeologi. Infatti, le forti piogge osservate durante l'inverno 2000-2001 nella valle del fiume Somme hanno sottolineato il contributo delle acque sotterranee alle inondazioni del fiume.*

Gli eventi alluvionali dei fiumi infatti spesso sono il risultato dell'integrazione di diversi fenomeni, che includono le precipitazioni, il deflusso superficiale, l'infiltrazione, il flusso delle falde acquifere profonde e superficiali, così come i meccanismi di scambio di flussi tra le falde e le acque superficiali. Per di più, lo stato o le condizioni del suolo e del sottosuolo – cioè l'umidità presente nel suolo e la zona insatura, il livello di falda negli acquiferi....- possono giocare un ruolo importante nella generazione di alluvioni durante un episodio piovoso; si è perfino ritenuto che in alcuni casi, la zona insatura può diventare la sede per un meccanismo che dia l'avvio a un secondo fenomeno alluvionale.

Un nuovo tipo di modello di valutazione del rischio di alluvione che ora sta operando su base regolare nella valle del fiume Somme è stato sviluppato agli inizi del 2000. Esso prende in considerazione l'intero ciclo dell'acqua. Ciò aiuta a migliorare la valutazione del rischio degli episodi alluvionali del fiume Somme; ma anche estende il periodo di previsione oltre la misura dell'evento piovoso, permettendo in tal modo una migliore gestione delle alluvioni e più genericamente degli episodi di piena. Il bacino del fiume Somme non un caso unico e l'intero ciclo dell'acqua rivolto alla valutazione del rischio di alluvione potrebbe portare significativi benefici per questo tipo di analisi.

Introduction

Water is the base for life, but also for socioeconomic development, and these are the reasons why river valleys have since the beginning attracted a great number of human communities and settlements, which with time grew to be cities and urban areas, and which, nowadays, can extend over great distances. However, every so often, during prolonged wet climate conditions rivers are swelling and sometimes overtake built land areas, triggering what is now known as" floods" or "flooding episodes", which often bring along considerable damages to the socio-economic context, not mentioning losses of life. Fighting against floods is one priority, and this can only be achieved with a thorough understanding of how hydrosystems work, in order, on the one hand, to improve flood forecasting procedures and, on the other hand, to set in place the necessary regulations, protection structures and equipments to minimize their consequences and allow for optimum flood management. This paper only deals with the forecasting aspect, namely with flood risk assessment, focusing on groundwater.

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Until the 2001 Somme river flood event, floods were believed by most of the community in charge of their forecast to be essentially epiphenomena or surface phenomena, involving schemes based on rainfall –runoff principles or equivalent. The unusual flood event which affected the Somme river in France during the winter 2000-2001, clearly showed that this was not always the case as suspected already by several hydrogeologists for many years based on their work on the water flux exchanges between surface water and groundwater notably carried out in the course of integrated water resources management studies (Pennequin et al., 1991, 2002, 2003, Weng et al., 1999).

Flood events indeed result from the integration of several phenomena, whose major components starting with rainfall at the ground surface, include surface runoff, shallow or hypodermic subsurface flow, groundwater flow, or at least the final portion of the subsurface part of the water cycle, water flux exchange between groundwater and surface water and river flow (Pointet et al. 2003). The relative weight of these components notably depend on (1) the morphological structure of the river basin, (2) the hydrogeological context, (3) the nature of the ground surface – *type of soil* -, (4) the land development configuration and (5) time dependent factors such as the initial catchment conditions and the historical rainfall events which often greatly affect soils and subsurface conditions – *moisture content of soils, vegetation cover, frozen state in winter, degree of saturation the unsaturated zone, groundwater levels, …*-. As the time dependent components may significantly fluctuate, it becomes apparent that flood generation mechanisms are complex and floods may show different characteristics in time in the same river catchment for a given rainfall event. Floods are very often non-linear phenomena.

