Assessment report on the 2016 flood event on the Seine and Loire basins (France)

Final report

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1 Introduction

From 28 to 31 May 2016, a heavy rainfall event reached the northern part of France. The episode was persistent and followed by additional rainfall that lasted until 3 June. The high amounts of rainfall led to severe flooding in northern France, mainly over the Upper and Middle Seine river basin and in several tributaries of the Middle Loire river basin. The flooding wave propagated downstream until 10 June, reaching the Lower Seine-Normandy and Lower Loire river basins (see map of hydrographic districts in Figure 1). The peak flow at the Seine River in Paris (6.10 m, whereas it is lower than 1.5 m in usual conditions) was reached in the early hours of 4 June. It was estimated to be the highest level in nearly 35 years (it is estimated that the 1982 flood reached 6.18 m). It caused flooded banks and forced landmarks located close to the river (such as the Louvre and the Orsay museums) to shut down.

The atmospheric phenomenon that caused the persistent, multi-day rainfalls was characterized by a blocking pattern bringing widespread rain over the areas of the affected catchments. It was the same extensive, slow-moving low-pressure systems (named Elvira and Friederike in Germany) that brought heavy rainfalls over Germany and Belgium in the same period, causing also severe localized flooding in these countries.

In France, the weather perturbation coming from northern Europe was fed by warm, moist air pulled northward from the Mediterranean Sea, feeding the storm system. Rain fell over soils that were already wet due to previous rainfalls over the month of May, contributing to the high river levels and flooding.

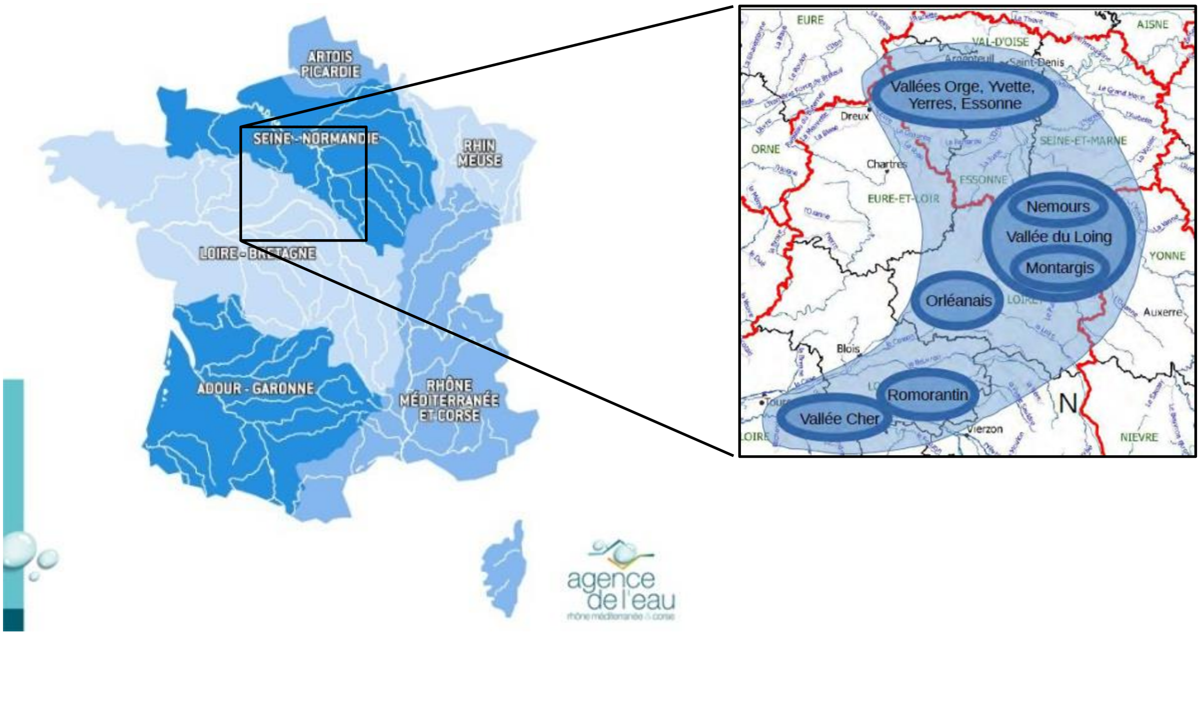


Figure 1: Left: The six main hydrographic districts in France (source: Agences de l'Eau); Right : the most impacted zone (source : Perrin et al. (2017))

According to Météo-France, May 2016 was the rainiest month of May in northeast France (regions of Bourgogne, Centre - Val de Loire, Île-de-France and Picardie) since 1959. In Paris, a total point rainfall accumulation was observed at 178.6 mm, which is a record for this month since 1873, when measurements started. June was also an active month with several record breaking events. Rainfall accumulations over June-May were 1.5 above normal in the Central and Val de Loire region, as well as on the northern and eastern country borders. In Île-de-France (Paris and its surrounding area), these totals were even up to 3 times the average at given rain gauge locations.

This report aims to provide a brief overview of the 2016 flood event on the Seine and Loire river basins in France. It must be noted that, at the time of writing, post-event analyses carried out by the national flood forecasting centers were either ongoing or just finalized (DREAL Centre-Val-de-Loire, 2016; DRIEE Île-de-France, 2016)[1]. Other institutions, e.g. reservoir managers (EPTB Seine Grands Lacs, 2016), also provided post-event feedbacks. The Ministry of the Environment also published a general overview on the event and its consequences[2].

We collected available data and information from several sources: Météo-France summary climatology, informal meetings with forecasters from the Vigicrues national flood forecasting network, contacts at EFAS, French press media, summaries from Governmental websites, insurance overviews, among others. Several hydrological data collected by gauging stations are still under critical analysis, since measurement devices showed signals of malfunction in real-time and rating curves are under investigation to provide more reliable estimates of discharges on the basis of measured water levels. Work on re-forecasting the flood event and understanding uncertainties from precipitation forcing, rainfall forecasts and hydrological modelling is therefore ongoing. Nevertheless, we tried to provide in this report an overview of the event, with focus on its main hydrological impacts.

[1] http://www.driee.ile-de-france.developpement-durable.gouv.fr/IMG/pdf/rex4m_spc_smyl_mai_juin_2016_vf.pdf
[2] http://www.ladocumentationfrancaise.fr/rapports-publics/174000194/

2 General description of the study area

The analysis focuses on parts of the Seine and Loire basins, which were most affected by the event (see Figure 2). These two basins have a common boundary and have some similarities in terms of hydroclimatic characteristics, as described in the next sections.

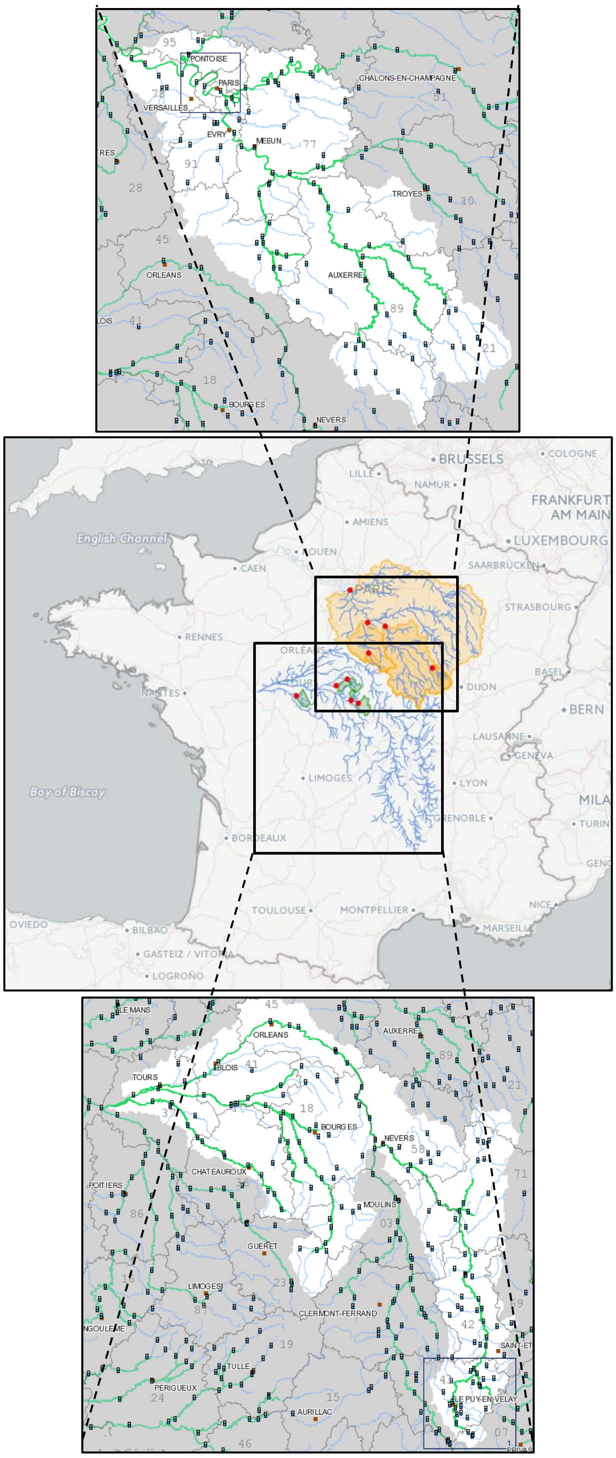


Figure 2: The Seine basin at Paris (orange) and the Loire basin upstream Tours and the zones monitored by the flood forecasting services impacted by the 2016 flood event on the Seine (SPC SMYL, top) and on the Loire (SPC LCI, bottom) (Source, based on: http://www.vigicrues.gouv.fr)

2.1 The Seine basin

The Seine basin is located in the northern part of France, with a total area of 79000 km² (43800 km² up to Paris). Upstream Paris, the Seine River is fed by several main tributaries, which, from upstream to downstream, are: the Aube (4600 km²), Yonne (11000 km²), Loing (4200 km²) and Marne (13000 km²) rivers (see Figure 3). In the Paris surrounding area (Île-de-France), the Seine River also receives water from several smaller tributaries, which were strongly impacted by the event: Orge (950 km²), Yerres (1000 km²) and Essonne (1900 km²).

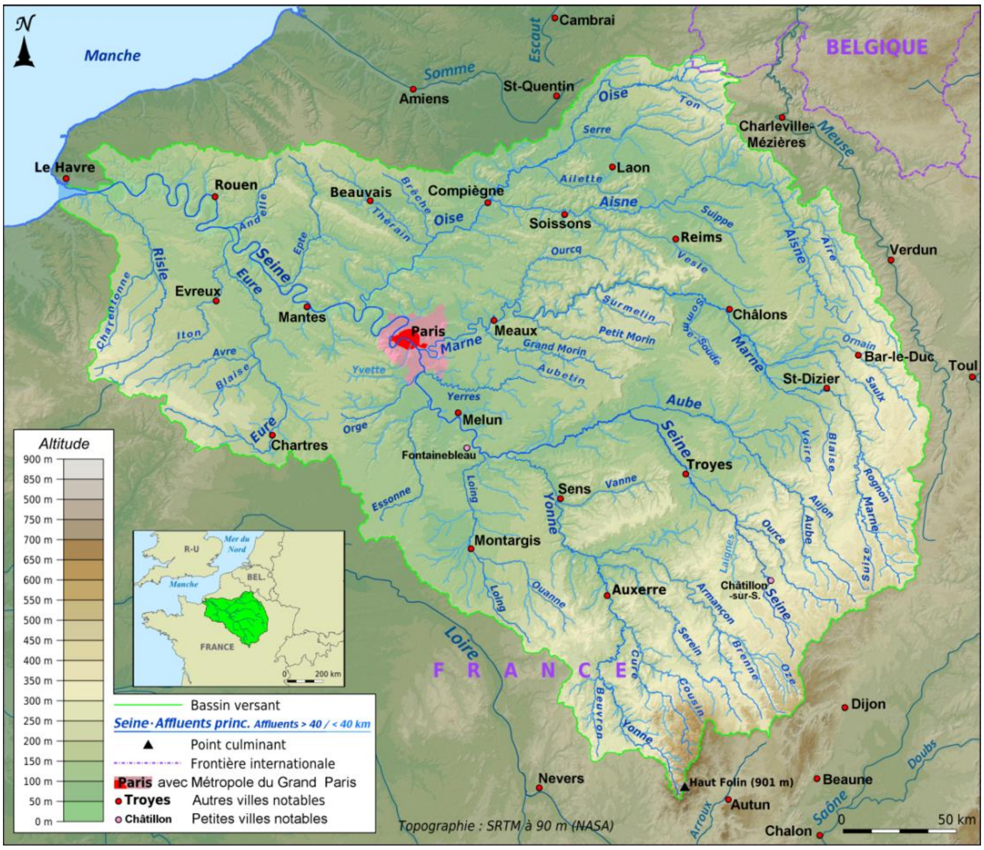


Figure 3: The hydrographic network of the Seine basin (Source: Wikipedia)

The relief is moderate: the Seine sources are at around a 446 m altitude, and the altitudes in the river basin are generally under 300 m. The maximum altitude is in the Morvan, a mountainous massif in Burgundy (901 m), in the most southern part of the basin (Yonne basin). Hence the influence of snow on floods is limited on the basin. Concerning the precipitation regime, the Seine basin is under oceanic influences (see Figure 4). Precipitations are quite homogeneously spread over the year, with a total of about 800 mm/year. Temperature (annual average around 11°C), and potential evapotranspiration (annual Penman average around 700 mm) show a marked seasonality, with a maximum in summer (July and August). This results in a flow regime showing high flows in winter (December to March) and low flows in summer (July to September). Mean annual flow of the Seine River in Paris is about 300 m^3/s. Floods of the Seine River are generally quite slow and can last a few days to a few weeks. However several smaller tributaries, especially the Yonne, are known to have short reaction times to rainfall.

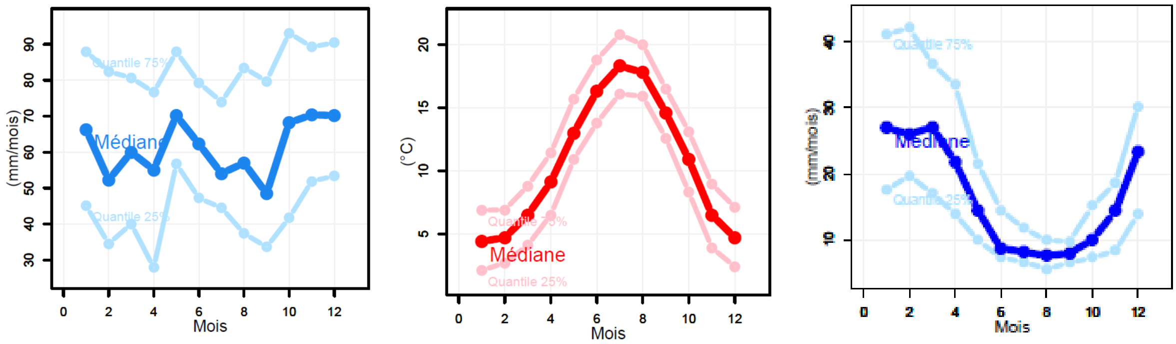


Figure 4 : Climate conditions (left: monthly precipitation, mm/month, and centre: monthly temperature, °C) and flow regime (right, mm/month) on the Seine basin at Paris

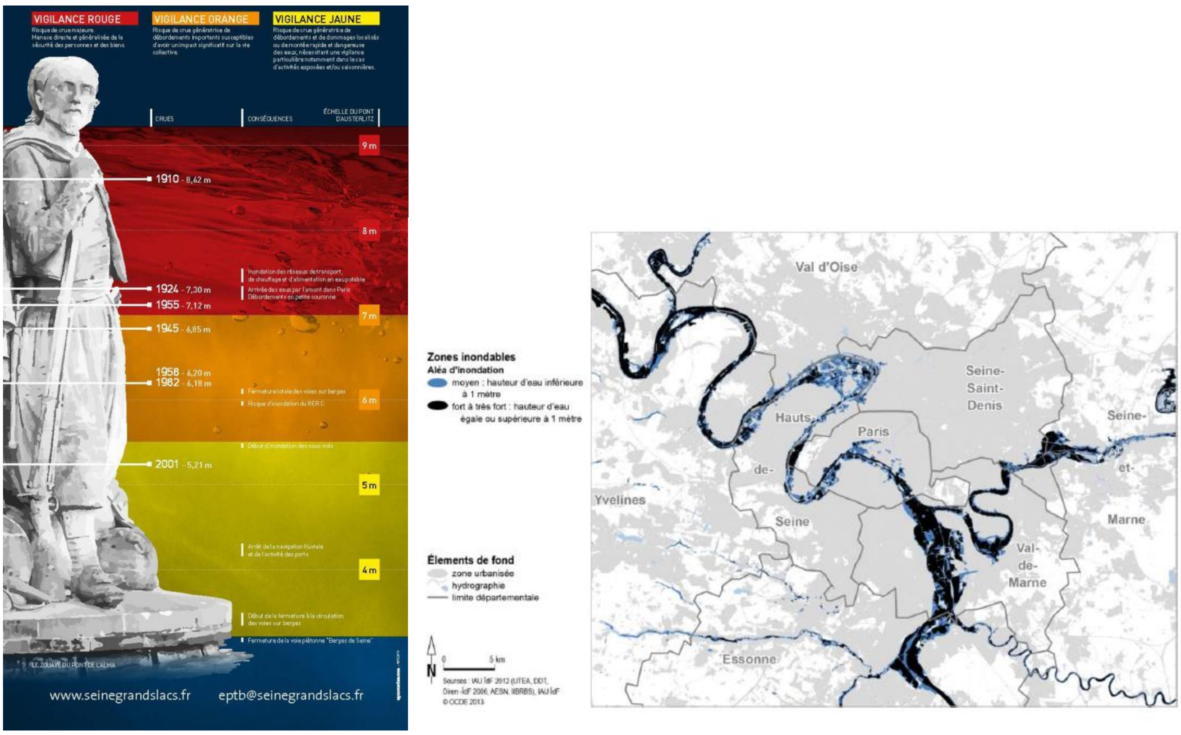


Figure 5: Left: Major flood records on the Zouave at Pont de l'Alma in Paris with the three colour thresholds used for flood watch (Source: Seine Grands Lacs) and right: flooded areas within the Paris area for the 1910 flood event if it happened today (Source: OCDE, 2014)

