# Urbanisation and the fluvial risk factor

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# Urbanization and the fluvial risk factor

**ABSTRACT**: *What is the impact of urbanization on the vulnerability of a watershed? Partial or total soil waterproofing increases the vulnerability of the territory, on both hydrological and urbanistic aspects, during river level rises due to a short and intense rain, or during exceptional floods. This vulnerability can be addressed for each area by calculating the river risk after urbanization. Initially, the wish was to find a tool that could be used on any territory, in a single and convenient way. But each watershed, each urban area, each neighbourhood has its own uniqueness and its own development. The solution is then to use a polyvalent tool that incorporates the territorial specificities of the studied area. This analysis is based on the watershed of the Seine and Thames rivers, including a "zoom" upstream and downstream of Paris, and one between Greenwich and Bexley, downstream of London. To analyse the flooding risk, the whole watershed morphology needs to be observed. Then can come the catchment basin (or part of it) model calculations. At first, this river risk factor proceeds from the calculation of the flow increases. Then can come the calculations of the material vulnerability. The latter is determined by mixing the urban area (and its networks) growth with the local G.D.P. one. Human vulnerability is then calculated by taking into account demographic and planning realities. Finally, the factors of material and human vulnerabilities are multiplied. This global fluvial risk factor allows – before any scheduled urban development – to have a prompt idea of the vulnerability of a city crossed by a river, provided local data is taken into account. It also gives a short, medium and long term impact prospective concerning any urban project, beyond the apparent safety of artificial structures to protect against flooding.*

**Keywords**: urbanization, flood, vulnerability, watershed

## 1. Introduction

This article discusses the impact of urbanization of a watershed, or of a portion of it, on the river flows. To calculate the flood and storm water flood factor is relevant for highly urbanized watersheds. We can take as an example the Paris and London basins. Their geographical morphology - the two capitals are located at the bottom of pools - and their great urban sprawl makes them sensitive to (rainfed or not) floods. However, the draining of these two basins limits the risk…as long as floods remain within medium range.

Rain-fed flood means the fact that a stream flow increases in a spectacular manner, over a time period of a few hours, following an intense rain fallen on the river catchment area. Rain flooding can happen during a period where the usual flow is rather low, because for example of evapo-transpiration (example: the Seine during the month of August in Paris). It can also happen during a period of high waters (the river Seine in January in Paris).

Rainstorm flood, after a heavy rainfall on a watershed, is differentiated from a flood which corresponds to exceptional water level reaching, on comparison of the usual mean high waters calculated over several years. A "rain-fed flood" has therefore a more punctual aspect than a "flood". The rising phase of a rain-fed flood does not exceed a period of 15 hours (Lazzaro, 1990). The flood of the river Seine in Paris, in 1910, required about 10 days to reach its peak (8.62 m in Paris January 28th).

Initially, the desire was to find a tool that could be used on any territory, in a uniform manner. But it was forgetting that each space is unique. Each watershed, each city, each district has its own uniqueness, non- reproducible.

One chooses to design a river risk calculation tool after urbanization, based on the Seine and Thames watersheds in Paris in London. A "zoom" will put on the loop of the Seine located between Chatou and Montesson[1], and another one on the curve between Greenwich Reach and Erith Reach, East of the British capital. Pr Jean-Noël Solomon (1997) recommends, in order to analyze a flood risk, to first study the morphology of the entire basin watershed. Then can come the modeling or probability calculations, on the whole watershed or part of it. Stéphanie Beucher (2007), also stresses the need to proceed first by the territory because it includes all of the actors and issues concerned with the river. Similarly, N. Meschinet de Richemond and Mr. Reghezza denounce the fact that despite the official speeches, hydrological studies are often separated from territorial reality. These researchers therefore advise to proceed first by a geographic and historical analysis overall - in fact, the understanding of the field - and only after by the mathematical calculations.

If literature is quite abundant on the risks of flooding in the Ile-de-France region, it is mainly composed of either purely topographic analysis or of statistical methods, as shown by the symposium organized by the “Société Française d'Hydrologie”, in Paris, in June 2010. Taking Jean-François Gleyze and Mr. Reghezza’s example, this study will not only be on hazards - the latter are extremely complex - but mainly on the material and human vulnerability. About the physical aspects, we will put together all geographical/urban and economic issues including using the concept of Local Gross Domestic Product (LGDP). This including use of both urbanistic and economical visions is rarely cited in the literature; However, the « Grands lacs de Seine » administration conducted a study (published in 1998) on a today “1910 type” flood.

This text is intended as the opening of a reflection, and not as an exhaustive analysis of the flooding risks in the two capitals. Indeed, it was confronted, at the beginning of the research, to many unknowns. Among the most obvious, we can cite the problem of calibration to the zero elevation, as one was conducting a comparison between the two capitals. Indeed, the "zero" elevation is not the same for sea and land maps. Moreover, the calibration is also different not only between French regions (e.g. Marseille and Brest), but also between French and British charts. A surveyor from the Institut de Geographie National (IGN), Mr. Alain Coulomb, brought a response to the different calibrations of the "zero" height. He had performed comparative surveying in the channel tunnel, at the time of its construction, had determined precisely the altitude calibration differences between the IGN 69 surveying system (France) and the Ordnance Survey one (United Kingdom) : 0.42 m more for the French measures

[1] Those two towns are located around ten kilometers West from Paris, in the “Département des Yvelines” (78), in France.

(Coulomb, 1996). Therefore, one could establish a first comparative link between French and British land maps.

Both capitals have similar urbanistic points that lead to do a comparison. They are in a strong national centralization context, are not only political but also economic and demographic main areas, and are confronted to a hardly controllable urban extension. Geographically, the two cities are crossed by a river. Geologically speaking, Paris and London are located in the same big sedimentary basin with a kind of gutter (Beaujeu-Garnier, 1972) in the middle: the English Channel. From around 2.6 to 1.8 million years BP, "in the early Pleistocene, the coastline of the North Sea was located on the very North of the today Pas-de-Calais region, along the axis that linked East Anglia to Antwerp" (Battiau-Queney, 1993). As a result of glacial periods and the presence of ice on the British Islands, the channel was a river which used to flow into the Bay of Biscay. During this geological time, the Seine River and the River Thames were part of the same river system.

Conversely, on the hydrological point of view, the two cities are facing different situations: Paris is threatened by floods of rain origin only, London by floods of rain origin too, but primarily of maritime one. The geographical positioning difference from the estuary makes the British capital particularly sensitive to sea level rise and to the winds of the atmospheric depressions located over the Atlantic ocean and Northwest British Isles area. These winds will rush into the channel strait - which causes a Venturi effect - and then follow the River Thames estuarine corridor. When a high tide, with a strong coefficient, combines with this type of wind, as well as possibly a fluvial flood coming from upstream, the level of the River Thames increases strongly, and can cause heavy flooding.

After an overview of the main geological characteristics of the Paris-London basin, the "flood" event components and the material and human vulnerabilities in the Paris and London regions will be analyzed. Physical vulnerabilities in Paris and London areas designates all structures - and the benefits that these latest make - likely to be damaged by a flood, as a result of his exposure to flood hazards. Human vulnerability means the population living in these two (peri)urban zones and exposed to a risk of physical and/or psychological damage more or less serious.