Too often before, the role played by groundwater in flood events was minimized and at best, reduced to the sole contribution of accompanying alluvial aquifers, which most often represent a minor component of the whole hydro-system. During high water episodes however, these alluvial aquifers quickly loose all their regulating function and they only contribute to transferring upward groundwater flow from deeper aquifers into the rivers, playing the role of a transmitting belt between larger deeper aquifers and the surface waters. The river basin when underlain by an extensive high yield aquifer formation, as it is the case in the Somme river catchment, has the groundwater component of the flow of its major river and tributaries mostly fed by the main groundwater reservoir, and not by the alluvial aquifers. This is the reason why during summer and drought conditions, many rivers can still have a significant baseflow; relying on the sole alluvial aquifers, they would most often rapidly dry up.

Groundwater flow and river flow are therefore intimately linked in many cases and when considering river flow in many regions, it is necessary to have a full water cycle approach at the catchment scale, including all surface flows and all major sub-surface and groundwater flows upstream from the point of interest.

The 2000-2001 “Somme river flood”

The Somme river is located in northern France in the Picardie region (cf. Fig. 1). Upstream, it springs up in the Saint Quentin area, to slowly flow toward the Sea amidst a wide low gradient marsh rich plain. The height drop between Amiens - *mid Somme area*- and the sea is only about 24 m. The river bed is made up of alluvial materials that only reach a few meters in thickness in most areas. These rest directly on the regional upper Turonian and Senonian Chalk aquifer system.

The Somme river is imbedded in the chalk plateau which can at times be located 150 meters above the river. Even if the depth to groundwater on the chalk plateau can extend up to 20 to 70 m below the ground surface, and if high permeabilities are not fully developed everywhere – *permeability contrasts can easely reach 2 orders of magnitude between the wet valleys and the inter-dry valleys plateau area*- the groundwater reservoir is nonetheless huge and powerful, and it is often located several tenth of meters above the Somme river a few kilometres away from the main valley.

The flood which occurred in the Somme valley in the winter 2000-2001 showed unusual characteristics, both in terms of flooded area and in terms of duration of the event. Indeed, the Somme water level began to significantly rise starting in November 2000. A first flood wave then peaked in the valley in February 2001, followed by a second major flood wave which reached a maximum amplitude in April. In the Somme river valley itself, the water level rise generally did not exceed 1 to 2 meters above the average river water level, but this was far above the levels reached by normal high floods and it was sufficient to inundate a large portion of the valley, including many urban areas, as Abbeville, and many areas that have never been under water before. Beside the Somme river, the flow of all tributaries also greatly increased, sometimes slowly, sometimes more rapidly, as seen in Figure 2, leading to water level rises that sometimes reached more than 4 meters above the average levels.

But the peculiar aspect of this flood event consisted in the fact that it was not only confined to the wet valleys, or to the Somme river and its tributaries alone: in addition, several low portions of the plateau area became inundated forming new lakes, and new rivers started to flow in what was called “dry valleys” in the chalk region. Several wells also became flowing artesian wells.

The second unusual aspect about the 2001 flood event in the Somme river catchment was its long duration or the time it took to deflate the hydro-system: high water conditions in the hydrographical network remained for at least 2 to 3 months in most areas, and up to 6 months and more in some others. The Somme river flow rate for example exceeded 80 m^3/s - *the critical yield prior to flooding several low areas* - downstream from Abbeville during a time period extending from February to June 2001.

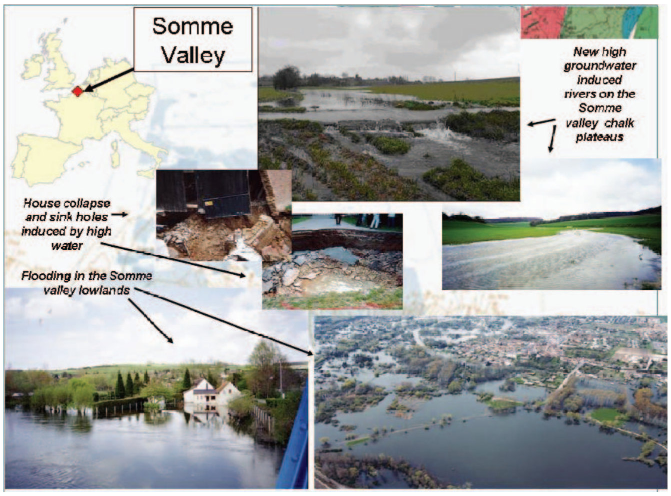

Fig. 1: *The Somme river basin and the consequences of the 2001 flooding and high water event. These included high water in the Somme river, in its tributaries and the formation of new ponds, lakes and rivers on the plateau area - (Source : modified from BRGM and Lefrou, 2002).*