Most major past flood events on the Seine basin occurred in winter (see Figure 5): February 1658 (which was the largest ever observed, with a maximum height of 8.96 m), January 1910, January 1924, February 1945, January 1955, March 1958, January 1982, March 2001. The 1910 flood, with a maximum discharge of about 2400 m^3/s, was estimated as a 100-year flood and is the reference flood on the Seine basin. Many analyses were done on this event (Lacaze et al., 2011; Brun and Gache, 2013). It had dramatic consequences and it is estimated that a similar flood today would cause between 3 to 30 billion euros of direct damages and a GDP reduction of 0.1 to 3% (Viennot et al.). More than 2 million people may be directly impacted by such a flood in the Paris area. The 1910 flood was a generalized flood over the basin and is the reference for many tributaries of the basin. More recently, the 1982 flood had a discharge estimated at 1800 m^3/s. Over the last century, the urbanization of the Paris region developed strongly in the inundation zones, further increasing the vulnerability to floods (Brun and Adisson, 2011; Brun and Gache, 2013). Upstream Paris, four large artificial reservoirs were built in the 20th century on the Seine (1966), Aube (1990), Marne (1974) and Yonne (1949) rivers, totalling a capacity of 850 Mm^3 and controlling 17% of the basin upstream Paris (see Figure 6). Note that the Loing basin, which was heavily impacted by the event, is outside the influence of these reservoirs. They are managed for flood control and low-flow augmentation by the Seine Grands Lacs Institution (http://seinegrandslacs.fr/). Since low flows and floods occur at different seasons, the reservoir management is mainly based on filling curves, with the objective to have the reservoirs almost empty at the end of October and almost full at the end of June.

The regional service in charge of flood forecasting and flood watch in the Paris area is the Seine moyenne-Yonne-Loing service (SPC SMYL). It issues flood forecasts for most of the Seine basin upstream Paris, except the upper parts of the Marne and Seine rivers (which are controlled by another regional service, the SPC SAMA, Seine amont-Marne amont). Flood forecasts are made through hydrological and hydraulic models. The expected “vigilance” (flood watch) lead time is 24 hours, but the Prefecture, in charge of coordinating rescue services, requires 3-day lead time forecasts. Flood watch messages are accessible to the public on the Vigicrues website, coordinated by the Central service for flood forecast in Toulouse (SCHAPI, http://www.vigicrues.gouv.fr/niveau2.php?CdEntVigiCru=7).

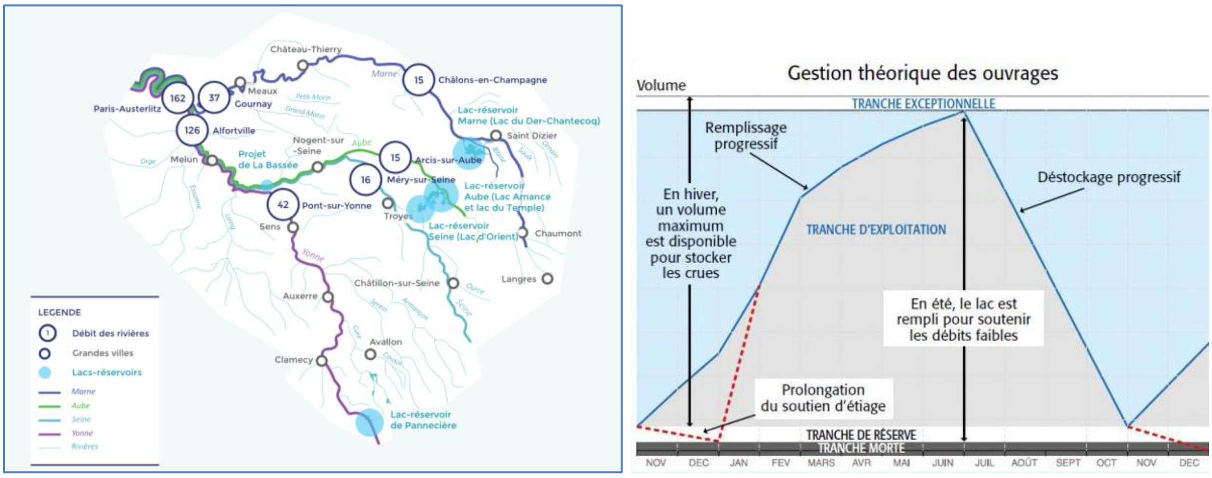


Figure 6: Left: Location of the four large reservoirs on the Seine basin (blue circles) and right: Typical objective filling curve for dam management (Source: Seine Grands Lacs)

2.2 The Loire basin

The Loire basin drains a large area of 117000 km² in central France, with 42200 km² at its outlet in Tours (see Figure 7). The relief is more contrasted than in the Seine basin: the highest relief reach 1856 m and the sources of the Loire are at an altitude of 1400 m. Up to Tours, its main tributaries are the Allier (14300 km²), Arroux (3200 km²), Beuvron (2200 km²) and Cher (13900 km²) rivers. A few kilometres downstream Tours, the Indre (3400 km²) joins the Loire. The Cher basin (and its tributaries, such as the Yèvre and Sauldre), and left-bank Loire's tributaries between Orléans and Tours were the most impacted part of the area during the June 2016 event.

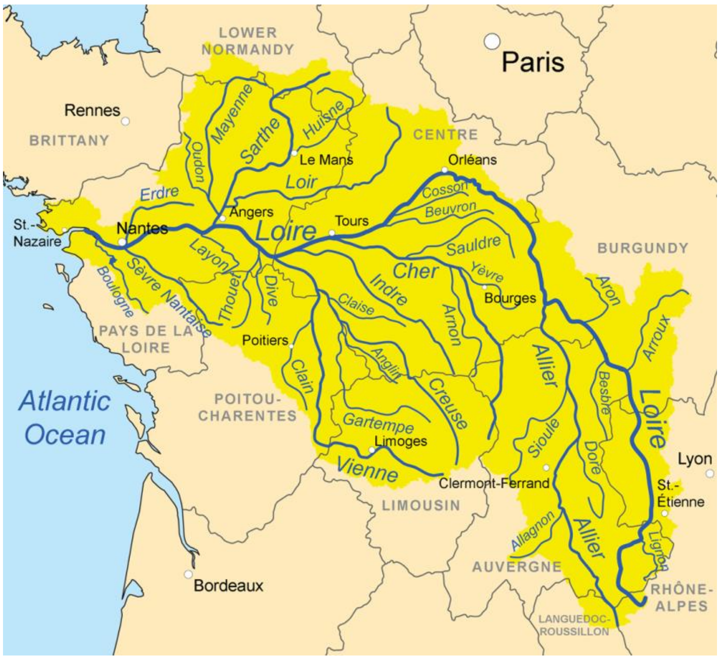


Figure 7 : Hydrographic network of the Loire basin (Source: Wikipedia)

The Loire basin is mainly under oceanic influence, but also has mountainous and Mediterranean influences in the upstream part of the catchment, which is located in the Massif Central. Precipitations are spread over the year, with a maximum in the spring season (see Figure 8). The upper part of the basin may be impacted by strong precipitation events coming from the Mediterranean during the autumn (Jubertie, 2006). Temperature shows a marked seasonality. The upper part of the basin can be significantly influenced by snow, but the impact of snowmelt is limited on the lower reaches of the Loire River. High flows occur in winter and low flows in summer.

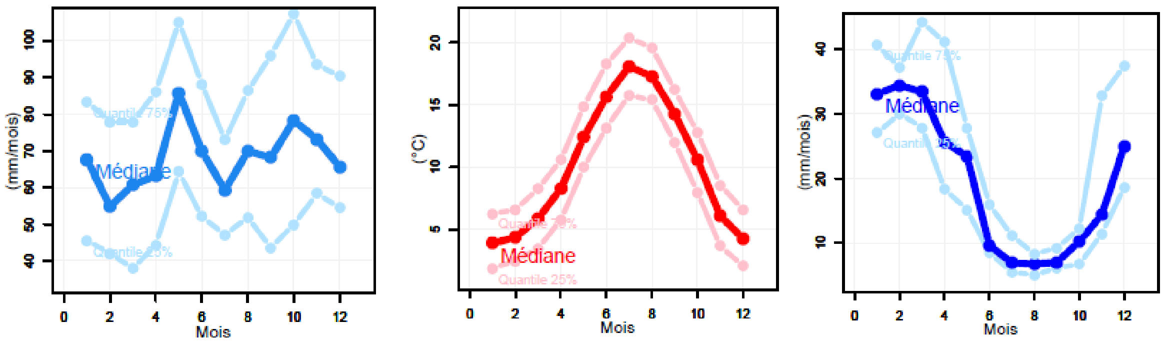


Figure 8 : Climate conditions (left: monthly precipitation, mm/month, and centre: monthly temperature, °C) and flow regime (right, mm/month) on the Loire basin at Tours

The largest historic floods in the basin (see Figure 9) occurred in autumn and winter, but floods can also occur in autumn, spring or even at the end of the summer season in the upper part of the basin (Brun and Adisson, 2011). The largest floods are mainly due to a combination of « cevenol » heavy storms in the upper part of the catchment and of prolonged precipitation from ocenanic fronts (Feuillette et al., 2016). In the 19th century, three major floods (1846, 1856 and 1866) had devastating impacts on the basin and remain the reference. It is estimated that direct damages of such events today would be at around 6 billion euros (CCR, 2016), and a major Loire river flood is also estimated to be the second most costly natural hazard in France (after a major flood on the Seine basin).

Month	Year	Height (m)
June	1856	7.10
September	1866	6.92
October	1846	6.78
December	1825	6.00
October	1907	5.25
October	1872	5.23
August	1804	5.20
June	1835	5.01
February	1841	4.79
October	1855	4.45
March	1895	4.25
January	1924	4.24
May	1836	4.23
March	1845	4.20
October	1893	4.04

Figure 9 : The 15 largest flood events in Orléans (Loire basin) and illustration of a corresponding scale (Source: DREAL CVL; Photo: MH Ramos)

Two dams are located on the upper reach of the Loire basin, Grangent (66 Mm^3) and Villerest (106 Mm^3). They are mainly managed for hydropower, and Villerest is also used for flood control. On the Cher basin, the only large dam, Rochebut (26 Mm^3), is on the very upstream part of the basin and is run for hydropower. It had no significant effect on the 2016 flood.

The regional service in charge of flood watch in the middle Loire (Loire-Cher-Indre, SPC LCI) is based in Orléans. The tools for flood forecasting are mainly based on rainfall-runoff models and hydraulic models. Flood watches from SPC LCI can be found on the Vigicrues website (http://www.vigicrues.gouv.fr/niveau2.php?CdEntVigiCru=10).

3 What caused the floods?

The low-pressure systems of the late May-early June period were fed by warm, moist air from the Mediterranean Sea, bringing heavy rainfalls over the northern part of France. Mesoscale convective systems were embedded in these rainy systems, causing localized, intense rainfalls and flooding in several tributaries and river reaches of the Seine and the Loire river basins.

The atmospheric phenomenon, more common in the affected areas during the winter season, was characterized as an extraordinary event given its time of occurrence within the year as well as its persistent aspect, responsible for several days of rain accumulations that were record breaking at several rain gauge locations.

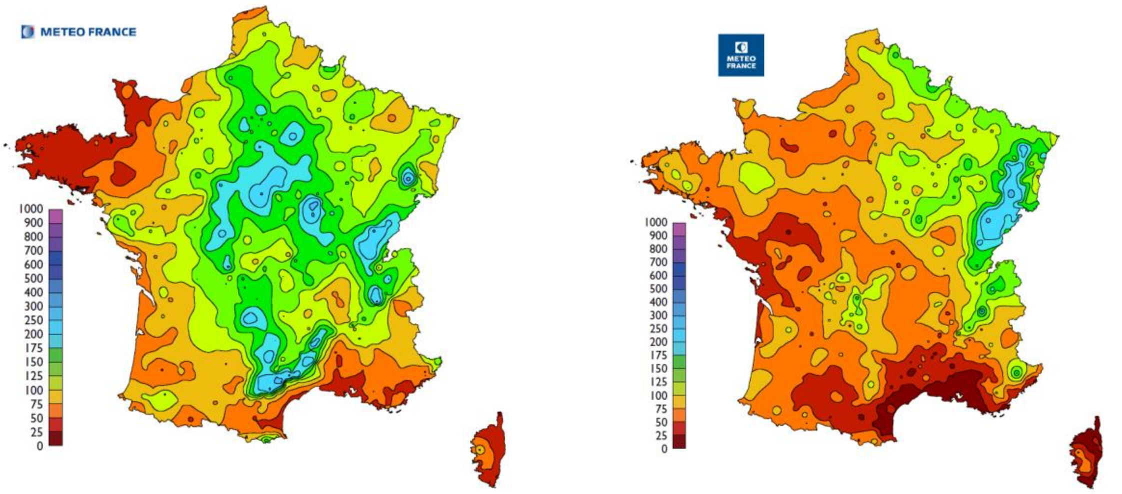
According to the bulletins of Météo-France for the months of May and June 2016 ("Bulletins climatiques" published in the journal *La Météorologie* by Météo-France DClim[3] (Climatology department) and available on Météo-France open-data website [4,5]):

- May 2016 was the rainiest month of May over the period 1959-2016 in the Centre, Île-de-France, Picardie and Bourgogne regions, with totals 1.5 to 3 times above the climatological mean (estimated over the period 1981-2010)[6,7]. Temperatures were slightly below or on the seasonal average, while the number of windy days was below average in the north. The north of the country also suffered from a deficit of sunshine (compared to climatology). Locally, this deficit was above 20%.
  In summary, Météo-France noted that May 2016 was one of the wettest months of May of the past 50 years, even if it has not reached the records of the extraordinary years of 1981 and 2013. On average, monthly rainfall over France was 40% above the 1981-2010 average. Overall, spring 2016 was characterized by a strong storm activity (more than 118435 lightning strikes – of which 76193 were observed in May), late frosts in late April/early May, particularly in the north, and the strong rainfall event of end of May.

- June 2016 was marked by several rainy periods, mainly observed in the north of France from 1 to 5 June. It was also marked by a low number of sunny days (the deficit of sunshine in the northern part of the country was above 30%), average to above-average monthly temperatures and a low frequency of strong winds. Rainfall was abundant in the north of the country, with totals 1.5 to 2 times above the climatological mean (estimated over the period 1981-2010). On average, monthly rainfall over France was 25% above the 1981-2010 average.

[3] Météo-France DClim, Bulletin climatique : Mai 2016, *La Météorologie* N°94, p. 77-79. Association Météo et Climat, 2016, URI: http://hdl.handle.net/2042/60715
Météo-France DClim, Bulletin climatique : Juin 2016, *La Météorologie* N°95, 10p. Association Météo et Climat, 2016, URI: http://hdl.handle.net/2042/61625
[4] https://donneespubliques.meteofrance.fr/donnees_libres/bulletins/BCM/201605.pdf
[5] https://donneespubliques.meteofrance.fr/donnees_libres/bulletins/BCM/201606.pdf
[6] http://www.lemonde.fr/planete/article/2016/06/01/intemperies-le-mois-de-mai-le-plus-pluvieux-depuis-150-ans_4929951_3244.html
[7] http://www.lefigaro.fr/sciences/2016/05/31/01008-20160531ARTFIG00327-precipitations-records-sur-une-grande-partie-de-la-france.php

The cyclonic circulation observed on 28-31 May brought heavy rainfalls over the country, mainly in its northern part. May 30 was the rainiest day of this period, with 24-hour totals equivalent of 1 month precipitation at locations such as Trappes (Yvelines) and Orléans (Loiret). Record 24-hour rainfall totals[8] were observed on 29 May: 85.1 mm in Palluau (Vendée), 99 mm in Saint-Même-le-Tenu (Loire-Atlantique), and 30 May: 76.2 mm in Ailly-sur-Noye (Somme), 77 mm in Cheverny (Loir-et-Cher) and 100 mm in Loury (Loiret). In some areas, the 28-31 May totals represented over 3 months of precipitation. On June 2016, record monthly totals were also observed: 161.5 mm in Lille (Nord), 182.8 mm in Strasbourg (Bas-Rhin), 2010.2 mm in Roville-aux-Chênes (Vosges) and 265.9 mm in Besançon (Doubs).