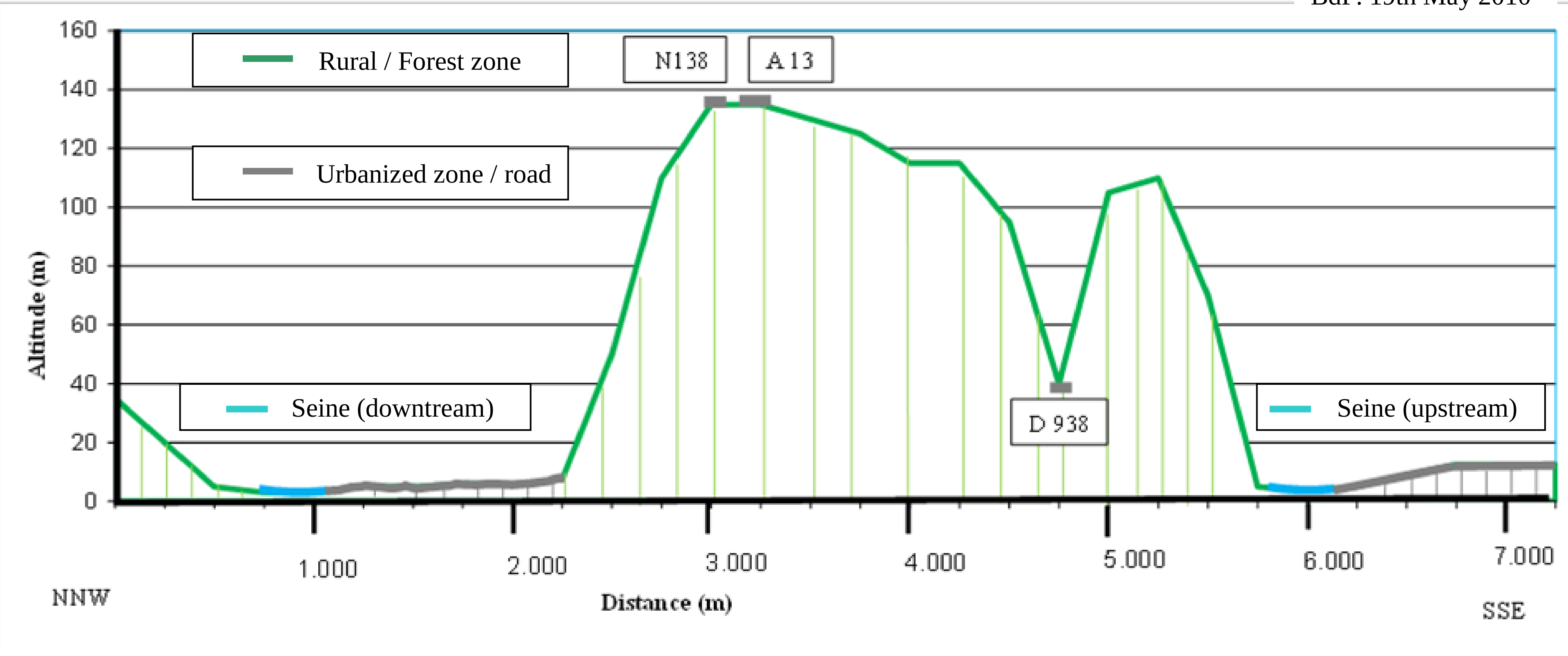
### *1.1 The Seine convex banks morphology near Paris*

The Seine portion grossly going from Troyes to Rouen is studied here. The Seine River, down to Moret-sur-Loing, is located in a rather flat territory, typical of a peneplain area. Beyond, the river must pass through the northwestern part of the Parisian basin which rose up by reason of a failover. That was a consequence of the Massif Central and the Alps orogenic movements: the Paris Southeast part was lowered, the Northwest part tilted upward. The Seine bed is surrounded by numerous ponds between Troyes and Moret, at the confluence with the Loing River. Downstream and therefore towards the Northwest, the Seine dug in calcareous sediments, with sometimes cliffs overlooking from more than 100 m, as downstream of Rouen.

The Seine meander convex sides received old (lower Pleistocene), intermediate (middle and upper Pleistocene) or recent (Holocene) alluviums. The more one approaches the current minor bed, the more recent the alluviums are. This poses a problem for the plains which are, in part or in whole, only slightly higher (maximum 5 m) that the level of the Seine highest known waters. Indeed, some alluvial deposits continue to fill the river bed, and this could raise the level of the river in case of flood. In the town of Montesson (Yvelines, France), if the bed of the Seine was raised by 5 m, a 1910 type flood would submerge almost a third of the plain. Moreover, exploitation of sand in the Seine river major bed, upstream from Paris, helps deteriorating the banks (Salomon, 1997). The degradation of these loads the water of mineral detritus that will fill the bed downstream. This decreases the space between the two shores - in the context of a transverse profile - and may cause an overflow of the banks and therefore a flood. Similarly the exploitation of sand and gravel in the Seine alluvial ground waters transforms careers into ponds (Mottet, 1993). Thus, some zones, classified as non-liable to floods, might find themselves vulnerable in a period of 10 to 50 years.

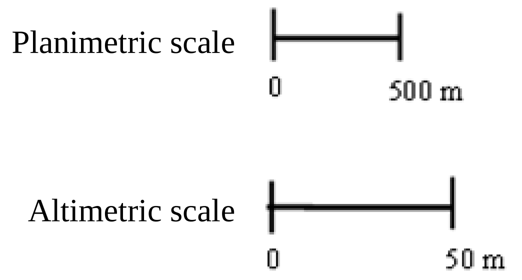
D1. **Topographic cut: Mont Miré -> Saint-Aubin-les-Elboeufs (Rouen)**