Starting Hypothesis and demonstration of the role played by groundwater

Facing this event, several hydrogeologists made the assumption that groundwater played a significant role in the Somme river catchment flood (Pennequin et al., 2002, Pointet et al., 2003). Indeed, through analysing flow and level evolution graphs for surface water and groundwater (cf. Fig.2 as one example), and through simple computations using surface and groundwater flow, it appeared rapidly evident that the 2001 Somme flood was largely induced by groundwater. Since 1998, groundwater levels showed a steady increase in the catchment, both in terms of high and low waters, responding to 3 years of above average precipitations (cf. Fig. 3). In 2001, on top of high water conditions, 2 sudden additional rises in groundwater levels occurred in most piezometers in the catchment, during the months of January-February and April, concomitant with flow increases in the Somme river and in all its tributaries. This prompted several water wells located on the plateau area to switch from normal conditions - *below ground surface water levels* - to artesian flowing wells.

In fact, these graphs suggested that groundwater levels and river flow rates were linked in most of the Somme catchment.

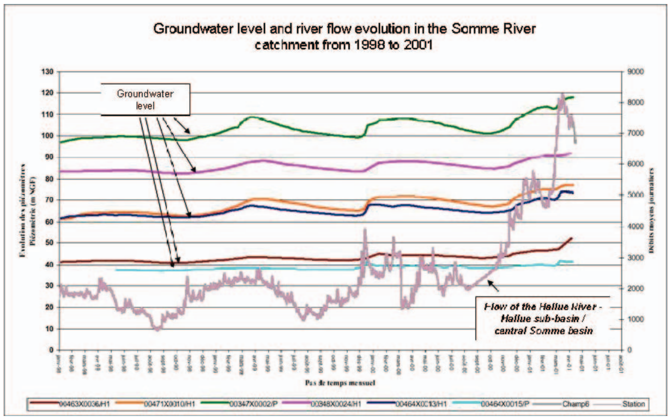

Fig. 2: *Evolution from 1998 to 2001 of (1) the groundwater levels (left scale – meters NGF) in several piezometers located in the central Somme Basin (Hallue sub-basin) and (2) the Hallue river flow rate (small tributary of the Somme River - right scale-m³/d). The impact of groundwater levels on the Hallue river flow rate is important - (Source: Mardhel et al., 2001, Pointet et al. 2003).*

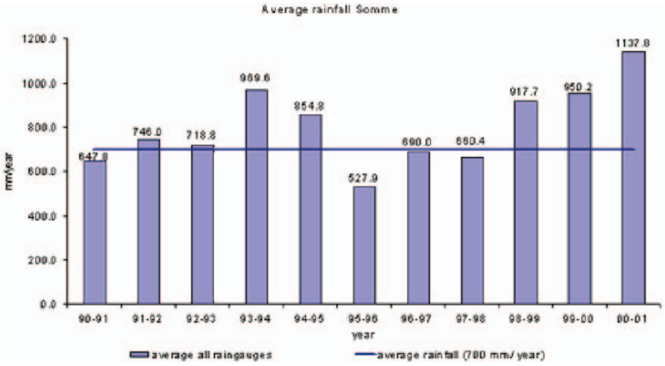

Fig. 3: *Average annual (hydrologic year) precipitation in the Somme River catchment - average hydrologic year = 700 mm (Source: Météo France).*

These first analyses were later confirmed by isotope studies that were carried on during the flood wave close to the peak episode and after (cf. Fig.4), and through mathematical and numerical modelling (cf. Fig. 5) whose results showed, among other things, that the 2001 Somme catchment flood pulled most of its water from the groundwater reservoir: indeed more than 80% of the flood water in the Somme river itself in the Abbeville area had a groundwater origin for example. This proportion was even higher in many tributaries and somewhat lower in others.