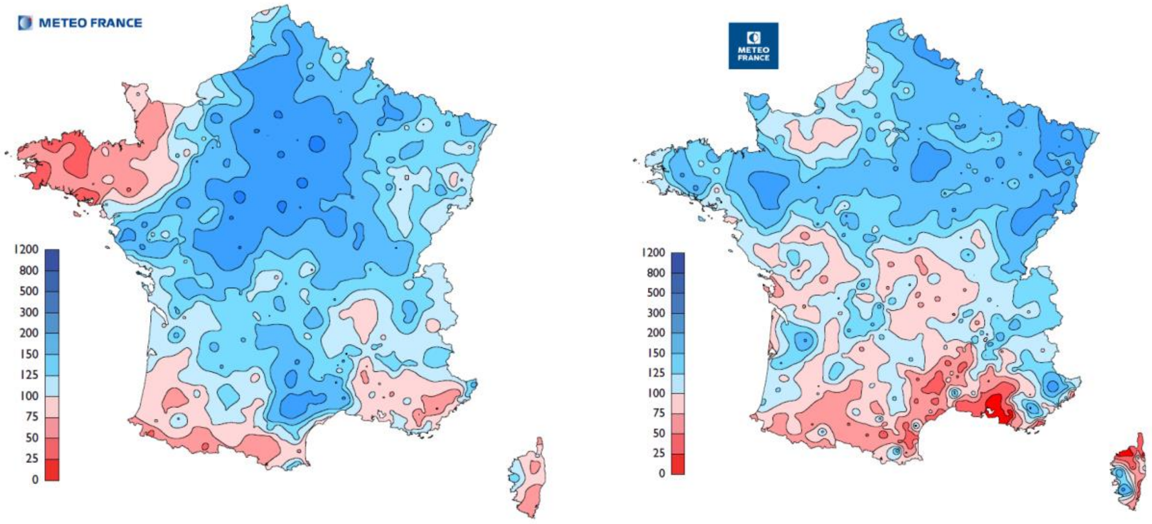
May 2016 June 2016

Figure 10: Total precipitation of May 2016 (left) and June 2016 (right) in France (source*: Bulletins climatiques de Météo-France*)

Figure 10 shows the amount of precipitation observed in France for the months of May and June 2016, while Figure 11 shows the deviation from average values (1981-2010), in percentage, of the total precipitation observed during the same months (source: Météo-France). The northern part of France that was affected by strong rainfall events during 26 May-3 June can be clearly seen, with monthly totals of 1.5 to 3 times above the climatological average.

Météo-France also noted that, while the year 2015 was not a particularly wet year, the first six months of 2016 were all above average. When the strong rainfalls of late May/early June stroke the north of the country, soils were therefore wet. This is illustrated by the map shown in Figure 12, where deviations from average values (1981-2010) of the soil moisture index (SWI) obtained from the modelling chain SIM of Météo-France are shown for France and for the 1st of June 2016. It can be seen that soils were saturated in the beginning of June 2016, notably in the central and northeastern parts of France, where the flooding events occurred.

[8] Average daily rainfall is about 30-50 mm.



May 2016 June 2016

Figure 11: Deviation from average values for the period 1981-2010 of total precipitation of May 2016 (left) and June 2016 (right) in France (in %) (source: Bulletins climatiques de Météo-France)

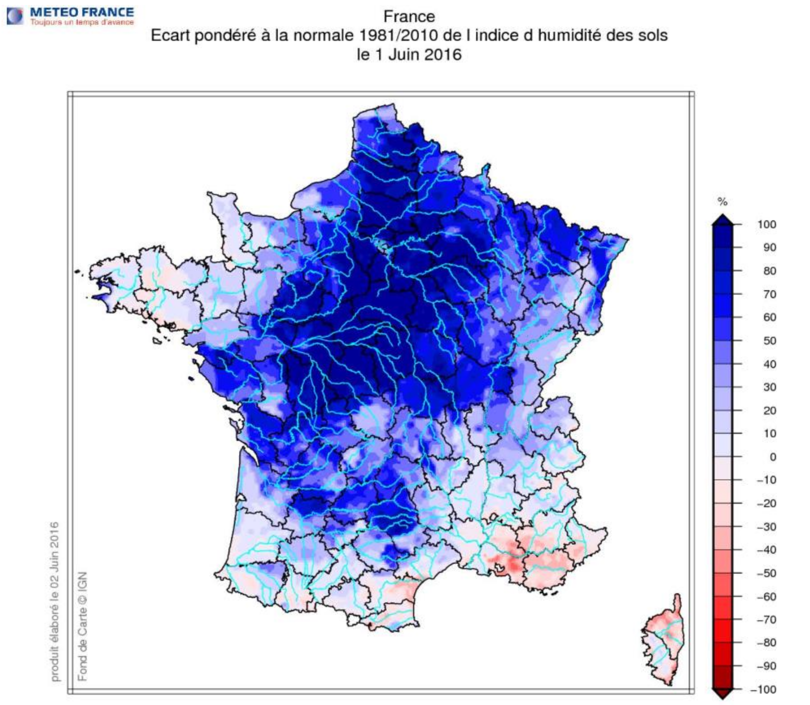


Figure 12: Deviation from average values (1981-2010) of the soil moisture index (SWI) calculated by the model SIM of Météo-France on 1 June 2016 in France (%) (source: *Météo-France – Portal Eau France* *http://www.eaufrance.fr/docs/bsh/2016/06/eau_sol.php*)

Concerning the hydrogeological situation, according to estimations of the BRGM, on the basis of groundwater data from the database ADES[9], after the overall rainfall deficit of the year 2015, the precipitation of the first months of 2016 allowed the replenish of water tables and aquifers with a near-normal level of groundwater rate filling in several parts of France. In most of France, including the north of the country, groundwater levels were either at their normal levels or above normal. Througout the country, it was observed that 36% of the surveyed points (locations of piezometers) were above normal, 39% were at normal levels and 25% were below normal on 1 June 2016.

Figure 13 shows the deviations of the mean river flow of May 2016 to the average value for the same month, computed over historic years available in the database Banque Hydro. It shows that 71% of the locations showed above average flows. The Loire and Seine river basins are among the areas showing a large number of river sections with flows above the average.

In summary, the period of late May/early June 2016 was marked by strong rainfalls falling over already wet soils and catchments with normal to above-normal groundwater levels. The high amounts of rainfall fallen on wet soils are the main causes of the observed floods in the Seine and Loire river basins. How the flood events progressed over the catchments is detailed in the next section.

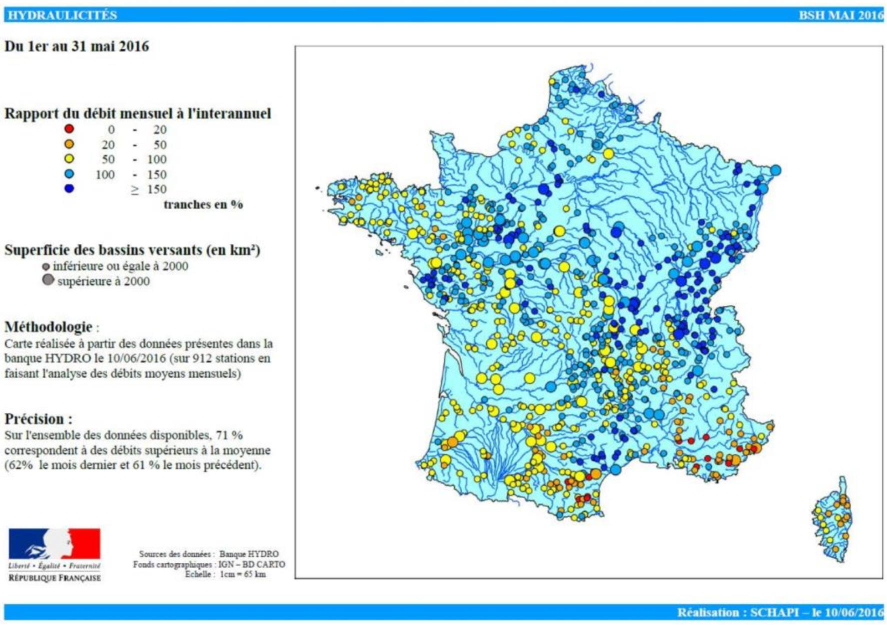


Figure 13: Deviations of the mean river flow of May 2016 to the average value for the same month, computed over historic years available in the database Banque Hydro (source: *SCHAPI – Portal Eau France* *http://www.eaufrance.fr/docs/bsh/2016/06/riv_hydraul.php*). Red dots indicate 0-20% of deviation; orange dots, 20-50%; yellow dots, 50-100%; light blue dots, 100-150%; dark blue dots, >=150% . The size of the dots indicate he size of the catchments (<= 2000 km² or > 2000 km²)

[9] http://www.eaufrance.fr/docs/bsh/2016/06/nappes.php

4 Progress of the event

According to information provided by the regional flood forecasting centres, we can summarize the following timeline of the events in the two major affected river basins (see example hydrographs in Figure 14):

- In the Middle Seine-Yonne-Loing regional forecasting centre:
  - The first intense and localized rainfalls of the 28 and 29 May caused the quick rising of water levels in the upstream parts of the catchment (rivers: Serein, Upper Loing, Ouanne).
  - In the evening of 31 May, the historic levels of the 1982 flood and, subsequently, the 1910 flood were already exceeded in the Loing River. A maximum level is reached at the city of Montargis, with about 30 cm above the level of the record 1910 flood (the Loing River at Montargis has a catchment area of about 1650 km²). The red level is activated at 12:00 on the Upper Loing River that day.
  - At the rain gauge station of Paris Montsouris, 52.9 mm of rainfall are measured on 30 May and a total of 89.1 mm is observed from 28 May to 31 May.
  - On 1 June at 8:00, the red level (maximum) is activated at the Lower Loing River. The peak flow will be reached in the evening of 1-2 June at the city of Nemours (the Loing River at Némours has an area of about 3500 km²) and in the early hours of 2 June at Episy (catchment area of about 3900 km²). During the day, the levels at the Middle Seine River will rise fast with the arrival of the flood wave coming from the Loing River.
  - On 2 June, the levels at the Seine River in Paris were rising due to the flood waves coming from the Marne and the Upper Seine rivers. The Seine will peak in Paris in the early hours of 4 June, at a flood level close to the level observed in 1982.
  - On 5-6 June, the flood wave coming from the Essone River (left-bank tributary of the Seine River before Paris) arrives in the Middle Seine (the Essonne River at Ballancourt-sur-Essonne has an upstream catchment area of about 1870 km²).
  - On 11 June, all the river reaches under survey do not display watch levels anymore.

The statistical analysis of return periods for the flood event is ongoing at the regional flood forecasting center, since the observed flows are still going through a critical analysis. Therefore, we still do not have a final estimation of the return period of the flood at the different gauging stations. However, it was observed that:

- in the Loing River, the water levels exceeded the records for the 100-year 1910 flood.
- In several tributaries of the Middle Seine River, the maximum water level ever observed was exceeded and it is estimated that the flood was also a rare event in this area.
- In the Seine River, downstream to its confluence with the Loing River and up to its confluence with the Oise River, a return period of about 20 years is estimated.
- Due to the absence of floods in the Oise River (right-bank tributary of the Seine River after Paris), only a 10-year return period is estimated for the Seine River at the downstream of the confluence with the Oise River.
- In the Marne River at Ile de France, a return period of about 5 years is estimated.
- In the Yonne river basin, a return period of about 5 to 10 years is estimated.

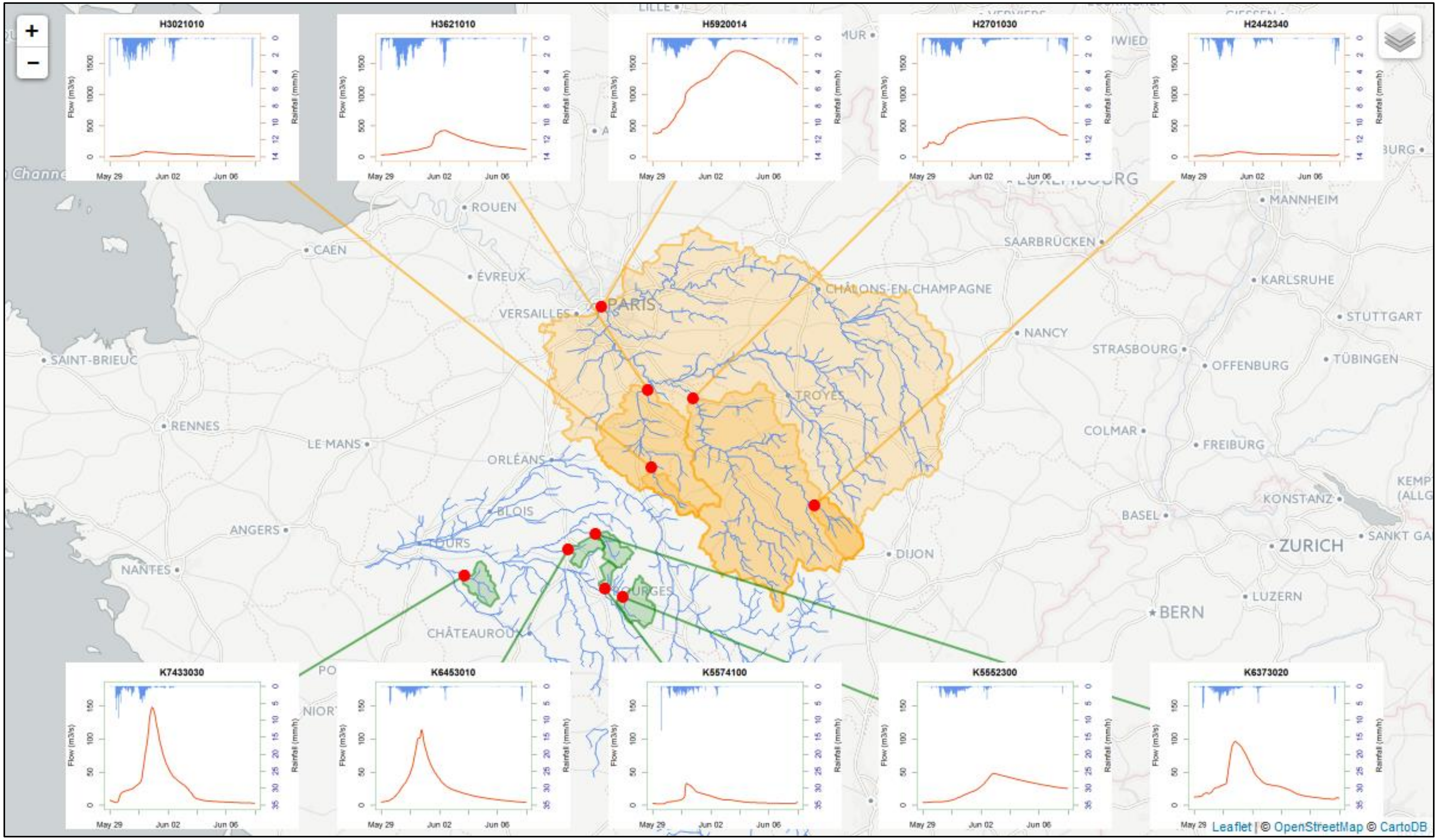


Figure 14 : A few hydrographs recorded during the flood event in the Seine and Loire basins (Source: O. Delaigue/J. Viatgé, Irstea)

- In the Loire-Cher-Indre regional forecasting centre:
    - Strong precipitations (thunderstorms) affected the Sauldre basin, the Sancerrois region and all the right bank of the Loire between Orléans and Tours. They started causing high flow levels already on 29 May on the Arroux river (~3000 km^2), as well as on its tributary the Bourbince river, located on the right-bank of the Loire River.
    - The majority of the rivers in the Loire basin started rising on 31 May, and the flood wave propagated until 10 June.
    - Peak flows were observed between 31 May and 1 June (Sauldre; right-bank tributary of the Cher River), 3-4 June (Lower Cher), 5-6 June (Lower Cher, at the level of the city of Tours).

Here also, the statistical analysis of return periods for the flood event is ongoing. However, first analyses indicate that several rivers had floods associated with 10 to over 100 years of return period. The floods in the Sauldre catchment, for instance, which has an upstream area of 2200 km^2 at its confluence with the Cher, are estimated to be 100-year floods or more. The Loire River has not registered important floods upstream its confluence with the Cher River, though high flood events occurred on small tributaries from the Sologne region. Downstream the confluence with the Cher River, the return period of the peak flows is estimated to be around 10 years. On some small tributaries of the Cher, The return period is around 50 years on the Auron and Yèvre and around 20 years on the Arnon rivers.

