The karst system exposed to flooding due to rainfall events. A relationship could be established between rainfall intensity/frequency (return period) and the corresponding elevation of the groundwater level within the karst conduits (or respectively, the relevant spring discharge rates). The known overflow springs have been added in the 3D model. The areas where (and when) karst groundwater is expected to reach the ground surface during extreme high-water events could be identified as potential overflow springs. Such draining sensitive areas have been delineated and mapped according to the calculated return period of multiannual, 30- and 300-years flood events and the relevant maximum discharge rates at the main outlets have been assessed.

Introduction
Flood events in the Swiss Jura Mountains are dampened/enhanced by karst overflows. The flood event of August, 1st 1804 in Porrentruy (JU) is a the largest known event of a flashy karst inundation (Prudhomme 1804). Associated discharges reaching 100 m$^3$/s have been reported—four or five times larger than big flood amount recorded for this karst system. Similar events were recorded in 1901 and 1910 (Figure 2). In addition to these events smaller - but still extreme events - occurred five times in the last 30 years (BG 2011). The most recent well documented flood event occurred on August 9th, 2007. The Creugenat overflow peak discharge approached 20 m$^3$/s.

The local authority (administration of the Jura canton) has to plan protective measures to diminish the potential damages from flooding to maximum extent possible. The understanding and prediction of such extreme situation...
is then required for assessing the probable occurrence and the intensity of such flood events, in order to manage areas threatened by flooding.

Two local civil engineer offices and the Swiss Institute for Speleology and Karst Studies (SISKA) - as a karst specialized institution - were asked to provide a model for the study region. The assessment was conducted applying the KARSYS approach (Jeannin et al. 2012) expanded with some hydraulic considerations. The aim was:

- To understand the significant characteristics of the groundwater flow routes and the position of the karst water table for various recharge scenarios. Recharge events with return periods ranging between 30- and 300- years were considered.
- To determine and map areas which are the most vulnerable to flooding assessed by the potential overflows of karst groundwater and to assess the related discharges at the outlets and - in a next work - within the subterraneous flowpaths.

The locations where karst groundwater is expected to reach the most forward ground surface are the most vulnerable to flooding. Having assessed the respective catchment areas of the underground tributaries, discharge rates can be assumed within the limitations of the project.

**Context**

The geological context refers to the Tabular Jura which is slightly folded and intersected by numerous strike faults (Kovács 2003, Sommaruga 1997). The Beuchire perennial karst spring emerges in the center of Porrentruy (see Figure 1) at an elevation of 423 m a.s.l. (meters above sea level). Its mean annual discharge is 800 L/s.

The spring reaches 1600 L/s at high water flow and may discharge more than 3 m³/s during a flood event. Groundwater flow moves through the Malm aquifer which is composed of alternating units of Upper Jurassic limestone and thin layers of marls. The Malm aquifer is underlied by a thick marl formation (Astartes marls, Laubscher 1963). This aquifer reveals to be the most karstified one in the region. Although the underlying marls are qualified as impervious, the Malm’s aquifer water exchanges with the lower aquifer are highly likely through discontinuities in the marls.

Upstream of the Beuchire spring, the Creugenat temporary outflow (see Figure 3) emerges at 451 m a.s.l. It becomes active only at high water stage. The global discharges in the city of Porrentruy may reach a maximum close to 30 m³/s (Grétillat 1996). Further upstream, at an elevation of 465 m a.s.l., lies the estavelle of Creux-des-Prés which functions as a second temporary outlet of the system and becomes active only during very high water stage (see Figure 4). The discharge series of the Beuchire spring and pressure series of the Creugenat temporary outflow have been measured at hourly time steps, respectively between 1998 to 2004 and 1998 to 2008. In addition to these three main springs, a series of minor temporary outlets do exist. Unfortunately they are badly documented due to infrequent activity (Les sources, Libecourt, etc.).
A 3D model to assess the aquifer geometry

In order to assess the geometry of the aquifer, a 3D geological model focusing on the aquifer basement (i.e. Astartes marls) was established for the area of interest (14 km by 9 km) at a scale close to 1/25,000 (see Figure 5) to meet the requirements of a pragmatic issue. This was possible thanks to an extensive compilation of all existing data relative to geological information (borehole logs, maps, cross sections, tunnel profiles, dye tracer tests results, etc.) and the previous work of Kovács 2003, which provided a strong basis of documentation.

Once the geological model has been established and the data checked, the hydrological features have been implemented within the 3D model. These features consist of major perennial springs as well as minor temporary ones. Then, the extension of the saturated part of the aquifer was assessed by following the KARSYS approach.

This approach assumes that at low water stage, the top of the saturated part of a karst aquifer is close to horizontal and can be represented within the model by a horizontal plane at the main perennial spring elevation (the Beuchire spring in the present case). The portion of the aquifer located underneath that horizontal plane should be close to the volume extension of the karst phreatic zone.
Aquiclude topography, sub-catchments and their respective “drainage axes” were rendered. Drainage axes are recognized as vadose ones if they are located above the saturated zones. They are assumed to be developed at the bottom of the aquifer along the dip of the basement. Phreatic passages located within the saturated zones are “drainage axes” linking input points into the phreatic zone to the main drainage axis linking of the Creugenat temporary outflow and the Beuchire spring. Phreatic flowpaths are mainly horizontal and a priori follow the shortest hydraulic distance to the outlet(s).