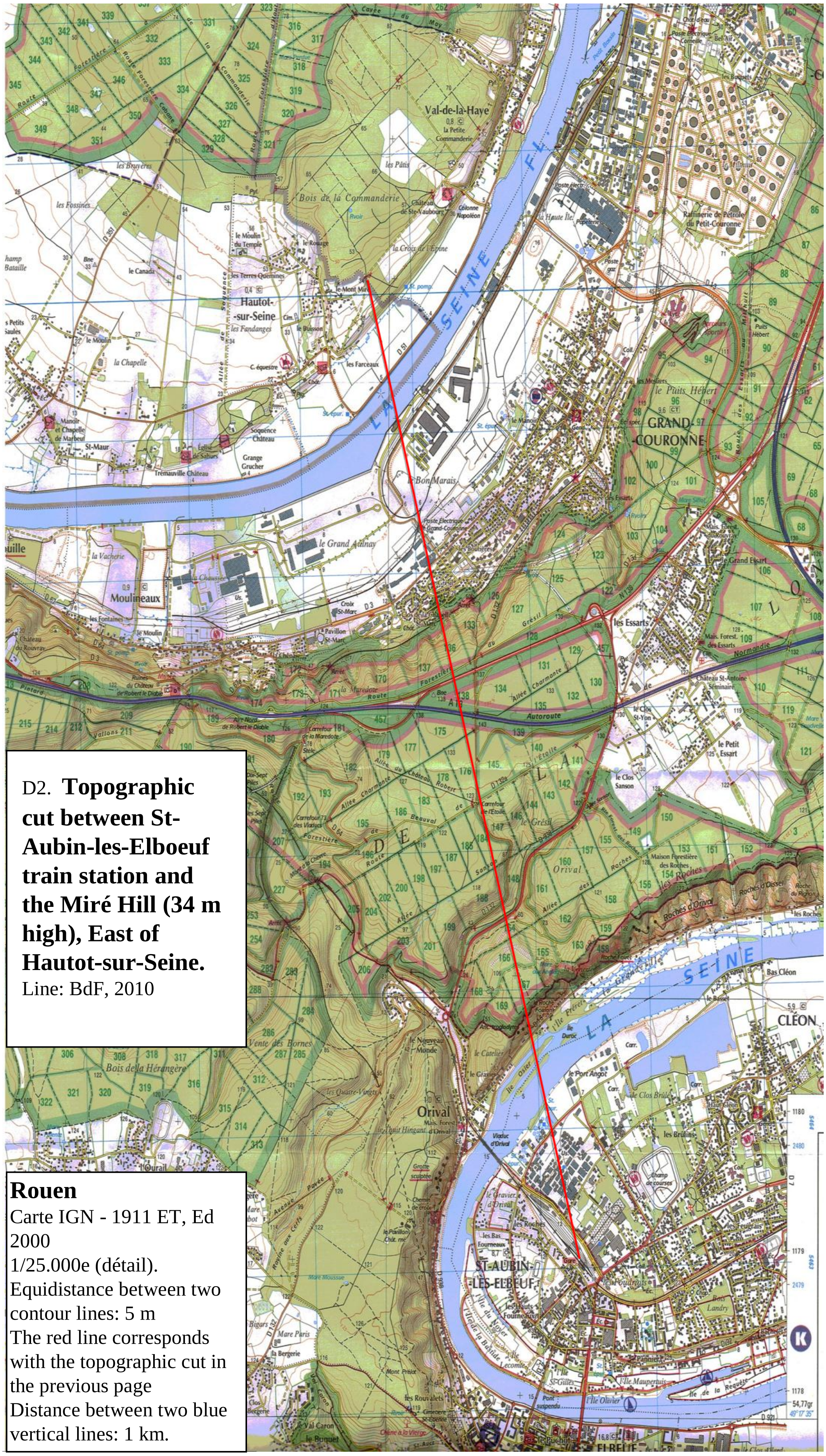
BdF. 19th May 2010




The urbanized zones are located at a barely higher altitude than the Seine one. The most flood-prone areas are the ones with the highest stakes.

The topographic cut shows more important height differences than in reality, because of the difference between the planimetric and altimetric scales.






D2. **Topographic cut between St-Aubin-les-Elboeuf train station and the Miré Hill (34 m high), East of Hautot-sur-Seine.**
Line: BdF, 2010

**Rouen**
Carte IGN - 1911 ET, Ed 2000
1/25.000e (détail).
Equidistance between two contour lines: 5 m
The red line corresponds with the topographic cut in the previous page
Distance between two blue vertical lines: 1 km.

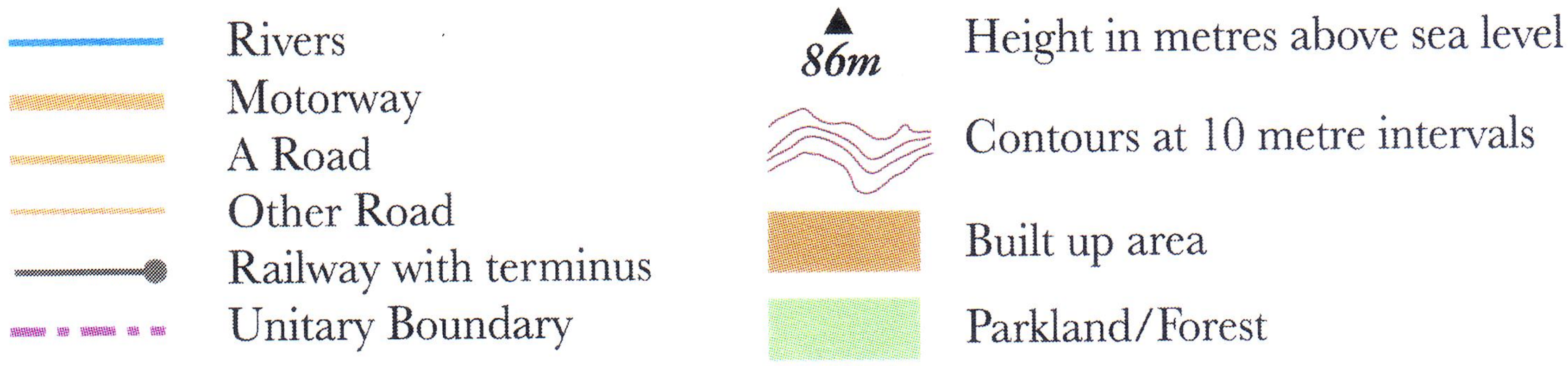
### *1.2 The morphology of the "Greenwich Reach - Erith Reach" loop convex side*

In London, the Thames is subject to two hydrological influences: the fluvial one and the marine one. The latter, with the daily tides, is stronger than the first. But the two causes of floods can mostly accumulate, making the urban area of greater London, particularly the East part, yet more vulnerable.

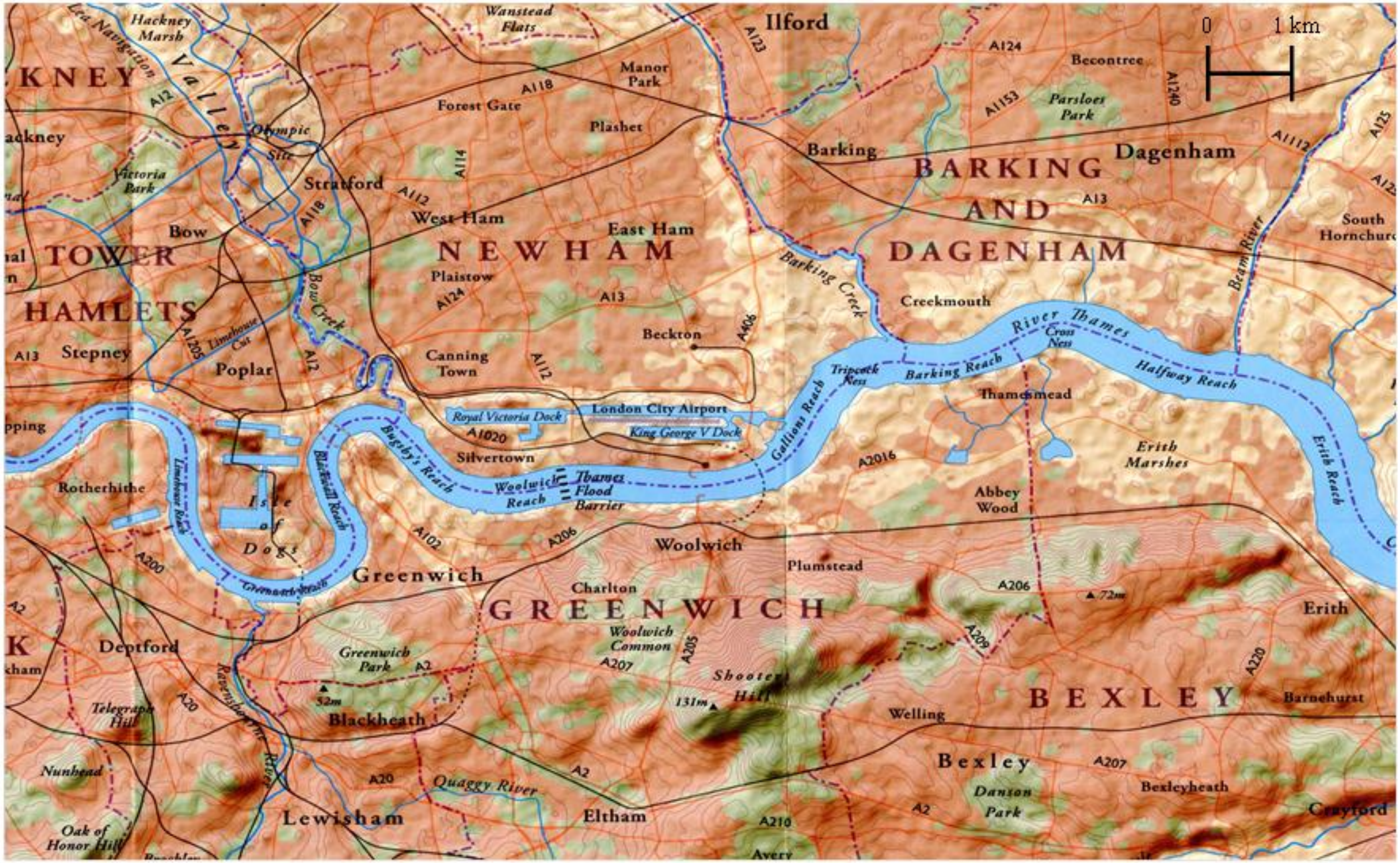
After studying the map below, the vulnerability of the London region East part appears in a spectacular way. "Flooding" hazard, especially during high spring tides, would be likely to cause a human and material disaster. It is not surprising, by the way, that it is the Dutch who developed the whole area called "Thames Gateway". In the late 18th century (at the soonest), the latter had drained most of the marshes, in order to bring their livestock from the coast to the London market (Farrell, 2010).