5 Effects of the flood event

The flood event had a large number of consequences, ranging from economic, social, industrial, environmental, etc[10]. A summary of the effects of the flood event is provided below, partly based on newspaper articles (see e.g. Figure 15). Note that there are long term consequences that are still under evaluation.


LE FIGARO

Une partie de la France noyée sous des crues historiques

Chloé

Libération

VENDREDI 3 JUIN 2016

«C'était le sauve-qui-peut»

Des milliers de personnes évacuées, des quartiers entiers submergés, reportage dans la vallée du Loing en crue alors que Paris s'y prépare.

Au PCF, le cas Mélenchon embarrasse

Canal+: l'hémorragie sans fin

Grenoble: la déception culturelle

NBA: le feu d'artifice vu par Batum

Le Monde

Paris à l'épreuve des inondations

Le Parisien

Votre offre week-end

Paris patauge

LA CROIX

Inondations, l'entraide

Le Monde

La France va perdre un médecin généraliste sur quatre en vingt ans

Les migrants du jardin d'Eole évacués pour raison sanitaire

Le Parisien

INONDATIONS

La solidarité s'organise

Figure 15: A few front pages of national newspaper on the 3rd and 4th June 2016 (from http://www.leblogtvnews.com)

5.1 Impacted zone

About 1150 municipalities were declared in a "natural disaster" status a few days after the event (decrees on 7, 13, and 21 June) (see Figure 16), and many others were declared in the following months, totalling more than 1500 cities in this status because of this event[11,12]. Note that many of them were mainly subject to agricultural damages, with limited or no impacts on household or infrastructures.

Seventeen administrative departments (18, 28, 36, 37, 41, 45, 58, 75, 77, 78, 89, 91, 92, 93, 94, 95; see Figure 17) were impacted by the event. The administrative departments of Seine-et-Marne (77) and Yvelines (78) were particularly impacted by the event. The cities of Montargis, Nemours, Moret-sur-Loing (in 45 and 77, along the Loing), Melun and Villeneuve-Saint-Georges (in 77 and 94, along the Seine) and Longjumeau (in 91, along the Yvette River). On the Cher basin, the cities of Romorantin and Salbris (41) were the most impacted.

[10] http://www.latribune.fr/entreprises-finance/banques-finance/assurance/inondations-des-indemnisations-superieures-a-un-milliard-d-euros-576823.html

[11] https://www.legifrance.gouv.fr/jo_pdf.do?id=JORFTEXT000032669529

[12] https://www.legifrance.gouv.fr/jo_pdf.do?id=JORFTEXT000032711772

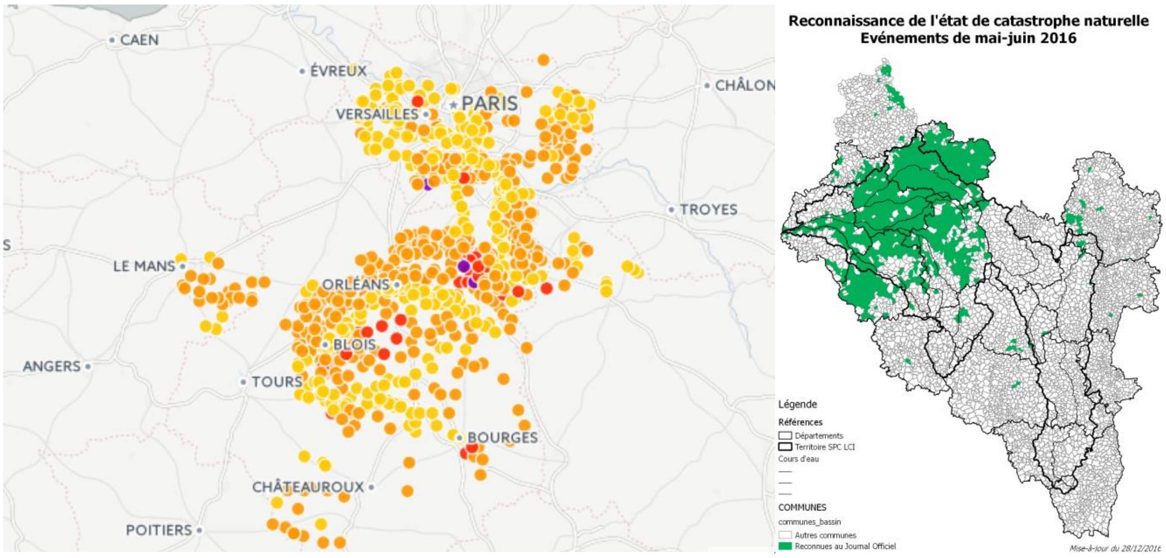


Figure 16: Left : Map of municipalities impacted by inundation or mudslides during the 2016 flood event[13] (colours correspond to the number of declarations); Right : Focus on Loire basin (Source : SPC LCI)

Figure 17 : Boundaries of administrative departments in France

13 http://www.lemonde.fr/les-decodeurs/article/2016/06/10/crues-quelles-sont-les-812-communes-placees-en-etat-de-catastrophe-naturelle_4947754_4355770.html

5.2 Impact on population

In France, 4 people died and another 24 were wounded in incidents linked with this event[14].

More than 20,000 people had to be evacuated[15,16,17,18] and were temporally rehoused outside inundated areas. This was the case in Longjumeau for example where the city centre was fully flooded. More than 20 000 houses suffered from electricity cuts[19], especially in the departments of Seine-et-Marne, Essonne, Loiret and Loir-et-Cher. The authorities however chose not to start the Neptune plan, in which the army can be asked for help[20].

5.3 Impact on industrial activities

The flood had also impacted on industrial activities[21]. The authorities had to warn several critical industrial sites along the Loing River[22]. The main oil depots along the Seine in Seine-et-Marne, Essonne and Hauts-de-Seine were prepared early and none were impacted by the flood[23]. In Île-de-France, almost 800 companies were directly impacted[24].

5.4 Impact on agriculture

Many agricultural activities were impacted by the floods: crops, market gardening, livestock farming, arboriculture, especially along the Mauldre, Yvette and Seine rivers and also on the Loiret and Loire-et-Cher departments. Large sectors of wheat, barley and oats crops were flooded with dramatic consequences on harvest. Harvests of hay were also lost in some sectors. Damages to the agricultural sector were estimated to 200 million euros[25]. Many municipalities which were declared as being under Natural disaster status mainly faced agricultural losses.

5.5 Impact on transports and infrastructures

In the Paris area, the regional train line *RER C* which goes along the Seine closed from 3 to 10 June to close all possible entries for water[26]. 500 000 people take this train every day in usual conditions. The

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[14] http://www.lefigaro.fr/actualite-france/2016/06/05/01016-20160605ARTFIG00122-les-inondations-ont-fait-quatre-morts-et-24-blesses.php

[15] http://www.lanouvellerepublique.fr/Indre-et-Loire/Actualite/Environnement/n/Contenus/Articles/2016/06/04/Le-risque-de-rupture-de-digue-existe-2739040

[16] https://www.francebleu.fr/infos/societe/inondations-evacuation-dans-le-calme-de-160-habitants-villandry-enindre-et-loire-1464872786

[17] http://www.lanouvellerepublique.fr/Loir-et-Cher/Actualite/24-Heures/n/Contenus/Articles/2016/06/01/VIDEO-41-Inondations-a-Romorantin-Le-Bourgeau-evacue-2735313

[18] http://www.lanouvellerepublique.fr/Loir-et-Cher/Actualite/24-Heures/n/Contenus/Articles/2016/06/02/Situation-de-crise-en-Sologne-2735622

[19] https://www.pressreader.com/france/la-r%C3%A9publique-du-centre-orleans/20160604

[20] http://www.lemonde.fr/planete/article/2016/06/03/paris-a-l-epreuve-des-inondations_4932545_3244.html

[21] http://meandre.net/: Bruno Ledoux (Ledoux Consultants)

[22] http://www.lefigaro.fr/sciences/2016/06/22/01008-20160622ARTFIG00185-une-quarantaine-de-sites-industriels-affectes-par-les-inondations.php

[23] http://www.actu-environnement.com/ae/news/industries-ICPE-Seveso-crue-inondations-POI-pollution-Seine-Loing-Driee-27051.php4#xtor=EPR-1

[24] http://www.lesechos.fr/24/06/2016/LesEchos/22220-114-ECH_inondations---800-entreprises-touchees.htm

[25] http://www.lefigaro.fr/conjoncture/2016/06/17/20002-20160617ARTFIG00319-le-bilan-des-inondations-pour-les-agriculteurs-est-tres-lourd.php

[26] http://www.actu-environnement.com/ae/news/crue-seine-bilan-inondation-risques-naturels-infrastructures-27215.php4

traffic on a few other lines had to be modified. Metro stations close to the Seine (Saint-Michel and Cluny-La Sorbonne) were closed for a few days (but fortunately not flooded).

The highway A10, which goes from Paris to Bordeaux (southwestern France) was also closed from 1st to 10th June close to Orléans. 5000 cars had been blocked on the 31st May on this highway and 300 damaged cars had to be evacuated in the following days[27,28].

A breach was opened in the levee of the canal de Briare, close to Montcresson, a few kilometres upstream Montargis. The water from the canal flew into the Loing River, which created unexpected flow.

5.6 Impact on monuments and tourist activities

In Paris, some museums (Orsay, Louvre, Grand Palais) were closed for a few days to prevent losses of art works. In the Louvre, where some collections are stored underground in inundable zones, 150 000 art works were evacuated [29]. The two sites of the national library, which are also along the Seine, were closed for a few days.[30]

The traffic of tourist boats was stopped, which caused economic losses estimated at 10 million euros [31].

The park around the Château de Chambord was inundated by the flood of the Cosson (a tributary of the Loire) and caused important damages[32]. Eight million euros were provided by the Ministry of Culture to cover damages[33].

5.7 Impact on water quality

Leaks of oil used for heating in flooded houses caused local pollutions[34]. But no major industrial pollution was reported during the event[35]. The flood transported large of wastes that had to be cleared after the event[36]. The Loire-Bretagne and Seine-Normandie Water Agencies launched studies to better evaluate the consequences of the flood on water quality.

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27 https://www.pressreader.com/france/la-r%C3%A9publique-du-centre-orleans/20160611/281547995166667
28 http://www.lesechos.fr/10/06/2016/LesEchos/22210-051-ECH_inondations---pour-valls----quelque-chose-n-a-pas-fonctionne---sur-l-a10.htm
29 http://www.lefigaro.fr/culture/2016/06/02/03004-20160602ARTFIG00298-crue-de-la-seine-le-louvre-met-a-l-abri-ses-oeuvres.php
30 http://www.liberation.fr/france/2016/06/03/transports-agriculture-electricite-tourisme-le-point-sur-les-crues_1457089
31 http://www.leparisien.fr/paris-75/paris-75005/paris-la-crue-de-la-seine-fait-perdre-10-meur-aux-bateaux-touristiques-06-06-2016-5861545.php
32 http://www.sudouest.fr/2016/06/04/inondations-les-images-impressionnantes-du-chateau-de-chambord-cerne-par-les-eaux-2388522-4971.php
33 http://www.culturecommunication.gouv.fr/Presse/Communiques-de-presse/Aide-exceptionnelle-de-8-millions-d-euros-pour-les-monuments-historiques-sinistres-n-appartenant-pas-a-l-Etat
34 http://www.leparisien.fr/espace-premium/seine-et-marne-77/apres-les-inondations-une-petite-maree-noire-13-06-2016-5877573.php
35 http://www.humanite.fr/inondations-pas-de-pollution-des-sites-industriels-classes-en-ile-de-france-610240
36 http://www.leparisien.fr/societe/essonne-apres-les-inondations-la-pollution-07-06-2016-5862663.php

5.8 Impact on dam management in the Seine basin

At the beginning of the event, the four dams were about 90% full and had an available storage volume of about 80 Mm^3. A volume of 40 Mm^3 was stored during the flood event, but the impacts on the water levels in Paris were limited because of the propagation time between the reservoirs and the Paris area. The zones which most contributed to the flood in Paris (typically the Loing river and small tributaries of the Seine in Île-de-France) were also out of the control of these four dams. Modelling tests show that dam management reduced the peak level of 5 cm in Paris, but had a larger impact of reducing the level by about 25 cm during the recession (EPTB Seine Grands Lacs, 2016).

5.9 Estimated cost of damages

The information provided here is mostly based on the work done by the "*Caisse centrale de réassurance*" (CCR, 2016). A first estimation of insured damages linked to the flood was made just after the flood, based on field observation and modelling. The cost of damages was first estimated between 800 million and 1.2 billion euros, but the actual estimate is closer to the higher bound[37,38]. The last estimates made March 2017 by insurance companies[39] indicate a total cost of 1.3 billion euros and 172,000 people having declared damages. The Seine-et-Marne, Loiret and Essonne are the most impacted departments, totalling 45% of damages. The damages are shared between households (800 M€), the agricultural sector (200 M€) and private companies (300 M€). This is the most expensive event since the "Cat Nat" system was implemented in France in 1982. This system is based on the fact that in case of a natural disaster with damages exceeding a certain threshold, the State will provide help to cover the insured damages, based on national funds[40]. The cities declared by the Ministère de l'Intérieur (Home Office) under the natural disaster status are covered by this system. But an exceptional emergency fund was created by the State in the case of this event to face to large amount of damages[41,42].

5.10 Post-event consequences

The damages caused by the event have long-term consequences. First, many households and infrastructures were impacted and many initiatives were undertaken locally to help getting back to normal conditions. This includes direct and immediate help to people whose houses were severely impacted[43,44,45], financial helps to riverine people from associations[46,47] or to impacted companies from municipalities[48]. Exceptional helps were also provided to the rural cities[49]

[37] http://www.argusdelassurance.com/institutions/inondations-427-nouvelles-communes-reconnues-en-etat-de-catastrophe-naturelle.109845#xtor=RSS-3

[38] http://www.lesechos.fr/30/06/2016/lesechos.fr/0211085057044_inondations---1-2-milliard-d-euros-pour-les-assureurs.htm

[39] http://www.ffa-assurance.fr/file/1206/download?token=tXX_-2jA

[40] http://www.latribune.fr/entreprises-finance/banques-finance/assurance/inondations-l-ocde-defend-le-modele-francais-d-assurance-576903.html

[41] http://www.lemonde.fr/economie/article/2016/06/07/inondations-l-etat-annonce-les-assureurs-assurent_4940667_3234.html

[42] http://www.latribune.fr/economie/france/inondations-le-gouvernement-veut-aller-vite-sur-les-indemnisations-576796.html

[43] http://www.leparisien.fr/villeneuve-saint-georges-94190/villeneuve-st-georges-les-derniers-naufrages-des-inondations-plient-bagage-23-06-2016-5907997.php

[44] http://www.liberation.fr/france/2016/06/23/inondations-le-pire-c-est-le-jour-d-apres_1461595

[45] http://www.lanouvellerepublique.fr/Loir-et-Cher/Actualite/Politique/n/Contenus/Articles/2016/06/17/Inondations-la-Ville-debloque-450.000-2753432

Reparation or maintenance works were also undertaken on levees or bridges, e.g. along the Loire[50], or to clear rivers[51] and collect wastes deposited by rivers[52]. Decisions were also taken for limiting vulnerability, e.g. by financing private riverine to settle out of the flood plain (e.g. in Beauvais along the Thérain River [53]) or buying houses too close to the river (e.g. Saint-Cyr-en-Val, along the Morchêne River, inundated on June 7[54]) to destroy and thus avoid further problems[55].

The events also strengthened the need for more information to the general public on floods and preparedness[56] and how to behave in flood conditions [57], and the duties of private owners living along rivers to maintain river banks in a good status[58].

It also re-opened debates on what would be done in case of a major flood event in Paris, like in 1910. In Paris, around 800 000 people may be directly impacted by the flood event[59]. The Prime Minister asked for detailed analyses on what could be done in terms of infrastructure and land management on the Seine basin (Feuillette et al., 2016)[60]. Other reflections started locally to find ways to limit risks and improve crisis management[61,62].