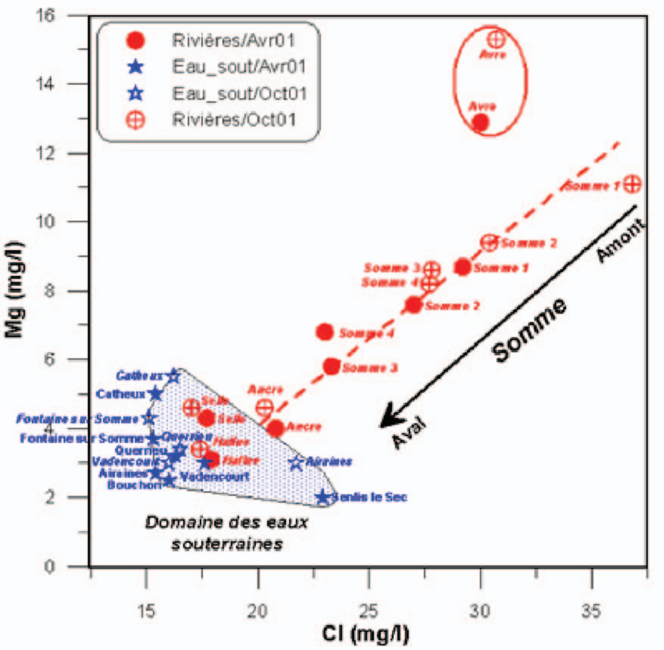

Fig. 4: *Variations of $^{87}Sr/^{86}Sr$ ratio with respect to chlorides content (Cl en mg/l) both in the surface waters and groundwater. The sampling point for the surface waters are represented by circles (April and October 2001 sampling campaigns), and those for groundwater by stars (April and October 2001 sampling campaigns) - (Source: Negrel et al., 2003).*

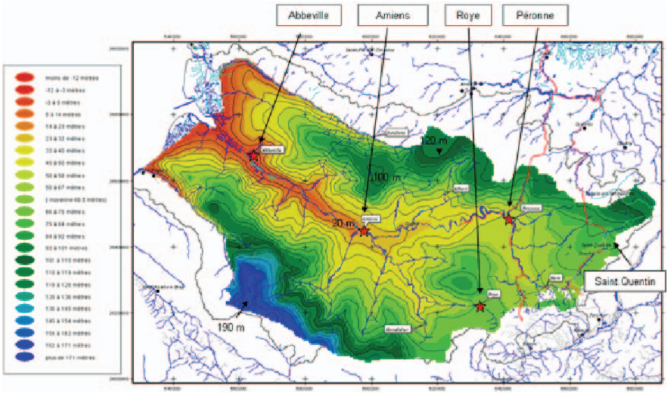

Fig. 5: *Computed groundwater levels in the Somme river catchment for an average year (1995) - (Source: modified from Amraoui et al., 2002).*

Developing full water-cycle flood risk assessment tools

The 2001 Somme river flood had not been forecasted by the existing flood risk assessment tools. It was therefore decided by the authorities in charge of flood problems, to build a more efficient tool for flood risk assessment in the Somme river valley. This task taken up by BRGM led to the elaboration of two new mathematical and numerical models, which took into consideration the full water-cycle for flood risk assessment.

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The first mathematical model was based on a global modelling technique which consisted of simulating the functioning and behaviour of the Somme hydro-system using a concept based on a principle of equivalent geometry and simplified physical transfer functions. The model, of the embedded-reservoirs type connected to each other by specific transfer functions, was built using the GARDENIA software (for the details see Thiery, 2003; Amraoui et al. 2002, 2004). It simulated all major known processes leading to flooding in the lower Somme valley downstream from Abbeville, including precipitation, evapotranspiration, overland flow, surface runoff and infiltration - *taking into consideration the initial state of the soils through an hydrologic soil moisture decay function*-, shallow subsurface flow, water table spill, deep groundwater flow and river flow, thereby addressing the full water cycle (cf. Fig.6).

This model was first used in the winter 2001 - 2002 to assess the risk for flood occurrence in the Abbeville area, and is now used on a routine basis. Basically, it operates using a 2-step approach: first, the model is being fed with the latest data to represent the current situation, and, next, it uses built in reconstituted artificial precipitation and river flow series, based on a 40 years data record and representing several return periods for both wet and dry years, to compute the risk for flooding to occur in the lower Somme river basin for the on-coming year (cf. Fig.7, additional details can be found in Amaroui et al., 2002, 2003, 2004; Pennequin et al., 2002 and Pointet et al., 2003).