At high spring tide, the height difference between the level of the River Thames and the streets adjacent to dykes, on the Greenwich heavily urbanized area (housing, offices and river sheds), is 6 m.

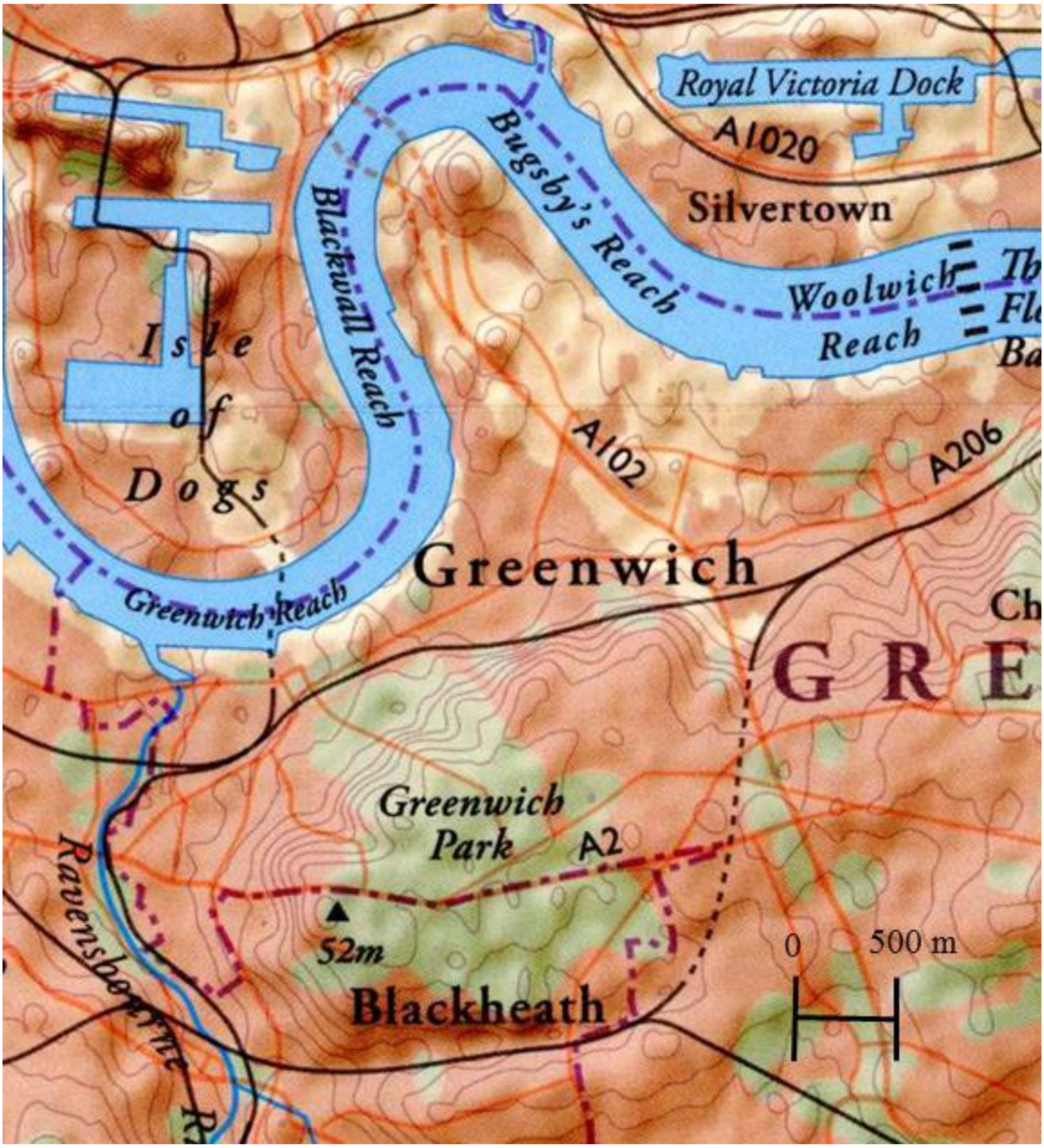
D3. **East London relief map legend**



## D4. **East London relief**




Sources : *The landscape of London*, Anderson Geographics, 2009. Ordnance Survey



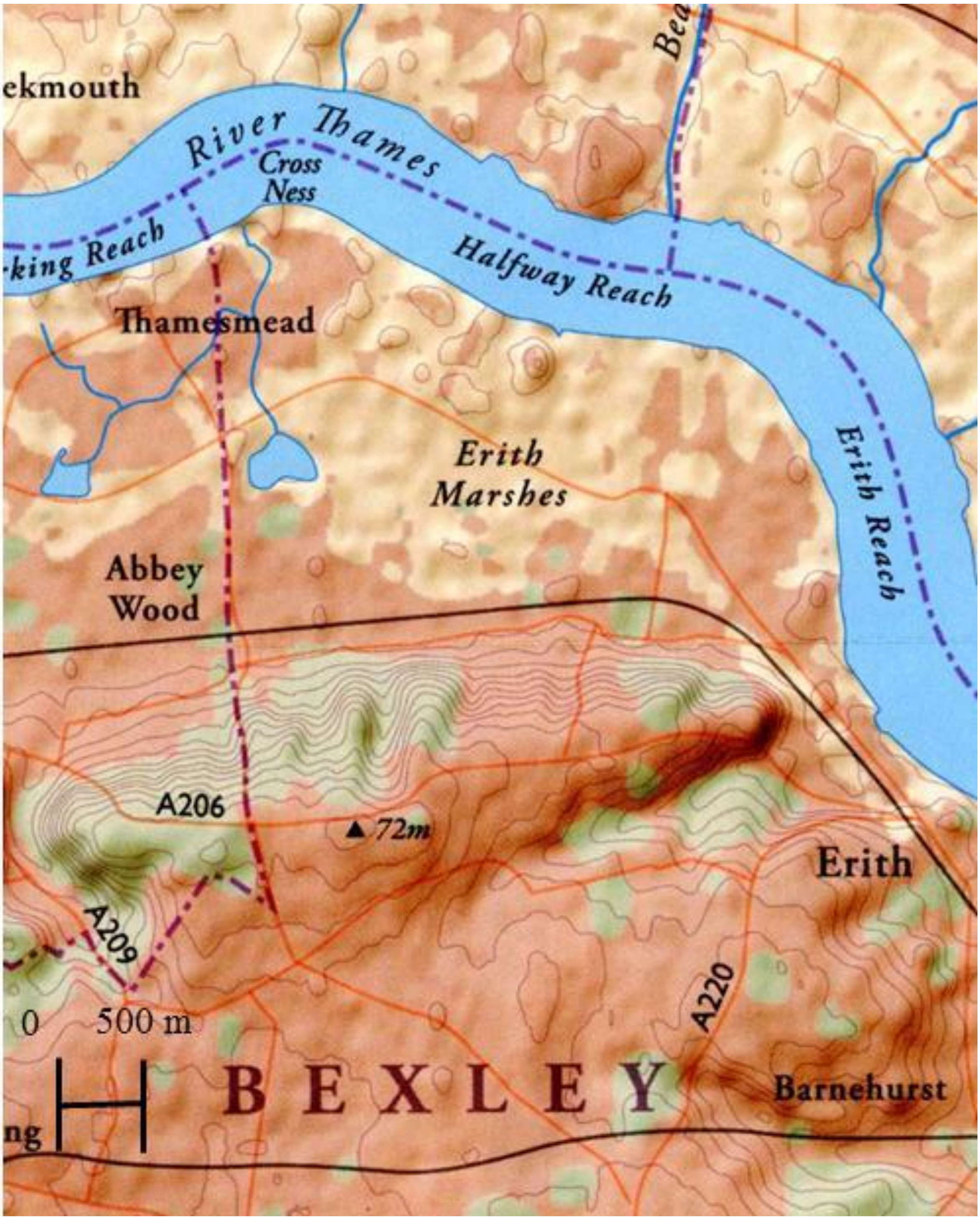

D5. **Relief at Greenwich**

Peak, West of Greenwich Park: 52 m.
There are nine contour lines before the Thames shoreline, which represents a difference in height of:

50 m - (9 x 5 m) = 5 m (+- 1m)

Therefore, the edges of the River Thames at this location are just at the level of the water, when the River Thames in London is at high tide. Indeed, the height of water at this location is 5 m, at high tide.

Sources : *The landscape of London*, Anderson Geographics, 2009. Ordnance Survey. Scale: BdF




D6. **Relief at Bexley**

Peak, to the South of the Erith Marshes (Marsh): 72 m.
There are fourteen contour lines before the shoreline, which represents a difference in height of:

70 m - (14 x 5 m) = 0 m (+- 1m)

The edges of the River Thames at this point are therefore below the water level, when the River Thames in London is at high tide. Indeed, the height of water at this location is 6 m above the shore at high spring tide, behind the dikes that keep the floodplain.

Sources: *The landscape of London*, Anderson Geographics, 2009. Ordnance Survey. Scale: BdF

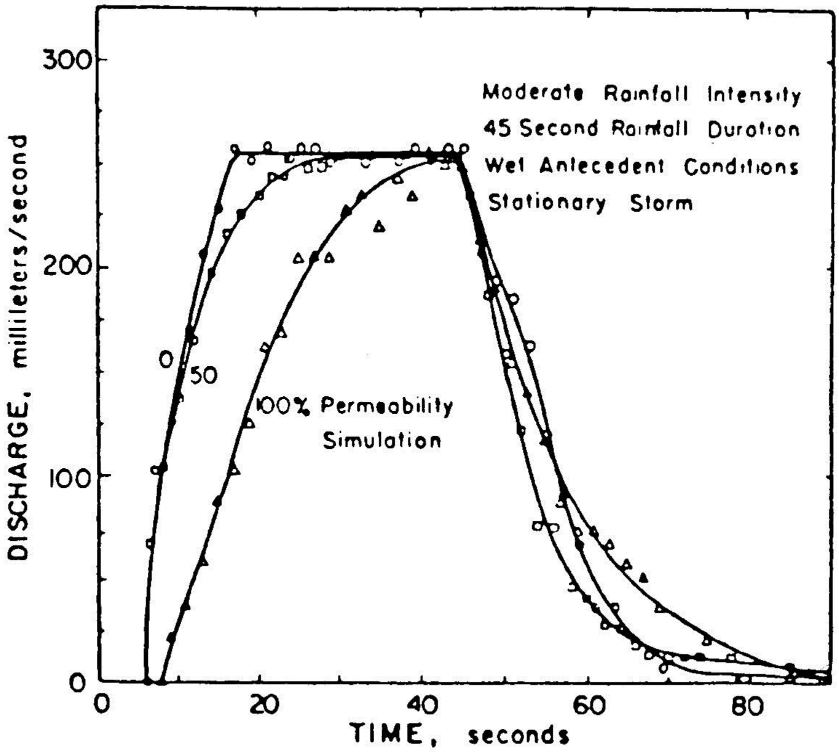
## 2. Calculation of urbanization impact on floods

Calculating the (stormwater) flood risk factor is relevant for highly urbanized watersheds. One takes as an example the Parisian basin and more particularly the right bank of the "Boucle of the Seine" portion: Genneviliers harbour and the plain of Rueil in the Hauts de Seine region, and the shores of Chatou, Croissy sur Seine and le Pecq in the