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46 http://www.lanouvellerepublique.fr/Indre-et-Loire/Communes/La%20Croix-en-Touraine/n/Contenus/Articles/2016/12/12/Inner-Wheel-verse-1.900-aux-sinistrees-des-inondations-2934652

47 http://www.larep.fr/fay-aux-loges/social/vie-associative/2016/11/28/le-lions-club-exprime-sa-solidarite-avec-les-sinistres-des-inondations_12185495.html

48 http://www.larep.fr/montargis/economie/emploi/2016/11/28/aider-les-entreprises-apres-les-inondations_12184994.html

49 http://www.lesechos.fr/29/06/2016/LesEchos/22223-359-ECH_inondations---2-milliards-d-aides-pour-les-communes-rurales.htm

50 http://www.lanouvellerepublique.fr/Indre-et-Loire/Communes/La%20Chapelle-sur-Loire/n/Contenus/Articles/2016/11/07/La-levee-renforcee-pour-lutter-contre-les-inondations-2894002

51 http://www.larep.fr/montargis/travaux-urbanisme/2016/12/13/de-nombreux-chantiers-le-long-des-cours-d-eau-apres-les-inondations-dans-le-montargois_12206927.html?f

52 http://www.leparisien.fr/espace-premium/val-de-marne-94/inondations-600-t-de-detritus-deja-collectees-23-06-2016-5906619.php

53 http://www.leparisien.fr/beauvais-60000/beauvais-rachete-une-maison-508-000-eur-pour-eviter-de-nouvelles-inondations-04-12-2016-6412191.php

54 http://www.larep.fr/saint-cyr-en-val/faits-divers/2016/06/02/saint-cyr-en-val-le-niveau-deau-baisse-mais-des-centaines-dhabitants-ne-peuvent-pas-rentrer-chez-eux_11940959.html

55 http://www.larep.fr/orleans/2016/12/02/suite-aux-inondations-la-ville-rachete-deux-maisons_12192280.html

56 http://www.lanouvellerepublique.fr/Indre-et-Loire/Communes/Saint-Pierre-des-Corps/n/Contenus/Articles/2016/06/23/La-Ville-preparee-aux-risques-d-inondation-2760260

57 http://www.leparisien.fr/espace-premium/hauts-de-seine-92/quand-il-y-a-eu-la-crue-j-ai-eu-peur-26-11-2016-6376566.php

58 http://www.lanouvellerepublique.fr/Loir-et-Cher/Communes/Salbris/n/Contenus/Articles/2016/12/17/Inondations-prevoir-et-agir-ensemble-2940477

59 http://www.leparisien.fr/paris-75/83-300-habitants-du-xve-seraient-touches-par-une-crue-centennale-04-12-2016-6412278.php

60 http://www.lesechos.fr/01/06/2016/lesechos.fr/021987214248_inondations---la-question-de-la-regulation-de-la-seine-ressurgit.htm

61 http://www.lanouvellerepublique.fr/Indre-et-Loire/Actualite/24-Heures/n/Contenus/Articles/2016/06/24/Quelle-lecon-tirer-des-inondations-2761157

62 http://www.lefigaro.fr/actualite-france/2016/06/06/01016-20160606ARTFIG00320-inondations-ce-qu-il-faudrait-changer.php

Last, there were feedbacks about the anticipation and the management of the event[63,64], which may have consequences on the future crisis management or on how forecasts are made and communicated. The difficulty to better anticipate the flood given the extreme conditions was noticed by some managers[65]. But some mayors found that the alert was too late, e.g. in Nemours[66], and people were questioning the rumor that some parts of the basin may have been over-flooded to protect Paris[67]. The role of urbanization was also questioned[68].

63 http://www.leparisien.fr/longjumeau-91160/inondations-a-longjumeau-une-maire-au-coeur-de-la-crise-07-06-2016-5864003.php
64 http://www.la-croix.com/France/Inondations-quatre-questions-gestion-crues-2016-06-05-1200766477
65 http://www.leparisien.fr/espace-premium/essonne-91/pouvait-on-prevoir-de-telles-inondations-07-06-2016-5862061.php
66 http://www.la-croix.com/Journal/Notre-coeur-ville-inonde-2016-12-01-1100807411
67 http://www.leparisien.fr/espace-premium/essonne-91/cinq-mois-apres-les-inondations-la-commune-toujours-sous-le-choc-19-11-2016-6346893.php
68 http://www.lefigaro.fr/sciences/2016/05/31/01008-20160531ARTFIG00327-precipitations-records-sur-une-grande-partie-de-la-france.php

6 Forecasts and watches

Here we provide a qualitative analysis of precipitation and streamflow forecasts issued in real-time by the public services (Météo-France and SCHAPI/SPC, respectively) for the 28 May-3 June 2016 event. We have put together some information on the evolution of watches issued. The information collected is summarized below. Other more detailed analyses were carried out by these services or are under way.

6.1 Weather watches

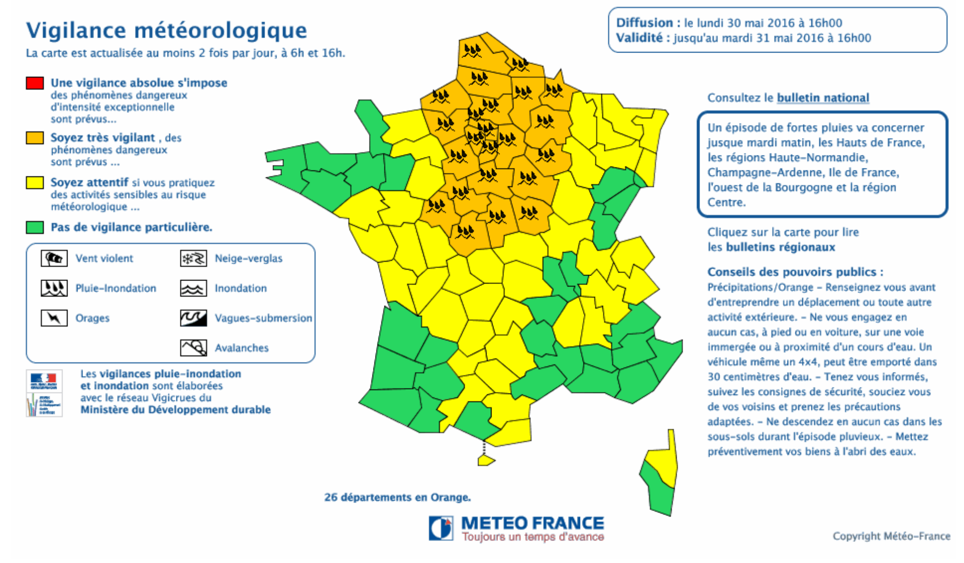
At the national scale, weather watches are provided by Météo-France through a "meteorological vigilance map" (http://vigilance.meteofrance.com/)[69]. Basically, this map defines the potential meteorological danger for the next 24 hours. It has four color-coded levels:

- **Green**: no particular vigilance is required;
- **Yellow**: be careful if you engage in activities that are sensitive to meteorological risk or vulnerable to flooding; forecasts call for phenomena that are usual in the region but may be dangerous occasionally and locally; keep informed of any developments in the situation;
- **Orange**: be extremely vigilant; forecasts call for dangerous phenomena; keep informed of any developments in the situation and follow the safety guidelines issued by the authorities;
- **Red**: utmost vigilance is required; forecasts call for exceptionally intense dangerous phenomena; keep regularly informed of any developments in the situation and make sure you follow the safety guidelines issued by the authorities.

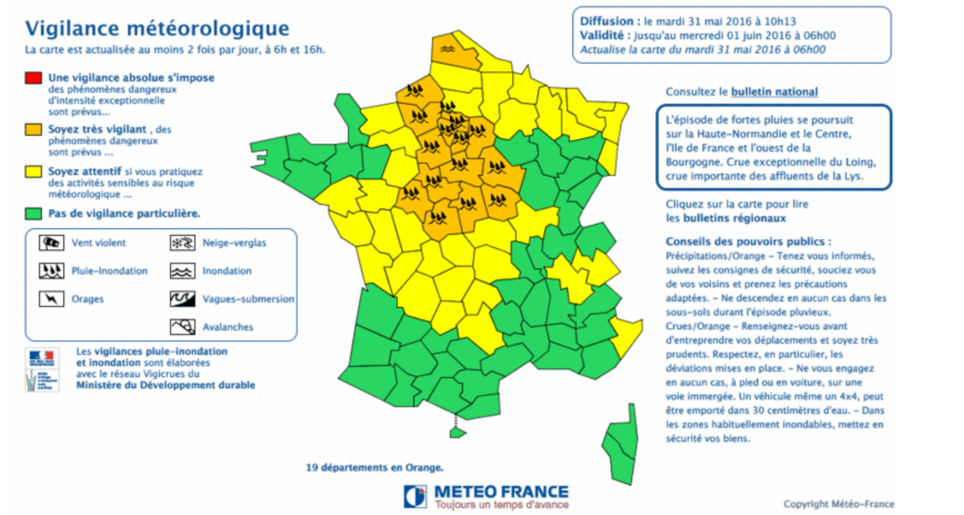
The watch map is coloured by French "departments" (considered the most suitable administrative units of the national territory for planning and crisis management) and updated at least twice a day (around 6am and 4pm). Bulletins with risk information and specific safety guidelines are produced by regional centres if orange or red watches are issued in any of the 96 French metropolitan departments.

According to the regional flood forecasting centres in charge of the areas affected by the May-June floods, weather forecasts of 28 May had already announced an important rain event for the 29-30 May, although its location and total rain remained very uncertain. It must be noted that flood forecasting centres receive quantitative weather forecasts as min/max intervals of daily accumulations over pre-established weather watch areas for days D, D+1 and D+2. The sequence of maps provided in Figure 18 to Figure 21 shows orange weather watches for strong rainfall events for several departments in the centre and north France on 30 May. The map of 31 May 2016, issued at 14h07, indicated red watches for the Central area (Loing river and Loiret department). These red watches persisted until 2 June. Note that the national watch map of Météo-France is the result of a multi-criteria analysis based on various risks related to meteorological phenomena, which include rainfall, temperature, wind, snow, ice, thunderstorms, avalanches, inundations and sea submersion [70]. The red colours of the Météo-France watch maps are mostly related to flooding situations.

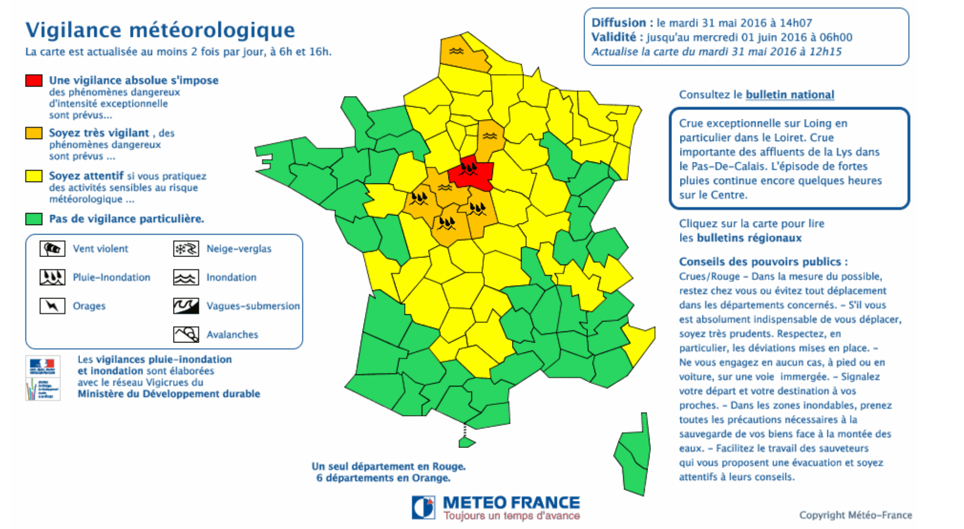
[69] See, for instance, Boretti, C., 2012, available at: http://www.wmo.int/pages/prog/drr/events/2016-EAG-MHEWS/documents/CH4-France.pdf
[70] http://vigilance.meteofrance.com/html/vigilance/guideVigilance/vigilance.html



30 May 2016 @ 16.00

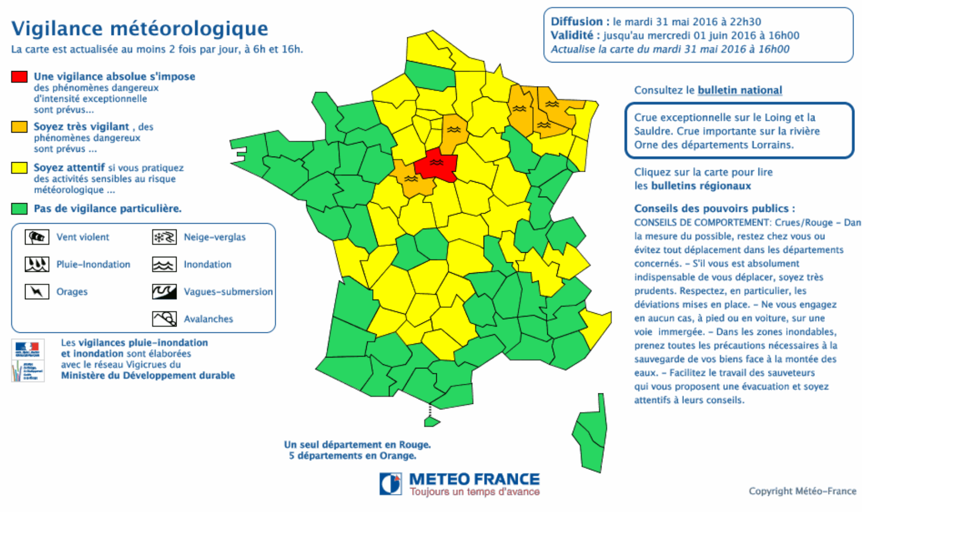


31 May 2016 @ 10.13

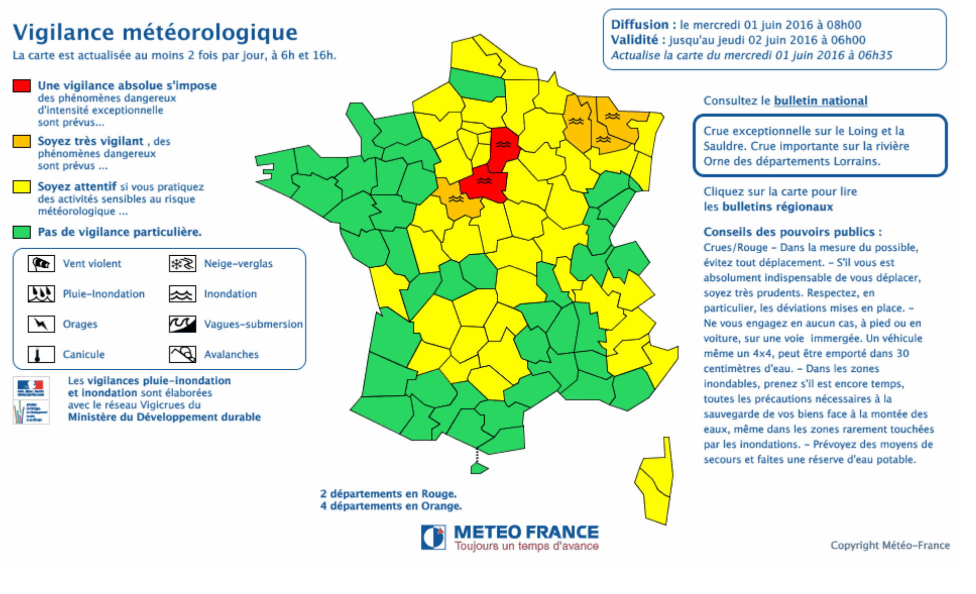


31 May 2016 @ 14.07

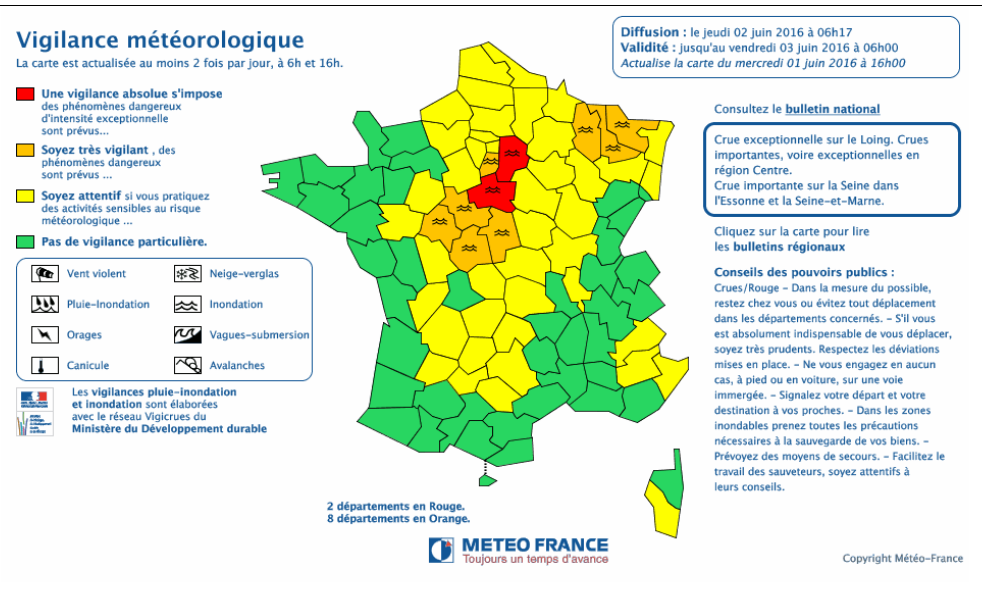
Figure 18: Examples of weather watch maps issued in France during the May-June flood event (source: Météo-France website at the time of the event) (1 of 4)