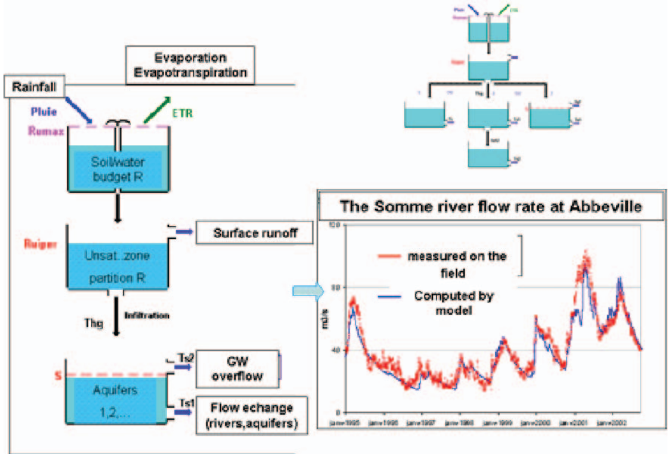

Fig. 6: *Semi-deterministic - global GARDENIA model using a full water cycle approach for flood risk assessment at Abbeville in the Somme river valley (Source: modified form Amraoui et al., 2002).*

Similar models were later elaborated to assess the risk of flood occurrence in several other parts of the catchment.

Nevertheless, the global modelling technique, although easy to implement, could only compute the risk for flood occurrence at one point of the hydro-system (one point for each of the models built). This may be enough to prompt flood alert procedures in sensitive areas whenever necessary, however uncertainties remained for the rest of the catchment. Secondly, the concept of "equivalent geometry" did not allow the flood alert service to have a realistic and sufficiently comprehensive knowledge on the hydrodynamic situation in all parts of the catchment, to ensure the efficiency of the actions to be taken in case of flooding episodes.

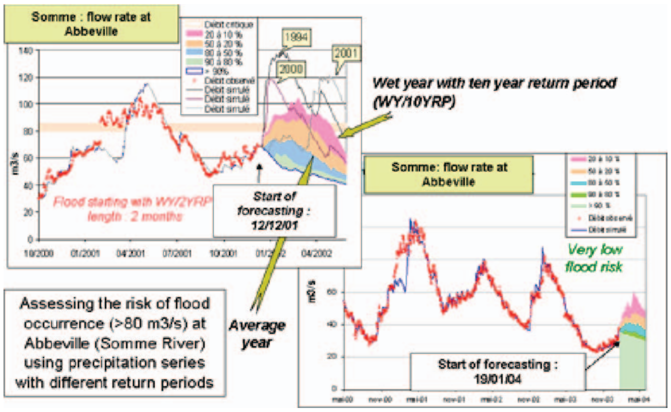

Fig. 7: *Use of the Global GARDENIA Somme valley model for flood risk assessment. On the left diagram at the beginning of winter 2002 when groundwater levels were still high after the 2001 flood, flood risks were high: flooding (flow rate of the Somme river at Abbeville > 80 m*^{3}*/s) would have occured starting with a wet year having a two year return period (WY/2YRP). On the right diagram, in early 2004, groundwater levels were lower and flood risks were low, even with a heavy rainfall period (Source: modified from Amraoui et al., 2002, 2003, 2004, and BRGM unpublished documents).*

A second model was therefore built to palliate for these deficiencies and to be used as a complementary tool to the first model when the risk of a very high water situation would appear in the Somme river catchment. The second model built for flood risk assessment in the Somme river catchment was a deterministic 3D nested grid groundwater flow model which notably computed surface runoff, infiltration, groundwater flow, groundwater heads, exchange water flux rates between surface and groundwater, and the flow rates for all rivers in the Somme catchment (Somme River and all tributaries). The model was built using the MARTHE software (for details see Thiery, 2007; Amaraoui et al, 2002, 2003, 2004; Noyer et al, 2006; Thiery et al, 2008). It was later combined with a 1D river flow model which could simulate potential extensions of the flooded areas in the Somme valley.