Yvelines. The geographical morphology of the Seine watershed, in the Ile-de-France, and its urban sprawl make it susceptible to storm floods. However, drainage and the presence of green areas limit the risk as long as flooding does not exceed the evacuation capacities of the upstream reservoir-dams. These dams can contain the equivalent of 70 cm height of water in Paris (Popelin, 2009) if a 1910 type flood happens again. Gérard Mottet defines the Seine as a "complex deferred scheme" (Mottet, 1993): different infrastructures (dams, reservoirs, dikes) contribute to smooth flow changes issued from multiple climatic hazards occurring on its basin. But these constructions reinforce the risks in case of exceptional floods.

After urbanization and therefore soil impermeabilization, the rain floods water level is three times higher than when the ground is "natural", i.e. not urbanized (Lazaro, 1990). A simple hydrograph shows the evolution of a river flow, after rain heavy enough to saturate the soil infiltration capacity and to fulfill the natural (lakes, ponds) and/or artificial (retention ponds) storage areas. The soil artificialization implied by urbanization changes the underground and superficial water storage capacity of a territory. Vegetation cover reduction or disappearance changes the local water scheme assessment. It reduces or removes soil infiltration. It increases runoff, and on the ground surface, the evaporation. The time needed to reach the flows peak, in a rain-fed flood over an artificialized soil, represents a third of the time required on permeable soil. A larger scale more clearly shows the acceleration in reaching the peak because of urbanization (cf: scheme "Urbanization impact on river flow"). On the Y-axis, rather than a cubic feet per second model, there is a cubic millimeter per second water level calculation. On the X-axis, instead of calculating the time in hours, it is counted in seconds. It is reminded that:

1 ft3 = 0.028 m3 = 28 dm3 = 28 x $10^6$ mm3
1 h = 60 mn = 3600 seconds

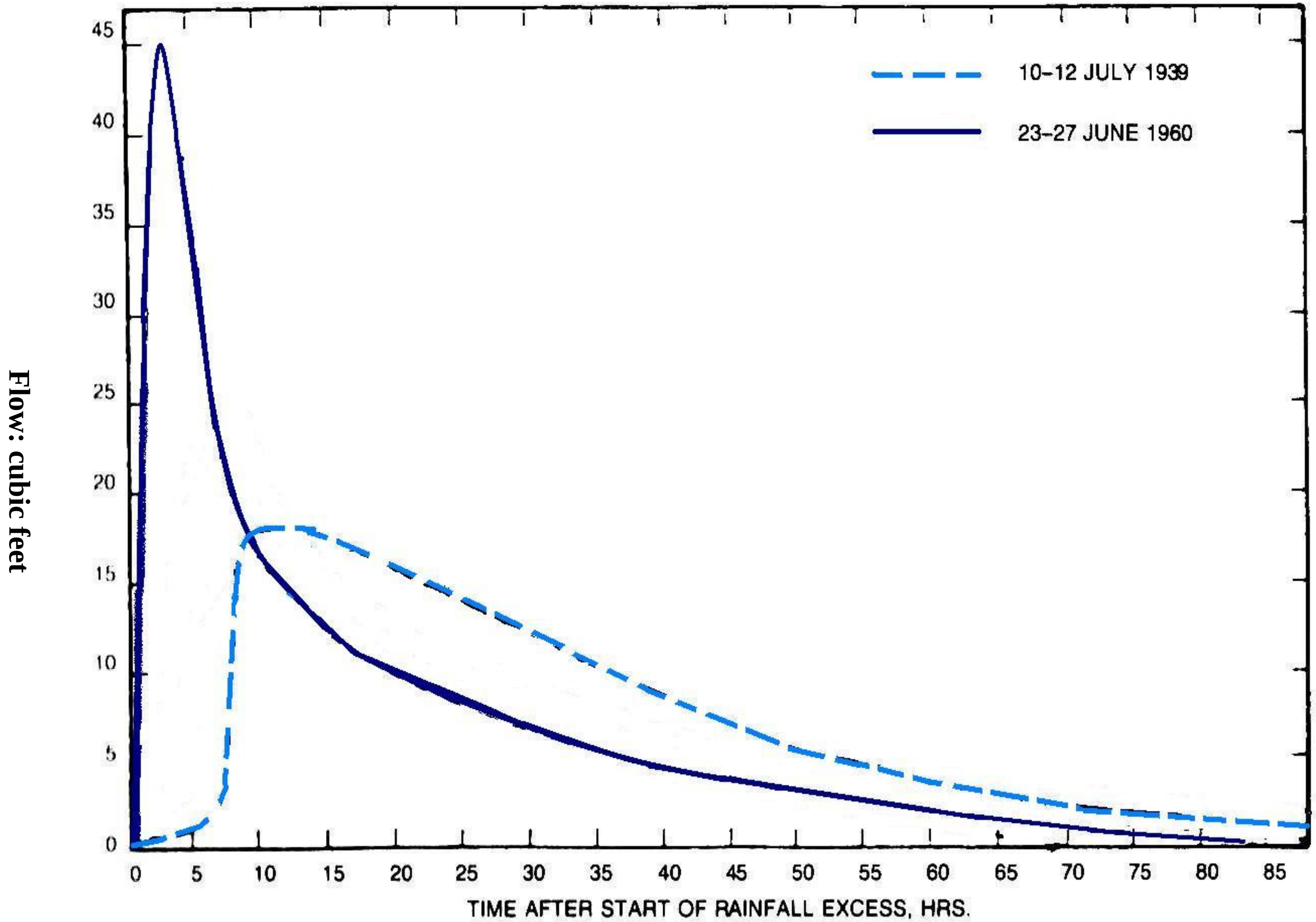
The scale is thus enlarged.




A unit hydrograph comparing surfaces of 0, 50 and 100% permeability [*Source*: Roberts and Klingeman (1970) (p. 405)].

This means that the acceleration factor is not only about the flow level. Flow will not exceed the reached peak (factor of three). However, the speed - at which this peak flow will be reached - will increase and will have a considerable impact. Not only the flow will be significantly higher in urban areas, but also the speed of this rise will be multiplied by three. Concretely, this means that in flood-prone areas, relief should be organized so that they can rescue more people faster, on larger areas.

For rainstorm floods - i.e. which arrive after a marked rain - we have an acceleration factor of 9.




D8. Unit hydrograph of two rain floods :

before (10-12 July 1939) and after (23-27 June 1960) urbanisation

Sources: Moore and Morgan (1969). University of Texas Press (p 217). Simplifications: BdF.

But what if this rainstorm flood comes at a time of high waters? The Seine river regime in Paris fits between mean high water of 545 $m^3/s$ and low average water of 94.5 $m^3/s$. The ratio is 5.7 that one can round up to 6, in order to facilitate calculations.

The "Seine river regime in Paris" (Demangeot, 2000-2002) pattern shows that rainfalls in Paris oscillate between 50 and more than 70 mm per month. Variations are low compared to the tropics with a rainy season (Senegal for example). On the other hand, flows move from 100 m3 /second on the month of August, to about 550 m3 /second in February. It is not precipitation which causes this difference, but evaporation, since the average temperature goes from a mean 18 ° C in August to less than a mean 5 ° C in February, i.e., less than a third of the summer heat. The winters, in the Paris region (temperate zone), are favourable to the normal high water, but also to the exceptional flood.

The fluvial risk factor, in an average regime river catchment basin, in moist temperate zone, after a strong rain, and between the beginning (0% waterproofing) and the end of urbanization (100% impermeabilization), is calculated as follows:

Peak flood rain ($f'q_{flood}$) = original flow x 3 → 3 is the flood factor
or: $f'q_{flood}$ = flood flow / before flood flow = 3
$f'q_{flood}$ = one-time flood derivative = ($y_2$-$y_1$ / $x_2$-$x_1$)

Rain flood speed ($S_{max}$) = original speed x (original time/flood time)
= original speed x 3 → 3 is the speed factor

} Watershed
(before and after urbanization)

Extreme flows ratio ($f'Q$) = original flow x 5 → 5 is the extreme flows factor
or: $f'Q$ = high waters flow / low waters flow = 6
$f'Q$ = extreme flows derivative = ($y_2$-$y_1$ / $x_2$-$x_1$)

That gives the following calculation:

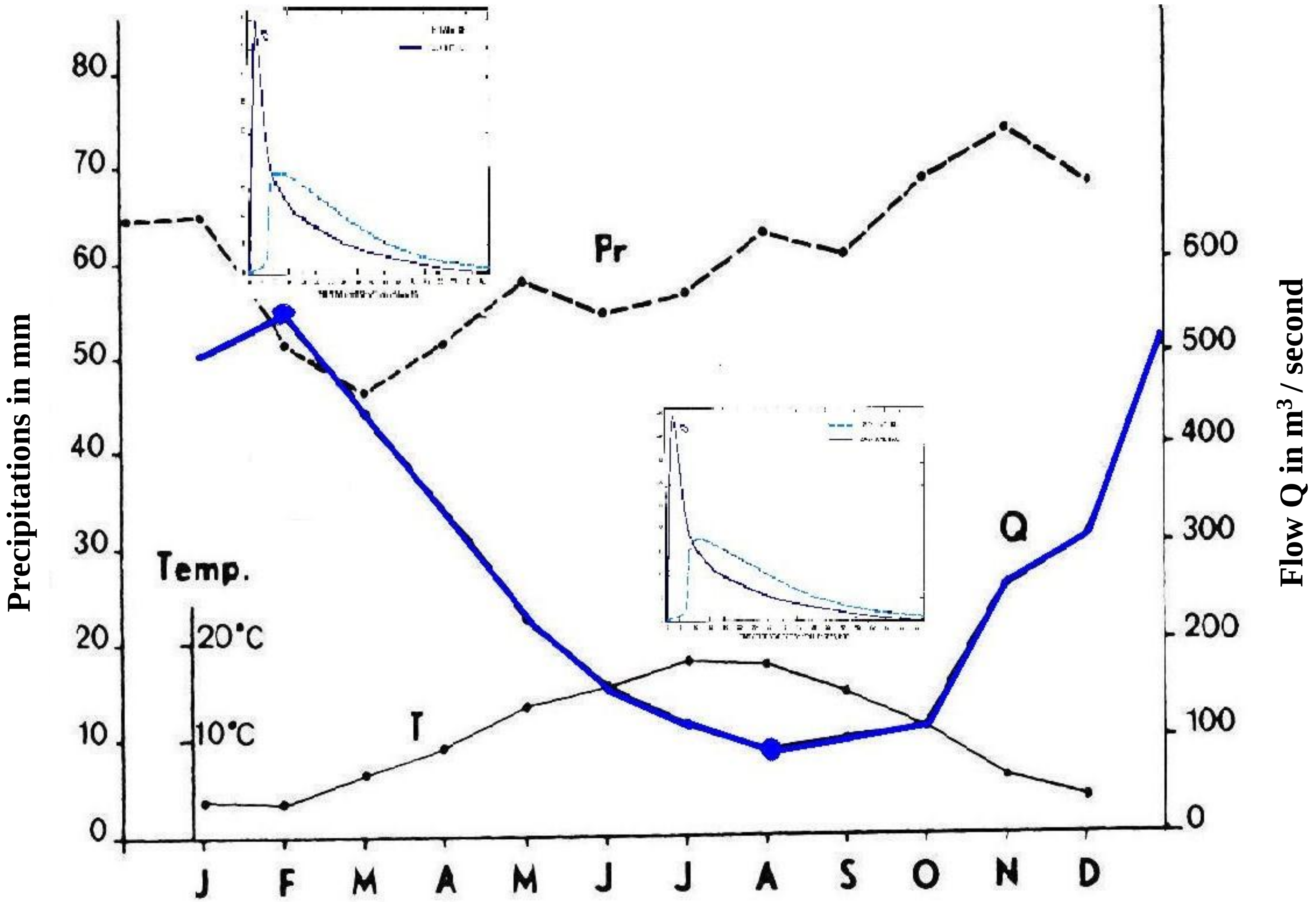
$f'q_{flood} \times S_{max} \times f'Q = f_{hydraulics}$

$3 \times 3 \times 6 = 54.$

The hydraulic risk factor, for a regime equivalent to the Seine River, is 45. The relationship between the Seine extreme flows (in Paris) is minimal (5.7), compared to the Nile (14.5) in Wadi Halfa (North Sudan), for example. But even in a medium regime, we have a strong factor between two situations:

- very low flood risk during low water in the month of August on a "natural" territory
- high risk during high water in February on a completely artificialized area

Taking into account all the fluvial risk factor sub-elements reflects the impact of urbanization and overall flooding risk. To this, should be added the exceptional flood situations (i.e 1910 in Paris) or extreme flows ratio calculation in rivers with very contrasting regimes.




**The Seine river regime in Paris**

D9. Sources: *Les milieux « naturels » du globe* (The « natural » globe environments), Jean Demangeot, ed. Armand Colin, Paris, 2000-2002 2e éd, p 59. Added elements: BdF.

## 3. Physical vulnerability to flood

### *3.1 The Ile-de-France urbanization growth factor*

The calculation of an urban growth factor (symbolized $f_{urb}$) proceeds from a comparison between the contemporary Ile-de-France (IdF) region urbanized area and the one at the beginning of the industrial revolution. Analyzing a territory urbanization evolution is a way to assess the extent of the damage that can cause a flood on that very territory. The more urban areas a flood will cover, the more dwellings, public buildings, factories, warehouse, businesses and various networks are likely to be affected.

D10. **Evolution of the size of intra-muros Paris** (Chadych et al, 1999)

| Epoques | Superficie de Paris (intra-muros) en hectares | Superficie de Paris (intra-muros) en $km^2$ (1 hect = 0.01 $km^2$ ) |
|---|---|---|
| Gallo-roman (52 B.C. – Vth century) | 52 | 0,52 |
| XIIIth c | 250 à 273 | 2,50 à 2,73 |
| XVIIth c | 1000 | 10,00 |
| 1859 (just before annexion) | 3402 | 34,02 |
| 1860 (Thiers walls) | 7802 | 78,02 |
| Today | 10539 | 105,39 |

Before the French industrialization – which started in the late 18th century - urbanization was limited to the “Fermiers Généraux” walls, i.e. an area of 3402 hectares approximately. The “Grande Armée” avenue was built in 1772, from Paris to the Neuilly bridge (www.parisrama.com, 2010). It shows well the urbanization level in 1800 in the area corresponding to the contemporary small Ring[1]. Another example: Emile Zola’s “Le ventre de Paris"[2] refers to the delivery of fruit and vegetables from Nanterre to the building of “les Halles”[3]. This novel describes the activity in les Halles and in the Victor Baltard pavilions (built between 1854 and 1870), at a time where urbanization had already progressed a lot since the very beginning of the 19th century.

The Ile-de-France urbanization growth factor may be defined as the ratio between the contemporary Ile-de-France urbanized area and the zone already built

[1] « La petite couronne » as said in Paris

[2] *Le ventre de Paris* (The belly of Paris), Paris, 1873

[3] « Les Halles », untill the establishment of the Rungis commercial zone, was the central market in Paris.

around 1800 (essentially Thiers's Paris). The Ile-de-France area is 12.011 $km^2$. Reducing the IdF area to only the portion that is strictly urbanized leads to multiplying these 12.011 km2 by 25%. Indeed, and this despite the advance of urbanization, three-quarters of the IdF territory are agricultural or green spaces (Charlier, 2006). To consider these not urbanized spaces as low value-added territories would be a mistake: they are synonymous with agricultural production and with recreation and leisure (if one looks at the IdF forests) and they bring a real property value to the neighboring areas. But for a simplification purpose, and in order to propose a calculation that rounds down the economic value of a territory, one retains only strictly urbanized areas and urban parks.

Therefore, the IdF urbanized areas currently have the following approximate area:

12.011 km2 x 0.25 = 3003 $km^2$

One divides this area by the 1859 Parisian urbanized area, i.e. that just before the annexation of surrounding communes in 1860:

3003 km2 / 34.02 km2 = 88.27
For the IdF: $Urb_{2010}/Urb_{1800} = f_{urb}$ (IdF 2010-1800) = 88.27

Between 1800 and 2009, the Ile-de-France region urbanized area increased by 88. The factor of urban growth is 88.

### *3.2 The London urbanization growth factor*

The area of London in 1800 was 305 $km^2$. Today, this corresponds to "Inner London". For the same reason than in the IdF region – which roughly is the size of the London Metropolitan Area (LMA) - only the urbanized area will be taken into account. Since the London green[1] belt is 4860 $km^2$, and the Oxford one[2] is 348 $km^2$, the urbanized and greenfield area is 22 265 $km^2$. Also, as "half of the land area is […] neither urban nor covered by any statutory protection[3]", the 22 265 $km^2$ surface will be divided in two. Therefore, the actual LMA (potentially) urban area is 11 132 $km^2$.