31 May 2016 @ 22.30

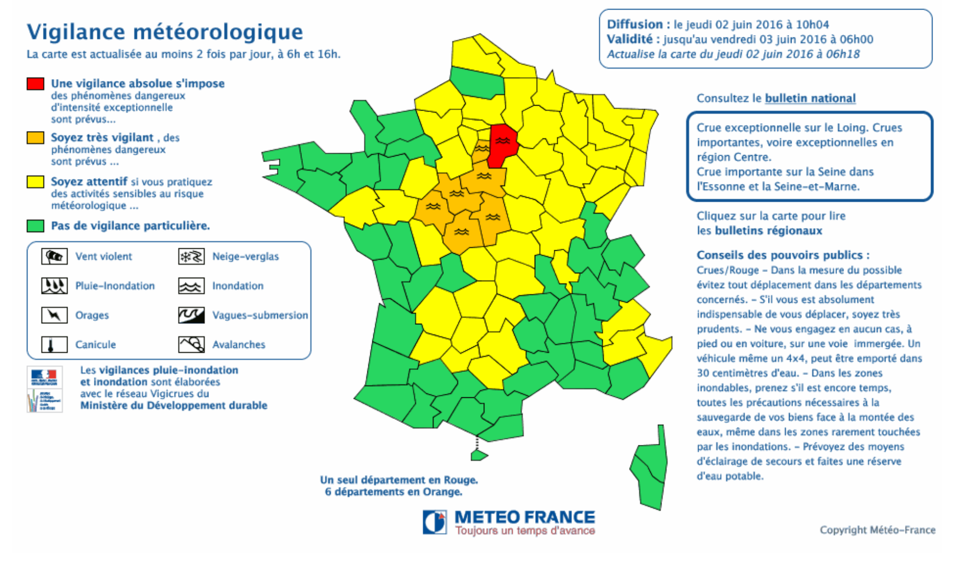


01 June 2016 @ 08.00

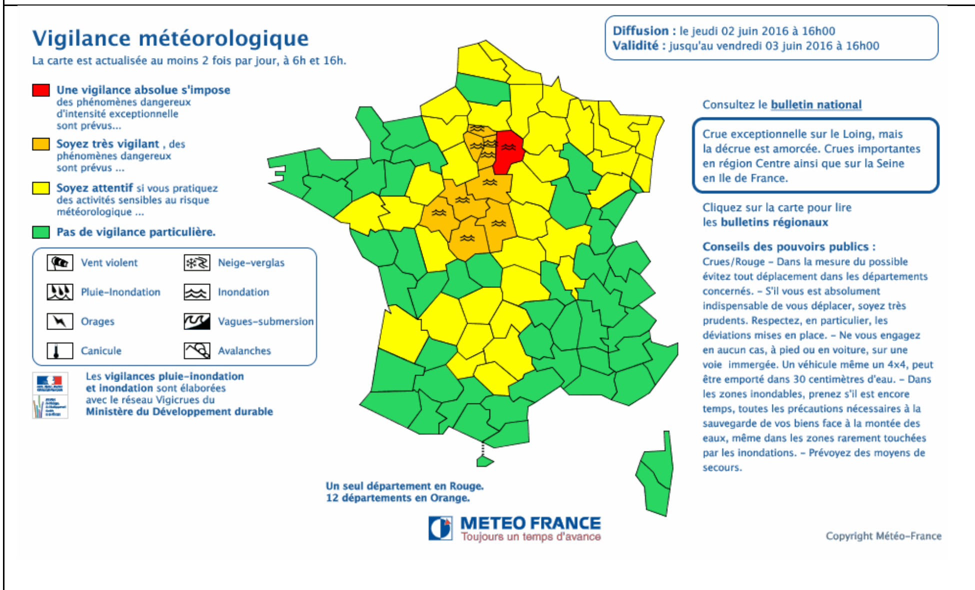


02 June 2016 @ 06.17

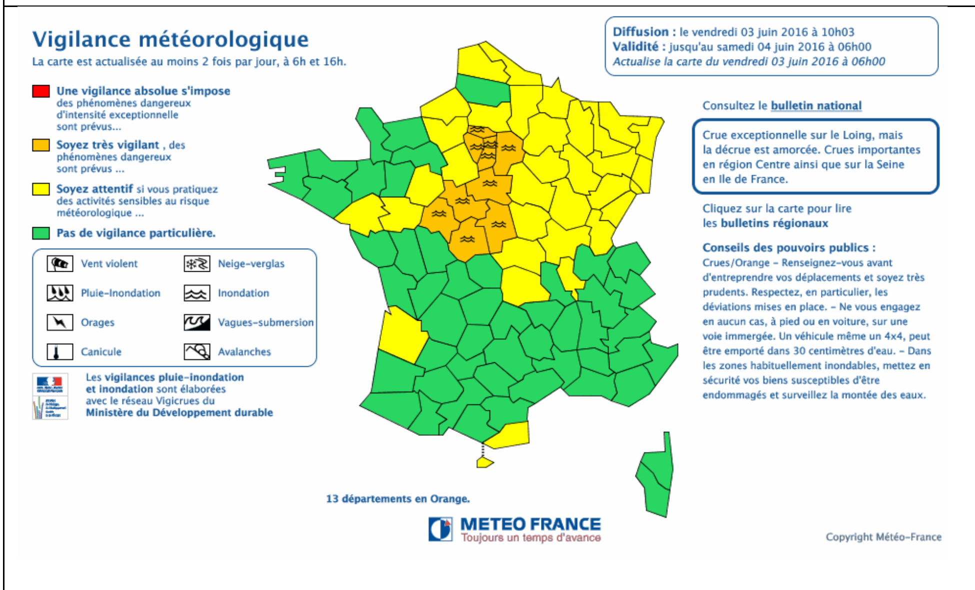
Figure 19: Examples of weather warning maps issued in France during the May-June flood event (source: Météo-France website at the time of the event) (2 of 4)



02 June 2016 @ 10.04

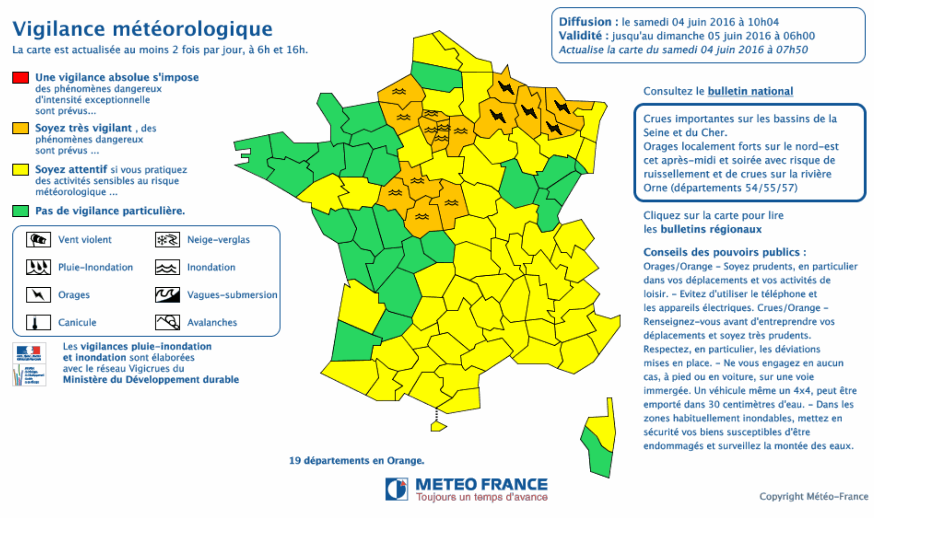


02 June 2016 @ 16.00

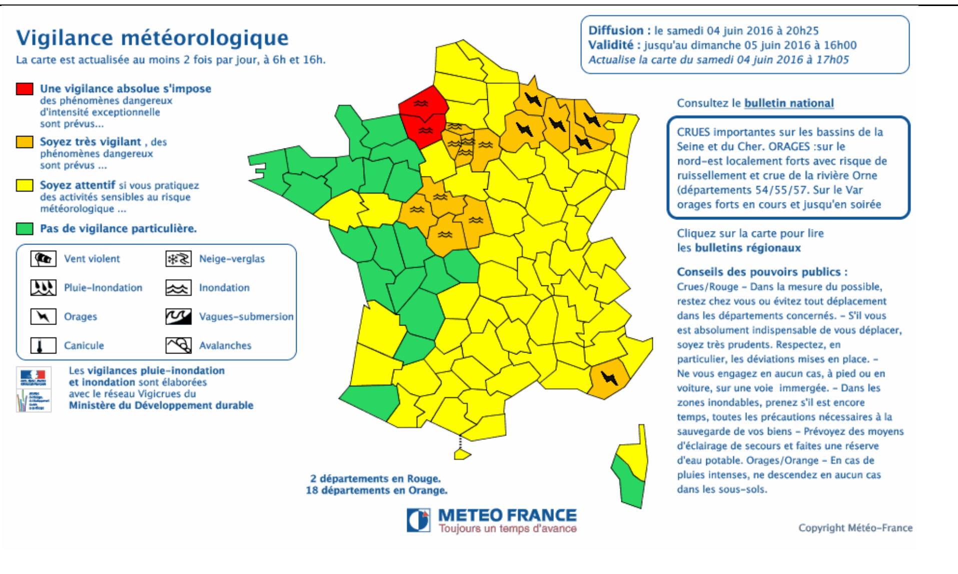


03 June 2016 @ 10.03

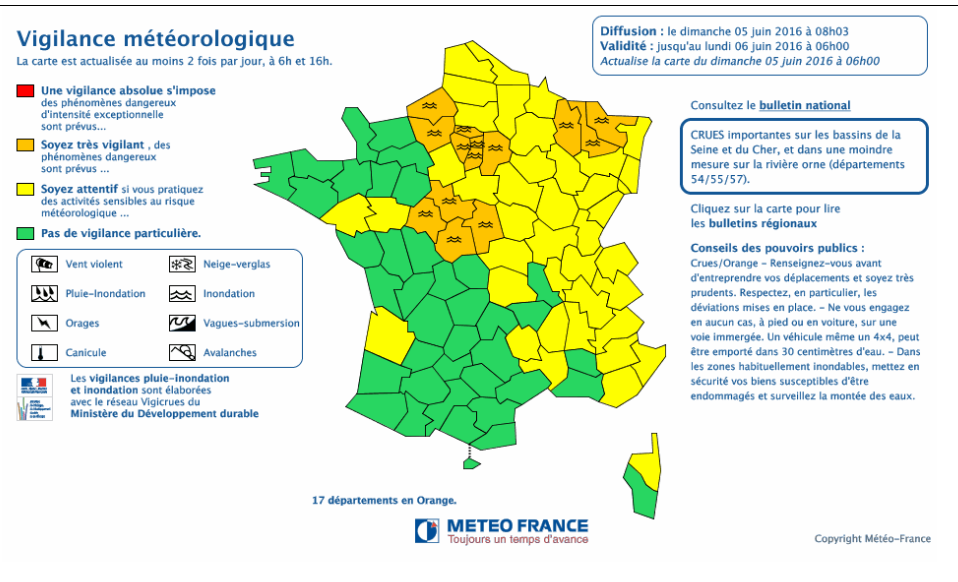
Figure 20: Examples of weather watch maps issued in France during the May-June flood event (source: Météo-France website at the time of the event) (3 of 4)



04 June 2016 @ 10.04



04 June 2016 @ 20.25



05 June 2016 @ 08.03

Figure 21: Examples of weather watch maps issued in France during the May-June flood event (source: Météo-France website at the time of the event) (4 of 4)

6.2 Flood watches

At the national scale, flood watches are provided to the public through a "vigilance map" which is available at https://www.vigicrues.gouv.fr/. Basically (see reference for more details[71]),

- Each river included in the map is divided into sections. Each section is given a colour: green, yellow, orange or red according to the flood watch level needed to meet flood dangers liable to arise within the next 24 hours (see below).
- It is possible to zoom in any concerned area and, by clicking on a hydrological station, to obtain a graph or table indicating the latest water levels, as well as information on the station. Currently, only the real-time situation (water levels or discharges, depending on the gauging station) is displayed in the plots. The display of hydrological forecasts, with 80% confidence intervals, is planned to be available in the near future nationally, but some forecasting centers (like the SPC LCI) already produce forecasts on regional web sites.
- The "flood vigilance map" is accompanied by national and local information bulletins. The map and the bulletins are usually updated twice a day at 10am and 16pm (French time), but in case of a flood event they can be updated more frequently and at any given moment.

The French flood watch maps use a four-color scale for a 24-hour forecast target:

- **Green**: no particular vigilance required.
- **Yellow**: risk of high or rapidly rising water not involving significant damage but requiring particular vigilance in the case of seasonal and/or outdoor activities;
- **Orange**: risk of flood with considerable overflow liable to affect significantly daily life and security of people and property;
- **Red**: major risk of flood directly and extensively threatening people and property;

The thresholds defining these levels reflect the local risk of flooding and are not publicly available. But they can be compared with historical floods through watch rules reports[72]

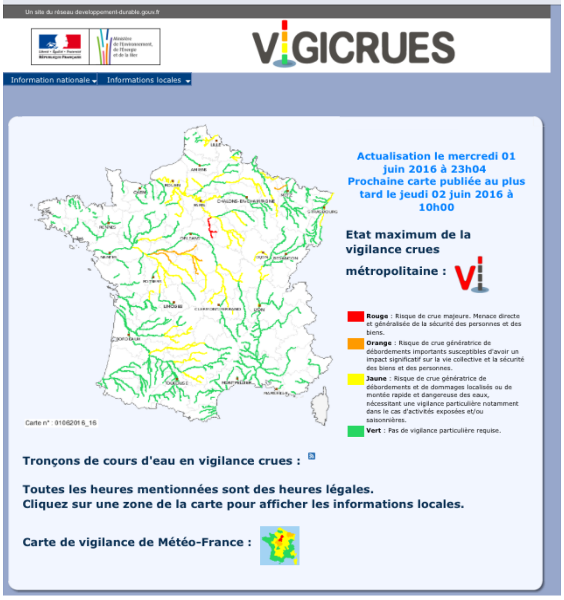
Examples of flood watch maps issued during the May-June event are shown in Figure 22 to Figure 25. They include detailed views of the affected areas of both the Seine and the Loire rivers and an overview of the watch maps issued on the evening of 4 June 2016, showing the propagation of the flood event downstream the Seine river basin to Normandy. From these maps and based on other more detailed information collected for this report, we can summarize the following:

- In the Middle Seine-Yonne-Loing regional forecasting centre:
    - the first forecast of the exceedance of the yellow watch level was displayed on 29 May for the Serein and the Upper Loing River, both upstream catchments of the Seine river basin;
    - the first forecast of the exceedance of the orange watch level was displayed on the evening of 30 May for the Loing River;

[71] See here for more information (in English) : http://www.developpement-durable.gouv.fr/IMG/pdf/09003-3_DGPR_Flood_Vigilance_4p_Mars-2015_DEF_Light.pdf
[72] http://www.vigicrues.gouv.fr/ftp/RIC/RIC_SPC_LCI_2015.pdf for SPC LCI and http://www.vigicrues.gouv.fr/ftp/RIC/RIC_SPC_SMYL_2013.pdf for SPC SMYL

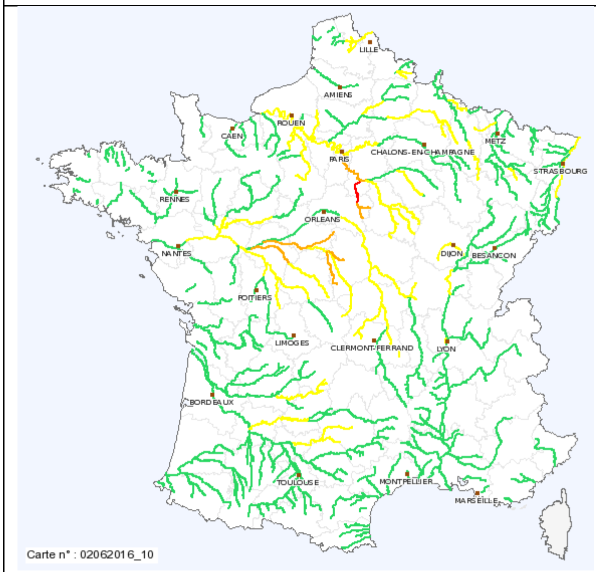
- the first forecast of the exceedance of the red watch level was displayed at about midday of 31 May for the Upper Loing River and on the first hours of 1 June for the Lower Loing. These river reaches remained in red watch level up to 2 June.
- the Loing River remained on orange watch level up to 3 June (upper reaches) and 6 June (lower reaches), and on yellow watch level up to 4 June (upper reaches) and 8 June (lower reaches);
- in the Middle Seine River, yellow and orange watch levels were issued, respectively, from 30 May to 9 June, and from 2 to 7 June;
- the Seine River in Paris was in yellow watch from 30 May to 11 June and in orange watch from 2 to 6 June;
- the Lower Seine River was in yellow watch from 31 May to 9 June and in orange watch from 4 to 5 June.