The model result for low water stage is presented in Figure 7.

The total groundwater catchment area in low water situations is thus estimated at about 79 km$^2$. GWB A flow is driven toward the Beuchire spring and GWB B flow is drained toward the Bonnefontaine spring, which is not visible in the figures for this paper.

**Assessing the system at high water stage (hydraulic gradients within the conduits)**

In the next step, the hydrology of the system is assessed for high water conditions, i.e. when overflow springs (Creugenat and Creux-des-Prés) successively become active according to the rise of the groundwater head in the conduits.

The discharge data from the Beuchire spring are compared with the head data recorded at the Creugenat temporary overflow (see Figure 8).
The graphic indicates that:

- As the Beuchire spring discharge remains lower than 700 L/s, the water level at the Creugenat overflow does not react (~438 m a.s.l). This indicates that both systems are disconnected by a threshold (a) situated at this elevation.

- As the discharge exceeds 700 L/s the water level progressively rises up and shows a threshold (b) at 443 m a.s.l corresponding to a discharge of 1,450 L/s.

- As the discharge exceeds 1,500 L/s the water level at the Creugenat rises up a second time until it reaches the output elevation (c) at 451 m a.s.l corresponding to a discharge of 2,250 L/s.

Contrary to previous studies (Grétillat 1998, Hessenauer and Meury 2002) which considered threshold (b) as a first activation of the Creugenat overflow, this analysis indicates that the Creugenat becomes active only when the Beuchire spring discharge exceeds 2,250 L/s. Then threshold (b) indicates that an intermediate overflow (or large storage) must exist in between (at around 443 m a.s.l). This could be a karst conduit or an outlet to the ground surface.

Assuming that the flows to Beuchire spring may follow the usual head-loss laws in pipes (Darcy-Weisbach type), the relation can be simulated using the following equation:

\[ Q = k'S \sqrt{\frac{dH}{dL}} \]  

(Eq. 1)

With \( Q \) [m\(^3\)/s], \( k'S = f(\text{section } m^2) \) [m\(^3\)/s], \( \frac{dH}{dL} \) = hydraulic gradient [m/m]. Application of this law is plotted on the chart (models 1 & 2, Figure 8).

Model 1 suggests that the hydraulic connection between the Beuchire spring and the Creugenat overflow is active when the water elevation in the conduits ranges from 438 to 443 m a.s.l. Below this value the system follows a head-loss equation. However, this model cannot explain the observed relationship of the water level between 443 and 451 m a.s.l.

Therefore, model 2 depicts a hypothetical outlet at threshold (a) downstream from the Creugenat overflow-i.e. at an elevation of 443 m a.s.l. The head-loss equation is valid for an outlet located at a distance of 4,000 m and with a k’S of 28 m\(^3\)/s (considering an average conduit diameter of 2.7 m) to reproduce the observed trend.

Previous observations led to the hydraulic schemes of the karst system presented in Figure 9 that depends on the groundwater level elevation. This provides a set of hydraulic gradients which can be implemented in the 3D model at various high water flow conditions. One result is displayed on Figure 10 where the gradients correspond to a usual overflow of the Creugenat (average annual flood event) at high water stage. Upstream of the Beuchire spring the hydraulic gradient strongly increases until it reaches the Creugenat overflow (the slope of the gradient is close to 0.7%). If the water level still increases the Creugenat overflow becomes active and the gradient does not rise significantly ahead. In Figure 13 areas that are susceptible to flooding during such events are mapped in yellow.

Similar scenarios could be established for two larger flood events: the 30- and the 300- years flood events. The August 2007 flood event, defined as a 30 years event (by analysis of the IDF curves, BG 2012) is characterized by the Creux-des-Prés overflow. Between the Beuchire spring and the Creugenat overflow the hydraulic gradient remains comparable to the value encountered above.
the gradient): its slope is approximately 1% extending the groundwater bodies as pictured in Figure 11. The areas which are vulnerable to flooding when such type of flood event occurs are filled in orange in Figure 13.

For a 300-year flood event (as the flooding in 1804) the hydraulic gradient within the conduits does not change between the Beuchire spring and the Creugenat overflow (0.7%) and between the Creugenat and the Creux-des-Prés overflows (~1%). Upstream of the Creux-des-Prés we allocated the gradient on the basis of the more elevated outlets (higher than 500 m a.s.l) and the shape of the versants. The gradient is therefore approximately 1.5%. Surfaces that are here vulnerable to flooding are the more extended ones (labeled in red in Figure 13).

Figure 9. Sequential evolution of the hydraulic gradient within the Beuchire-Creugenat karst system (i.e. the conduits) for an average annual flood event reaching the Creugenat overflow. The profile of the conduits is here supposed. Processes are the following:
1. The groundwater level at the Creugenat overflow is independent of the Beuchire spring discharge oscillations;
2. The water level at the Creugenat overflow is controlled by the threshold (a);
3. At 443 m a.s.l. the activation of an additional conduit (or a perched spring) show a lag in the water level elevation rise at the Creugenat overflow;
4. The rise of the groundwater level at the Creugenat overflow depends on the Beuchire spring discharge. At 451 m a.s.l the Creugenat overflow is now flowing!