A third model using inverse method principles that describes the operating mode of an hydro-system through analysis of impulsional responses was also built. The analysis of the impulsional responses was performed through deconvolution of input – output time series (rainfall – runoff /groundwater flow, rainfall – water levels, …). The probability of occurrence of different levels of flow rates were computed using a stochastic process; a rainfall-evapotranspiration scenario generator first allowed to built a great number of artificial net rainfall series for a full year, which were then used to produce the corresponding series of flow rates with the appropriate transfer functions (Pinault et al., 2005). This model was built using the TEMPO software.

All these models gave excellent results for low and medium frequency signals; they simulated correctly the evolution of the flow rates in the rivers and of the water levels in the aquifer system for nearly all hydrodynamic situations in the catchment (cf. Fig.6 and 7). They sometimes however underestimated the very high peaks, and particularly the flood peak of 2001, for which an additional water source was needed.

Aside for this last point, the approach used here for the Somme catchment, addressing the full water cycle to compute flood risk, and in particular considering the full groundwater component and the interactions, or water flux exchanges, between groundwater and surface water in the valleys, allowed to:

- generate more reliable high water and flooding predictions in the river basin compared to prior to the 2001 flood when models used mostly addressed superficial phenomena (i.e; rainfall - runoff): indeed, taking into account the full water cycle gave the possibility to better consider the initial state of the hydro-system prior to the forecasting step, resulting in improved precision in the forecast – *a medium size rainfall can generate a significant flood when groundwater levels are high for example, whereas when they are low, a large rainfall event may simply generate less than expected or even no flooding conditions at all, depending also on the nature and initial state of the soils and on the intensity of the rainfall* -.

- extend the forecasting period way beyond the rainfall event scale; indeed floods do not result only from sole rainfall events, but rather from the integration of several components, among which the initial state and the inertia of the groundwater reservoir, which tend to greatly lengthen the flood genesis and decay processes. This gives more time and in this case it allowed to determine in advance for different rainfall scenarios with specific return periods, if, when and where flooding would occur in the considered in-coming time period – *1 year in this case* -, and, if so, how long it would last and which areas would be concerned.

Better flood risk predictions and having the possibility to extend the forecasting period allowed the authorities in charge of flood alert and flood management to move only when it is really needed, and if so, to have more time to get prepared for the flooding event, to launch more efficient actions and to take adequate corrective steps in due time and for the necessary length of time, thereby reducing the cost to society.

Finally, as the models were built using all major components of the Somme catchment hydro-system (rivers and aquifers), and as they were calibrated using a 30 years historical data set, they seldom need recalibration.

The role of the unsaturated zone

Although the above described approach greatly improved the predictions for flood occurrence in the Somme river catchment, very high flow rate peaks and sudden rises in high groundwater levels could at times not be totally correctly, nor easily, represented. This was attributed to the presence of an un-modelled water reservoir.

The unsaturated zone was rapidly suspected to be this un-modelled reservoir. Indeed, this zone is almost always neglected in all computations, as the water present in it is believed to be relatively immobile most often due to the negative hydrostatic pressures which tend to retain absorbed water for long periods of time; however, the unsaturated zone can probably be releasing important quantities of water under certain hydro-meteorological conditions. This hypothesis was compelled by 2 observations: first considering the sudden unexplained rise of groundwater levels in many piezometers in April 2001 on the plateau area - *sometimes more than 10 meters in 3 days* (Pointet et al., 2003) – and secondly, looking at the results from preliminary water budget computations which tended to suggest that a significant water deficit affected the 2000-2001 hydrologic year even though the groundwater levels globally rose in the catchment; more water seemed to have actually left than entered the hydro-system during that year.

The hypothesis made here called for the capacity of the chalk to progressively absorb water in its unsaturated zone - *which can reach thicknesses exceeding 60 meters in some of the plateau regions* - during long lasting wet events, starting first in areas made up of porous bulk matrix, than extending to small micro-fissures zones and than to fractured areas, according to the pressure (suction) field configuration, until small saturated zones lenses start forming in what is normally the unsaturated area, and later build up and merge so as to ultimately become part of the groundwater, adding at the same time a large volume of new mobile water to the aquifer. The EU funded FLOOD1 research project which allowed for on site and in-situ measurements of the deep unsaturated zone was a first attempt to prove this hypothesis, and in spite of uncooperative climate conditions, it partially demonstrated the water pressure build up in the unsaturated zone (Noyer et al, 2006; Amraoui et al, 2008a, 2008b; Thiery et al., 2008).