- <u>In the Loire-Cher-Indre regional forecasting centre</u>:
    - the exceedance of the yellow watch level was forecast in upstream sub-catchments already on 29 May, with an anticipation of about 2.5 days to the actual exceedance. Over the entire region, the yellow watch level was displayed until 10 June;
    - the exceedance of the orange watch was displayed on 31 May in the Cher River, with an anticipation of about 12-14 hours. Orange watch levels lasted until 7 June;
    - up to 13 river reaches were simultaneously displaying the yellow or orange watch levels; 5 river reaches displayed orange levels at the same time from 2 June to 5 June;
    - no red watch level was issued. This is partly explained by the fact that no red threshold is currently defined on some stations, which is the case on the Sauldre basin.

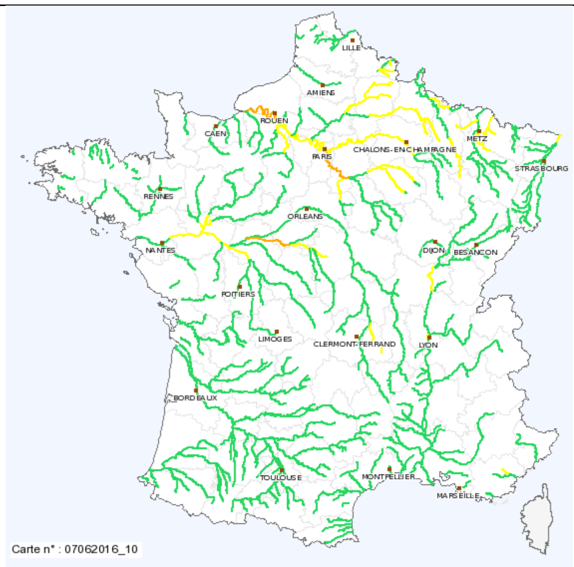


1 June 2016 @ 23.04

2 June 2016 @ 23.25

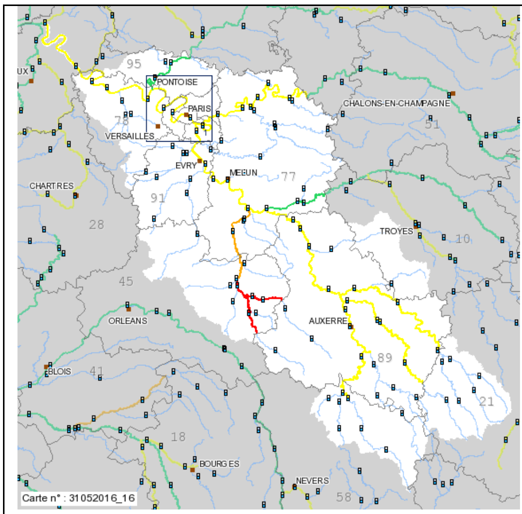


2 June 2016_10

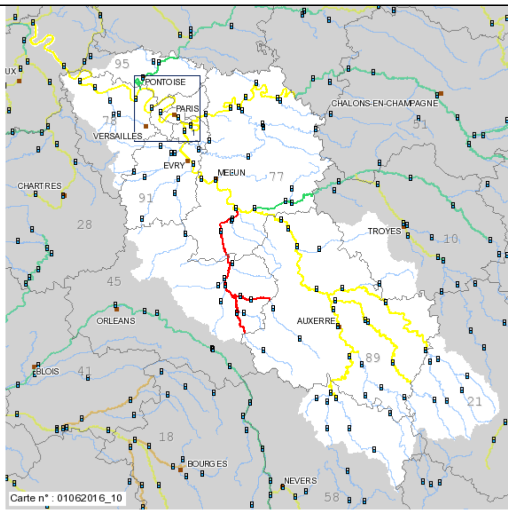


7 June 2016_10

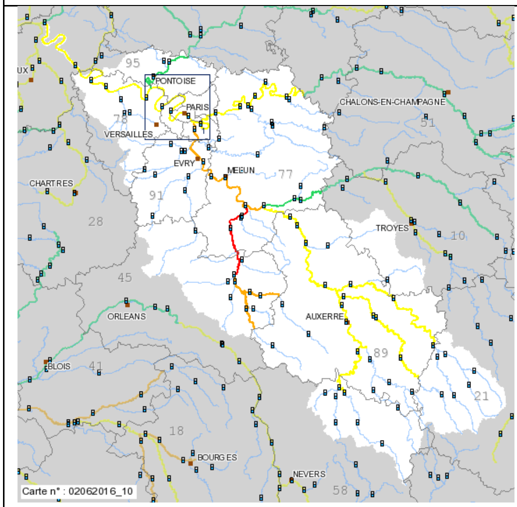
Figure 22: Examples of flood watch maps issued in France during the May-June flood event (source: www.vigicrues.gouv.fr at the time of the event)



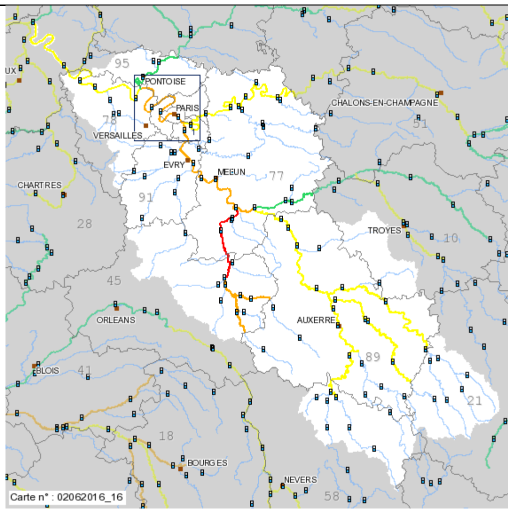
31 May 2016_16



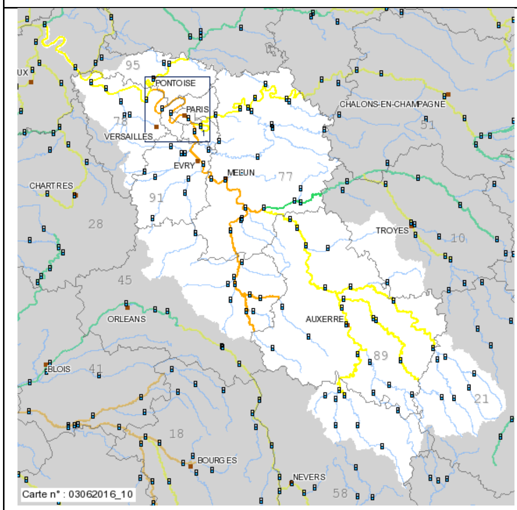
1 June 2016_10



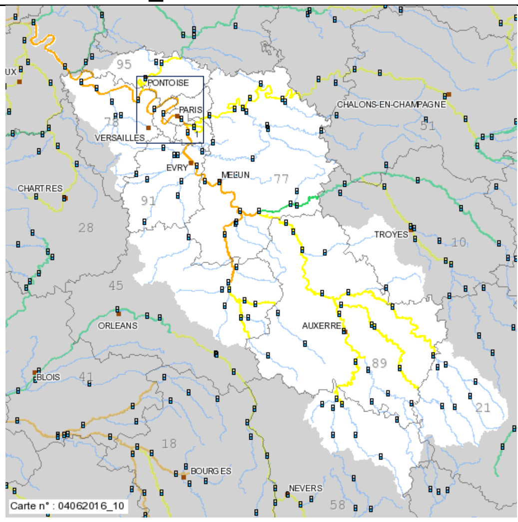
2 June 2016_10



2 June 2016_16

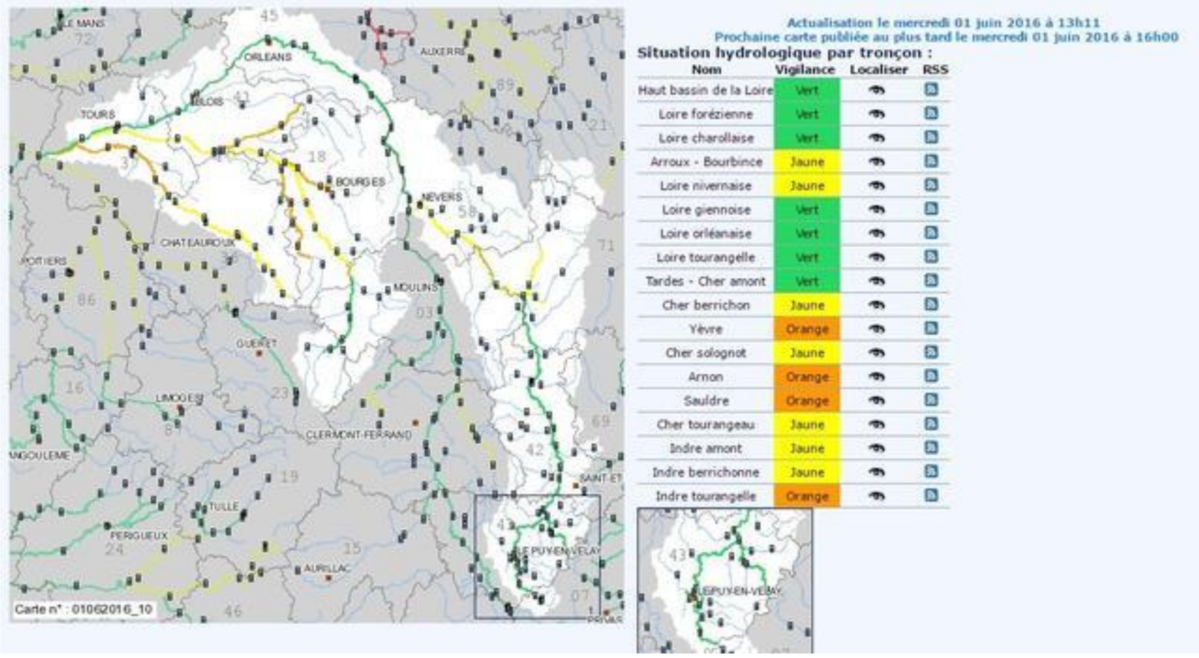


3 June 2016_10

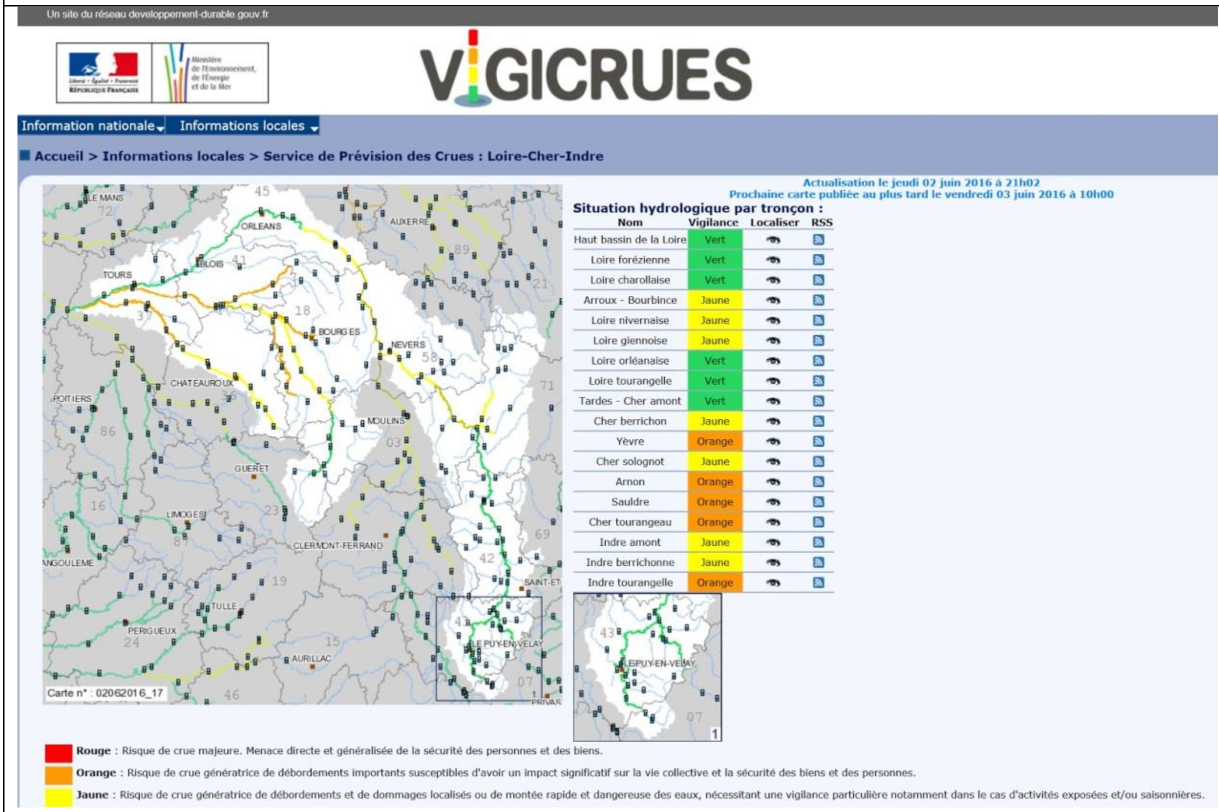


4 June 2016_10

Figure 23: Zoom for the Seine river basin: flood watch maps issued in France during the May-June flood event (source: www.vigicrues.gouv.fr at the time of the event)



1 June 2016 @13:11



2 June 2016 @21h02

Figure 24: Zoom for the Loire river basin: flood watch maps issued in France during the June flood event (source: www.vigicrues.gouv.fr at the time of the event)

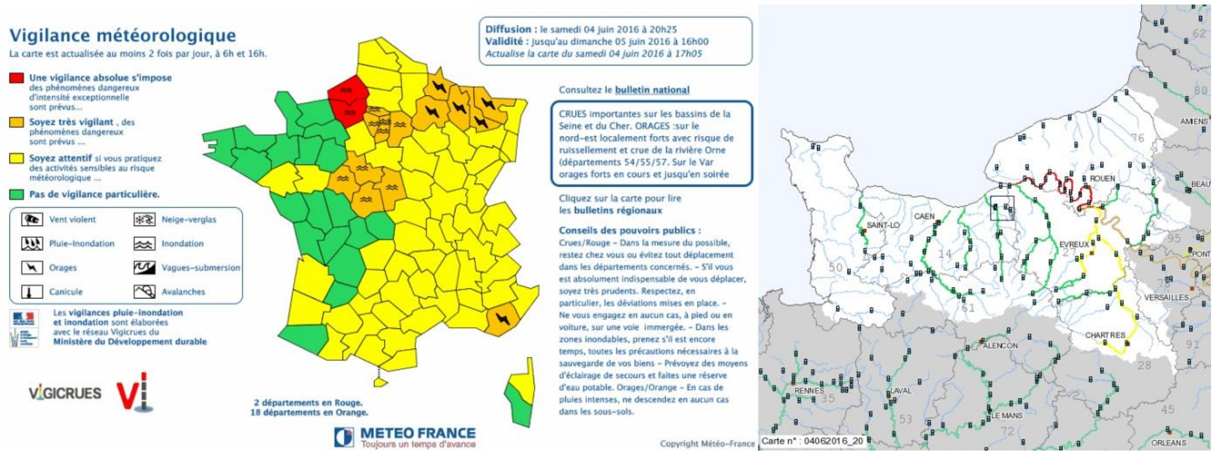


Figure 25: Weather warning map (left) and flood watch map (right) issued in France on the evening of 4 June 2016 showing the propagation of the flood event downstream the Seine river basin to Normandy (source: Météo-France and Vigicrues websites at the time of the event)

6.3 EFAS flood notifications

The European Flood Awareness System (EFAS; https://www.efas.eu/) operationally monitors and forecast floods across Europe. Forecasts are computed at the European Centre for Medium-Range Weather Forecasts (ECMWF, UK) and then disseminated on a daily basis by three centres (Rijkwaterstaat for France). Before and during the event, the notifications listed in Table 1 were sent to SCHAPI. On May 27, significant events were forecasted on the Cher, Seine and Yonne basins, with peaks expected between the 1st and 3rd of June. There was about a 60% probability of exceeding the 5-year return period and more than 30% of exceeding 20-year return period. On May 28 and 29, notifications were sent for expected flood on several departments (Essonne, Indre, Loiret) in the coming days. On May 30, warnings were sent for the downstream part of the Loire, with expected peak on June 5.