(~0.7%). Upstream of the Creugenat overflow, the hydraulic gradient of the groundwater flow in the conduits is here fixed by Le-Creux-des-Prés outlet and by the bottom of the valley (several outlets were active during the 2007 flood events providing some arguments to fix

Figure 10. Model prediction of the extension of groundwater bodies (GWB) A and B during a flood event reaching the Creugenat overflow (= multiannual occurrence = case 4 in Figure 9). Water from GWB B overflows over two passes and contributes to the discharge of the Beuchire spring.

Figure 11. Model prediction of the saturated groundwater bodies extension in the Beuchire-Creugenat karst system during a flood event reaching the Creux-des-Prés overflow (~30-year flood event).
In addition to these gradients some further temporary springs were observed previously in the field and reported by Bouvier 2006. They were used as controls for the prediction of potential outlets based in the 3D model.

Considering the respective values of the hydraulic gradients during these events, it is possible to estimate the associated volume of groundwater involved in the floods (or at least which should flow within the system). This implies to know or at least estimate a value of efficient porosity (i.e. density of conduits / volume of flooded aquifers) which could be taken as a first approximation about 0.5% (in the swiss Jura, according to Bauer et al. 1980, Burger and Pasquier 1984). This value may be refined in the further development of the project.

**Mapping the flooded areas**

According to the previous model results it is possible to map surface areas which could be affected by the potential flood events. The results for the Beuchire-Creugenat catchment are displayed in Figure 13. The next step in flooding hazard characterization is the expected drainage

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**Figure 12.** Model predicted storage in the aquifer (i.e. the karst conduits) and its development due to groundwater increase within the karst system for the respective flood events (average annual, 30-year flood events and ~300-year flood events). The associated volumes refer to water potentially involved in the floods (1.7 Mm$^3$ for an average annual flood event, 4.4 Mm$^3$ for a 30-year flood event and more than 6 Mm$^3$ for a 300-year flood event).

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**Figure 13.** Flood hazard map of the Beuchire-Creugenat catchment area. Color code refers to the considered occurrence: average annual flood event, 30-year flood event, 300-year flood event. Filled areas have to be considered as potentially exposed to flooding or at least as potentially impacted by an overflow from a temporary outlet. The interpreted drainage axes (both vadose and phreatic) are also displayed on this map.
a net discharge rates assessment for each type of flood event. This is possible once the catchments of these have been clearly delineated as well as their respective recharges. This assessment will be conducted in the second part of the project by the establishment and the use of a hydraulic model. In the present paper only the maximum discharge of the respective outlets (permanent and temporary ones) was assessed for a average annual flood event and a 30 years flood event. Such models are useful for designing future construction or hydraulic works.

**Maximum expected discharges at the outlets**

Discharge of springs usually increases as the level of the groundwater increases within the system until one overflow spring becomes active. Then, even if the groundwater level still rises in the conduit, the discharge of the lower spring does not increase significantly. Based on that principle, it is possible to estimate the maximum expected discharges at the Beuchire spring and the Creugenat overflow.

Regarding the Beuchire spring, the maximum discharge is limited by the overflowing of the Creugenat outlet (Figure 8). Even if the groundwater level in the karst system still increases the Beuchire spring cannot discharge more than 3.5 m$^3$/s.

The maximum discharge rate at the Creugenat outlet can be estimated from the discharge of the stream in the city of Porrentruy as soon as the Creux-des-Prés overflow becomes active. Comparing the last 2007 flood event with a 30 years flood event and knowing the moment when the Creux-des-Prés overflow discharged - it was estimated that the maximum discharge rate at the Creugenat overflow is about 18 m$^3$/s.

**Discussion**

In June 2012 a collapse appeared in the middle of a road, on a straight line between the Beuchire spring and the Creugenat overflow (Figure 14, ISSKA 2012). The pit located at an elevation of 443 m a.s.l reached the depth of 8 m and at that time its bottom was dry. This collapse gave the SISKA the opportunity to install a pressure sensor with the aim to survey an eventual presence and oscillations of the groundwater within the pit. The recorded data (only few weeks available) show periodic rises of the groundwater with a maximal elevation of 438.6 m a.sl (~4.5 m below the surface) that led to a deepening of the collapse. The recorded oscillations of the groundwater are consistent with the previous interpretation related on Figure 9.

In addition to this flood event, new piezometric data were collected from a borehole (POR3) located in the vicinity of the Creugenat overflow. First comparison of these data with the recorded oscillations of the Creugenat overflow provides new calibration elements that improve the model functionality. Currently, a series of simulations are being conducted using the actual release of SWMM...
in conduit geometry characterization and to improve the hydrological model. The last could be applied in further hydraulic planning, especially in estimating the groundwater discharge contribution for each basin unit. Applications to assist the design of future construction and hydraulic works could also be envisaged.

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