Assuming then that the unsaturated zone can represent an important mobile water reservoir under specific hydro-meteorological conditions, simple hydrogeological computations carried on for the 2001 Somme River flood suggested that it could account for both the observed sudden groundwater rise on the plateau area, as well as for the possible "apparent water the deficit" computed for the 2000-2001 hydrological year (more water would in fact have been available to the hydro-system than first suggested through classical water budget calculations). However, this still needs to be proved.

What about beyond the Somme river catchment?

It is believed that the Somme River catchment does not represent a unique case where groundwater can play a major role in flood events. This can happen in many other parts of the chalk area as well: in fact, during the 2000-2001 winter season, similar flooding episodes occurred in several areas in the chalk basin both in northern France and in southern England, although, not to the same extent, time and space wise, as what happened in the Somme catchment.

More generally, groundwater can probably at times be a significant contributor to "slow floods" in many river catchments extending in major sedimentary basins, provided that they are underlain by important not too deep high permeability aquifer systems, with good hydraulic connections between surface water and groundwater; an first inventory of areas prone to "groundwater induced" floods was achieved in 2005-2006 for France (Machard de Gramont et al, 2006).

Groundwater can affect "flash floods" too in many areas, in particular in river basins underlain by karsts systems (Dörfliger et al., 2002; Bonacci et al., 2006; Maréchal et al., 2008, 2009). Indeed, recent work carried on in karst systems in southern France and in Croatia for example, showed or suggested that karst systems could greatly influence "flash floods", either by absorbing excess rain water when the reservoir is relatively empty after a long dry period, thereby reducing the amplitude of flooding for a given rainfall, or, on the contrary, by preventing any rainfall infiltration and/or by releasing excess water when the reservoir and its bulk matrix is fully saturated after an extensive wet period, thereby enhancing flooding conditions.

Conclusion

Floods are in fact more complex phenomena than it was originally believed. Indeed, even if it appears evident that rainfall is the ultimate prime driver, many other factors or components also do control and contribute to triggering flood events. Floods result from the superposition of many components including the nature and intensity of the precipitation, the morphologic setting of the catchment (topography, hydrographical network, …), its geological configurations, its hydrogeological properties, the initial state and the nature of the soils, the state of the vegetation cover, the initial groundwater levels, the depth and nature of the unsaturated zone in some cases, etc… All these components may have different weight in different river catchment, and it is necessary to identify the most important of them and take them into consideration to assess the risk of flooding with sufficient precision with respect to the stakes involved. In addition, different types of floods may occur within the same river catchment, depending on the "time dependent" components, such as the surface conditions of the catchment and its subsurface situation, and this should also be kept in mind when dealing with flood risk assessment.

In practice however, it is a difficult task to take into consideration all these factors in details, for the simple reason that it would often be impossible to collect and gather the necessary data sets for complex flood risk assessment modelling tools. Simplifications must often be made, however, the main operating factors or components of the hydro-systems need to be considered, and groundwater often represent one of them, as it can either (1) directly contribute large volumes of water to the flood episode, or prevent infiltration of part of the rainfall due to saturation of the subsurface, leading to direct or indirect enhancement of flooding, or yet, on the contrary, (2) absorb most precipitation in situation of low initial water levels, thereby reducing the consequences of the rainfall and buffering the flooding wave.

It is now evident that flood risk assessment must rely on a full water cycle approach, including the shallow and deep subsurface flow components, and water flow exchanges between groundwater and surface water. This approach contributes to improving the simulation of water fluxes in the catchment area, taking into consideration the initial subsurface conditions, and often gives better results for flood risk assessment. Further research still needs to be carried out on the unsaturated zone, to better determine the role it can play as a secondary mechanism to trigger floods, at least in particular hydrogeological contexts such as chalk and probably limestone, and to find a better way to take it into consideration in flood risk assessment procedures. Particular attention must also be paid to the river bed interface, as the river beds continuously evolve with time, leading to fluctuating permeabilites which can significantly affect – *increase, decrease* - water flux exchanges between groundwater and surface water (Pennequin et al., 1991, 2002, 2003).

Striving to improve flood risk assessment is necessary as damages generated by floods to the socioeconomic context are high, and potential damages are even much higher, notably in the light of climate evolution.

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