Forecast date	Region	Predicted start of the event	Earliest predicted peak	Comments
2016-05-27 12 UTC	Loire		Sunday 29th of May 2016 18:00	Percent of affected area susceptible to landslides: very high 0%, high 30%, moderate 22%
	Cher (Loire basin)	Tuesday 31st of May 2016	Friday 3rd of June 2016	Probability to exceed a 5-year return period magnitude: 63% Probability to exceed a 20-year return period magnitude: 45%
	Seine (Risle,Seine basin)	Tuesday 31st of May 2016	Thursday 2nd of June 2016	Probability to exceed a 5-year return period magnitude: 63% Probability to exceed a 20-year return period magnitude: 31%
	Yonne (Risle,Seine basin)	Monday 30th of May 2016	Wednesday 1st of June 2016	Probability to exceed a 5-year return period magnitude: 55% Probability to exceed a 20-year return period magnitude: 35%
2016-05-28 12 UTC	Essonne Region, Indre Region, Loiret Region		Sunday 29th of May 2016 18:00	Percent of affected area susceptible to landslides: very high 0%, high 1%, moderate 3%
2016-05-29 12 UTC	Aisne Region, Indre Region, Marne Region, Puy-de-Dome Region		Tuesday 31st of May 2016 00:00	Percent of affected area susceptible to landslides: very high 0%, high 5%, moderate 10%
2016-05-30 00 UTC	Loire, below Maine (Loire basin)	Friday 3rd of June 2016	Sunday 5th of June 2016	Probability to exceed a 5-year return period magnitude: 45% Probability to exceed a 20-year return period magnitude: 0% This EFAS Flood Notification is only informal due to the large forecast uncertainty.
2016-05-30 12 UTC	Saone-et-Loire Region		Wednesday 1st of June 2016 00:00	Percent of affected area susceptible to landslides: very high 0%, high 3%, moderate 13%
	Eure-et-Loir Region		Tuesday 31st of May 2016 12:00	Percent of affected area susceptible to landslides: very high 0%, high 1%, moderate 1%
	Loire, below Maine (Loire basin)	Friday 3rd of June 2016	Sunday 5th of June 2016	Probability to exceed a 5-year return period magnitude: 96% Probability to exceed a 20-year return period magnitude: 49%

Table 1 : List of EFAS information messages sent for the study area between the 27 and 30 May 2016

Ten-day-ahead forecasts made at Paris station on 26, 28 and 30 of May are illustrated in Figure 26. They show that part of the probabilistic scenarios quite well anticipated the peak for Friday 3rd and that an important flood event was coming, though the amplitude of the peak was variable between forecasts (the actual peak was between 1700 and 1800 m^3/s).

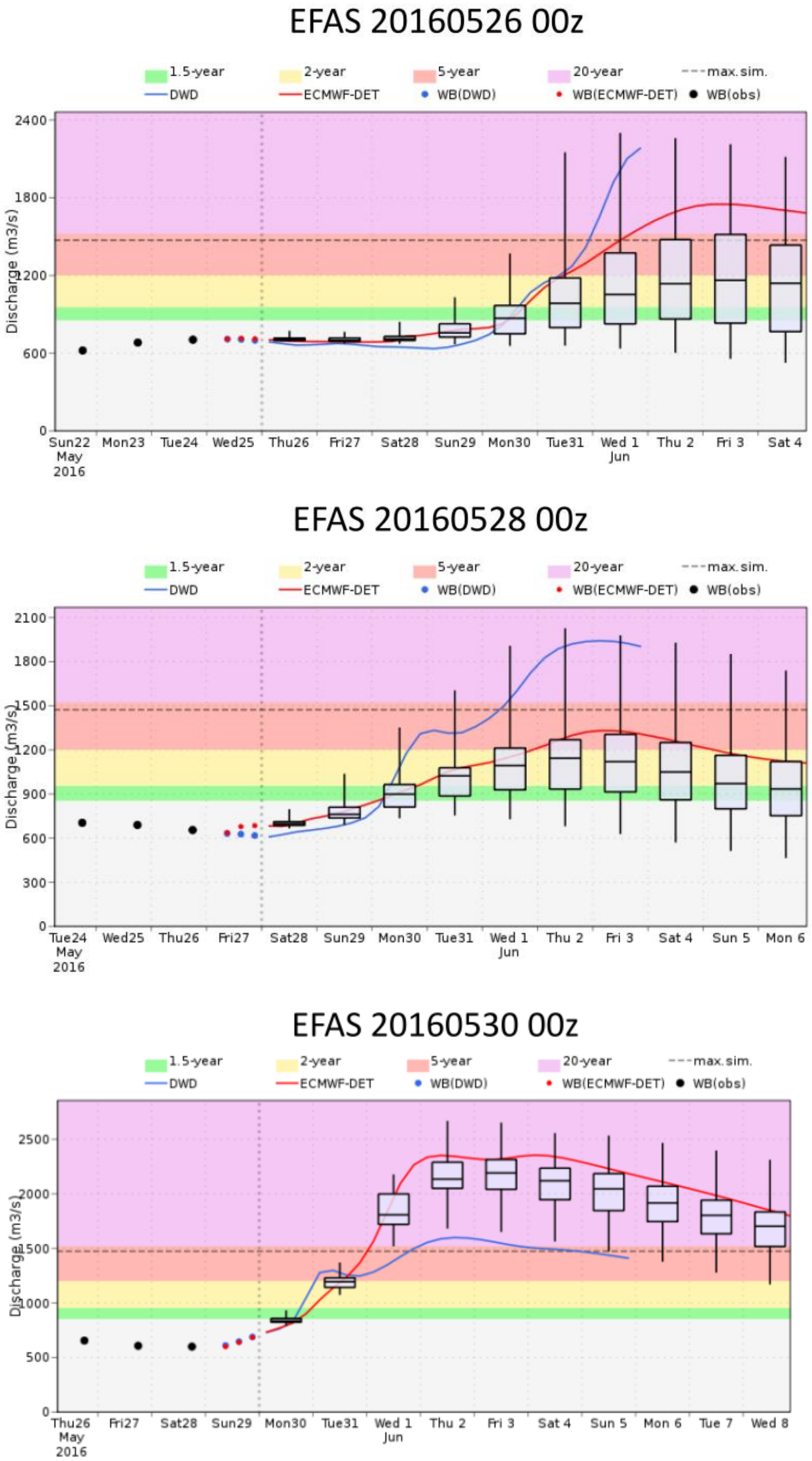


Figure 26 : EFAS outputs for Paris station (Source : ECMWF)

The post-event analysis made by ECMWF[73] states that:

- *"The EFAS forecast system indicated the possibility of river discharge levels with a return period of more than 20 years as early as 25 May.*
- *By 26 May, a flood notification for a 1-in-20 year event was issued by EFAS for the Loing River (a tributary of the Seine).*
- *On 28 May, the warning was extended to the Seine in Paris.*
- *As the event drew nearer, the magnitude of the predicted river discharge fluctuated between 30 May and 31 May depending on the expected rainfall for the event, but the timing was very stable, with the peak flow centred on Friday 3 June.*
- *The 2 June ensemble forecast generally slightly overpredicted discharge levels for the following few days. This was true for all ensemble members, indicating that the forecasts were not diverse enough to capture the observed intensity of the event. Although the ensemble spread cannot be assessed on the basis of a single case, we expect the ensemble to be over-confident as the EFAS system does not yet represent initial and model uncertainties in the hydrological model."*

6.4 Feedbacks from operational services on EFAS forecasts

The EFAS flood notification received on 27th May by SCHAPI was sent to the regional SMYL and LCI forecasting services. At that time, it indicated that a significant event could happen, though it was very unusual at that season of the year. Retrospectively, SCHAPI judges that the event had been well anticipated by EFAS, especially on the Loing basin. This indicates that this product could have an interesting added value in the case of this event to improve preparedness. When getting closer to the event, the subsequent notifications and forecasts (see example in Figure 27) quite well corroborated other information available at SCHAPI, typically the ensemble forecasts made by the SIM hydrological model (SIM-PE) driven by ensemble meteorological model outputs like ECMWF, thus with similar lead times as EFAS. Therefore, the added value of the EFAS information was quite limited.

Currently, the EFAS information is not routinely used by forecasters. There are several reasons which explain this situation:

- Only a few forecasting services are already using other ensemble meteorological forecasts, this is not a generalized practice. So there is still some work to be done to widen the use and interpretation of ensemble products.
- The amount of flow data observations sent by SCHAPI to EFAS in real time for data assimilation is limited due to technical reasons. Consequently, though the relative severity of the event is often interesting in EFAS outputs, the actual magnitude/timing of flows can still be difficult to interpret due to biases compared to actual observations. The portal which will be dedicated to data exchange in SCHAPI (HydroPortail) will be available in 2018/2019, which should therefore improve the EFAS outputs.
- In terms of flood watch, the mandatory objective is 24h anticipation for flood forecasting services in France. Though longer lead times are expected by civil security in some cases (e.g.

[73] http://www.ecmwf.int/sites/default/files/elibrary/2016/16523-newsletter-no148-summer-2016.pdf

3 days in Paris), the efforts are currently focusing on improving the quality of forecasts for this 24h (or sometimes 48h) lead time.

Therefore the EFAS products have the potential to become more widely used tools among the French forecasting services in the future. The wider use of probabilistic forecasts among forecasting services in the coming years should also develop the technical skills to interpret these tools.

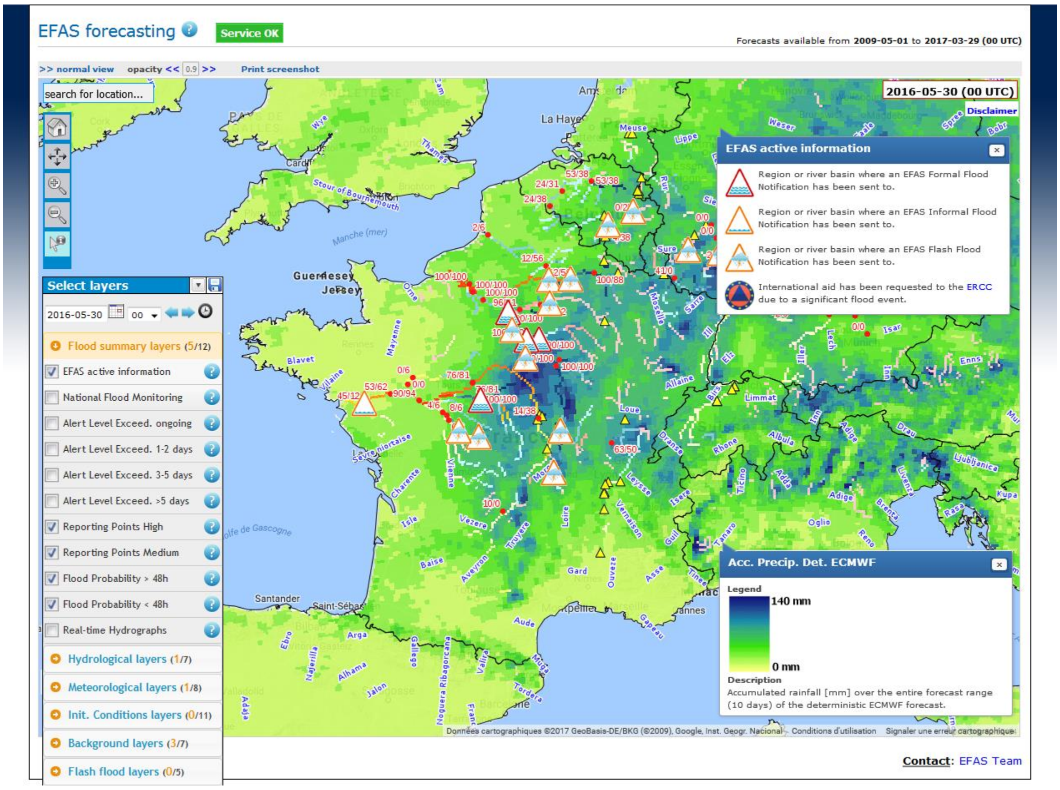


Figure 27 : Example of EFAS information available at SCHAPI on May 30 (source: SCHAPI)

7 Lessons learnt and studies needed

In general, from the hydrological point of view, the May-June 2016 floods in the Seine and Loire river basins in France presented the following main characteristics:

- Extreme total precipitations were the main driver of the floods. Precipitation over the flooded areas was characterized by a large spatial extent (precipitation was relatively homogeneous) and its long duration (multi-day precipitation). We can distinguish three phases in the rain events over the northern part of France: the first one from 28-29 May (with localized thunderstorms), the second with generalized strong precipitations from 30-31 June, and the last one with more limited rainfall events from 1-3 June. The event in May was reported to have been stronger in terms of rainfall totals and intensities.
- Soils were, in general, wet due to antecedent precipitation. The first six months of the year 2016 were all above the historic average (1981-2010 climatology) in the northern part of France, and the month of May 2016 was particularly rainy, with several record-breaking values of precipitation being registered at raingauge locations in the north of France.
- Severe floods occurred in two main river basins:
    - In the Seine river basin: the impacts were mostly on the middle reach of the Seine and its tributaries in Île-de-France.
    - In the Loire river basin: the Cher and its tributaries (e.g. Sauldre), as well as the Sologne region, were particularly impacted.
- The flood event was exceptional for the season in the Seine basin, where most large floods occur in winter.
- Overall, given the number of real-time flow gauging stations, real-time data acquisition worked well, although some gauging stations showed specific problems at some locations (e.g., in the Seine basin, at Paris-Austerlitz station), which brought challenges to data assimilation procedures adopted in real-time forecasting. In the Loire river basin, some concerns about the pre-established rating curves emerged at some locations, which were mainly attributed to the fact that, at this time of the year (which is normally a late period for spring floods), vegetation was already well developed over the floodplains, causing perturbations to the conversion of water depth into discharge (which is then assimilated in the hydrological models).

We remind the reader that this report aims to summarize information and data available after the flood event to better understand the causes of the floods and their consequences. However, it must be noted that it is still early to draw robust conclusions on several aspects of this severe event. In order to provide a complete post-event analysis, further investigation is needed on important components that usually contribute to an efficient short-term flood forecasting system. The Ministry of environment asked the national forecasting centre (SCHAPI) for detailed reports on this event, and a report was sent to the Prime Minister to better evaluate the measures still needed on the Seine basin to improve flood prevention. Flood prevention is currently an important topic in France: in January 2018, responsibility on flood protection and hydrosystems management will be transferred to intercommunalities (GEMAPI reform[74]). It is expected that actions towards the monitoring and management of flood protection structures such as levees and flood control dams will be enhanced.

First studies (DREAL Centre-Val-de-Loire, 2016; DRIEE Île-de-France, 2016) have been achieved to evaluate the performances of streamflow forecasts issued by the regional forecasting centres. Some more in-depth studies are still needed to clarify the ways of improvement and to further evaluate:

- the performance of the real-time weather and streamflow forecasts (including the performance of the hydrologic and hydraulics models running in real time at the regional forecasting centres): this could include the analysis of the forecasts for the location and time of the rainfall extremes, the spatial extent of the rain cells, the magnitude and timing of the peak flow at several river reaches and the model simulations of the runoff volumes, especially given the expected initial conditions of saturated soils and high water table levels;
- the uncertainties in the real-time forecasts and warnings, from the weather forecasts up to the local flood inundation estimations: this could include quantitative and qualitative uncertainties that were evaluated by the forecasters in real-time and the analysis of the potential and actual anticipation of the flooding;
- the flow of information from the weather centres up to the civil protection: this could include the communication of forecasts and associated uncertainties, as well as the use of human expertise in both the forecasting and the decision-making processes;
- the local flood damages, but also, importantly, the benefits of the early warnings issued and the timely emergency responses in terms of avoiding additional costs.

In summary, lessons were learnt from this severe flood event, but certainly additional studies are still needed to clarify the ways of improvement to enhance flood preparedness, crisis management and post-event recover. The first analyses have just begun to emerge and further contributions from applied research institutes, data providers and modellers, forecasters on-duty at the time of the event, emergency services, and the affected population will certainly enhance our comprehension of the event and clarify future actions to improve flood resilience.

The reasons for such an exceptional event at that time of the year are to be investigated. A recent study on the links of this event with the ongoing climate change was proposed by van Oldenborgh et al. (2016) (see also [75,76]). In this report, however, we did not analyse long-term trends or discuss climate-change attribution. Our focus was on collecting data and information available to better understand the causes and consequences of the flood event from a hydrological perspective. However, the issue of flood evolution in the future is the focus of Adaptation strategies to climate change which are being developed by Water Agencies. The Seine-Normandie Water Agency adopted its strategies in December 2016, with a large panel of measures to prevent floods in the Seine basin.

Last, in terms of preparedness, the event happened only a few weeks after the EU Sequana exercise (after the name of the Roman goddess of the Seine sources) had been organized in the Paris region (7-18 March 2016). It aimed to test the flood forecast-response chains and the efficiency of rescue

[74] See, in French: http://www.eaurmc.fr/gemapi.html and http://www.developpement-durable.gouv.fr/Qu-est-ce-que-la-GEMAPI.html
[75] https://theconversation.com/pluies-intenses-et-changement-climatique-quel-rapport-60519
[76] http://www.lemonde.fr/climat/article/2016/06/02/des-pluies-qui-surviennent-une-fois-par-demi-siecle-ou-par-siecle_4931492_1652612.html

services in case of a large event similar to the 1910 flood[77, 78]. This certainly helped authorities to better manage the exceptional June 2016 event.

[77] http://www.prefecturedepolice.interieur.gouv.fr/Sequana/EU-Sequana-2016

[78] http://www.driee.ile-de-france.developpement-durable.gouv.fr/exercice-eu-sequana-2016-a2620.html

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