The calculation of urban growth factor (symbolized $f_{urb}$) is:

$f_{urb}$ (London) = 11 132 $km^2$ / 305 $km^2$ = 36.50

Because Britain is very centralized, the whole influence of the London area is greater than the Metropolitan zone. This influence extends over the entire Southeast region (27.473 km2), and even beyond. The British capital weaves networks that materialize through the development of urbanization and transport lines. It is not uncommon that inhabitants of the counties outside of this Southeast region commute more than 200 km daily to come and work in London. The University of Cambridge is also located outside the S-E region. Yet, without London, it could not have its scientific prestige. If one takes into account this influence zone – the South-East of England - the factor of urban growth is stronger, because the ratio between contemporary London

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[1] « Greenbelt Land », www.buildinglanduk.co.uk, 25th May 2011

[2] Planning Policy Guidance (PPG2) – Green Belts, 1993, www.londongreenbeltcouncil.org.uk

[3] « Of green belts, green fields, and open land », www.uklanddirectory.org.uk, 25th May 2011

immediate influence area and British capital urbanized area in 1800, must be made. However, one will start with a low estimate to calculate the urbanization growth factor. The urbanized area of London (smaller than its influence area) corresponds more to the Metropolitan zone. Therefore the ratio between the present urban Metropolitan area (11 132 km2) and the 1800 London surface (305 km2), is chosen, and that gives the 36 factor.

### 3.3 Comparison between the two regions

The South-East England region ("South-East economic planning region") is different from that of the Parisian basin (in the geographic sense). The density is lower (669 h/km2). The British capital urbanization tends to sprawl, to the extent of the technical and organizational public (commuter train lines, the "tube" network, buses) and private (congestion charges) transport means, and due to the fact that London is the main pool of jobs in Britain.

However, in the Parisian basin, with the TGV[1], different medium cities more than 200 km away from the capital, are just 1H15 maximum from Paris: Lille, Metz, Nancy, Tours. Of course, to this duration, should be added the time needed to commute to the stations of departure and arrival, which can go up to double the theoretical time by train. Nevertheless, that "TGV effect" is greatly involved in attracting new professionals living in the province, sometimes called the "rurbans". This helps to limit - to some extent – the Paris region urbanization to the benefit of regional towns on the periphery of the IdF.

In terms of area and population, the region of South-East of England (27.473 km2 and 18 M.hab) will be compared to the IdF (12,000 km2 and 11.6 M.hab). The Ile-de-France region has an area of daily attractiveness which extends to a circle defined by the cities located approximately at 150 km of Paris or at 1 H 15 maximum of TGV: Reims, Metz, Nancy, Orleans and Tours, Rouen and Le Havre, Amiens, Lille and its agglomeration.

### 3.4 The Gross Domestic Product (GDP) growth factor

The Ile-de-France region GDP in 2007 was 552.7 billion euros (US $ 654 billion)[2], making it the 17th world economy (INSEE, 2010), just after Holland. It is the first European Union urban area in terms of GDP. The London Metropolitan Area has approximately the same GDP than its French counterpart (PricewaterhouseCoopers, 2009): the US $ 654 billion number will be kept.

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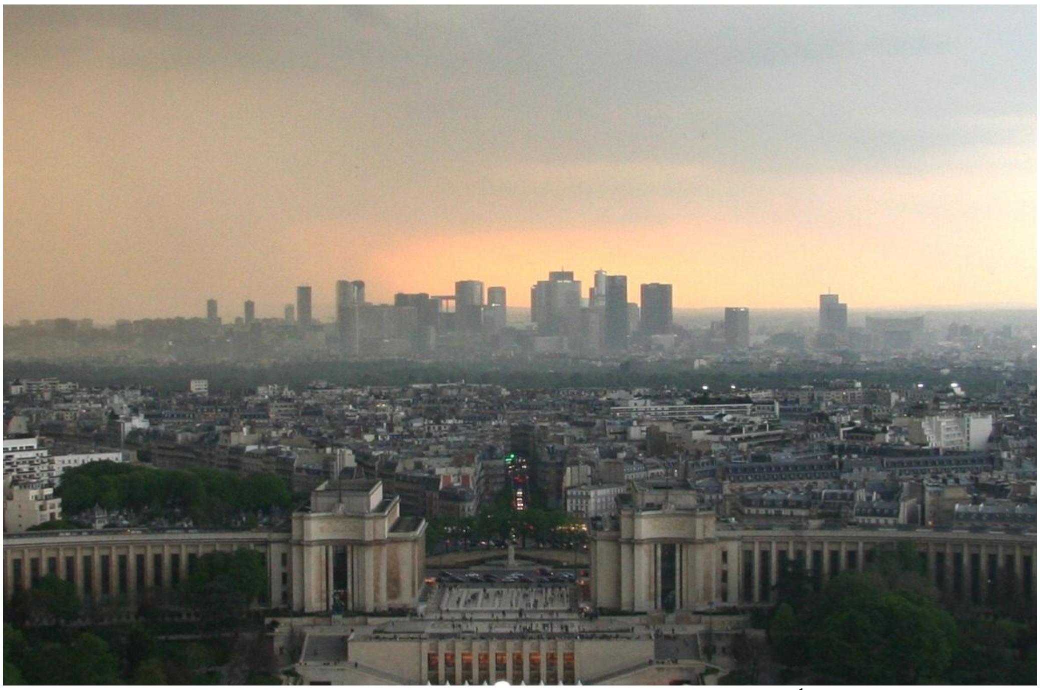
[1] TGV : train à grande vitesse. It is the French « great speed train »

[2] As the historic 1800 GDPs are calculated in 2005 value, one takes the mean US $ value for the whole 2005 year: €1 = US $1.2448. So IdF GDP was worth around US $654.40 billion (www.xe.com).



D11. La Defense, seen from the Eiffel Tower[1].
This business District (3.35 million $m^2$ of offices) is the largest in Europe
and is located on the banks of the Seine, downstream from Paris.

French GDP in 1800 was $ 1388 (2005 value) per capita[2].
French population in 1800 = ~ 30 M.hab (29.620.167 inhabitants exactly)
French GDP in 1800 was therefore 41.11 billion US $ (2005 value).

British GDP in 1800 was $ 2717 (2005 value) per capita[3].
British population in 1800 = ~ 15 M.hab (14.687.880 inhabitants exactly)
British GDP in 1800 was therefore 39.90 billion US $ (2005 value).

If one uses the theoretical principle that Paris and London represent 1/5th of their national GDP, we can make the following calculation:

GDP Paris1800 = GDP France 1800 / 5 = 41.11 x $ $10^9$ / 5 = US $ 8.22 billion (2005 value).
GDP London 1800 = GDP UK 1800 / 5 = 39.90 $ 109 / 5 = US $ 7.98 billion (2005 value).

Physical vulnerability (Ile-de-France GDP) growth factor will be symbolized $f_{PIB}$ (idf)
$f_{PIB}$ (idf 2007-1800) = (IdF 2007 GDP / IdF GDP 1800) = (654 / 8.22) $ $10^9$ (2005 value) = 79.56

Physical vulnerability (London GDP) growth factor will be symbolized $f_{PIB}$ (London)
$f_{PIB}$ (London 2008-1800) =
(London 2008 GDP / GDP London 1800) = US $ (654 / 7.98) $10^9$ (2005 value) = 81.95

[1]Sources for the photo: wikipedia. Auteur : Bigal888 ? Date : 2006 ?

[2] Sources : http://www.gapminder.org/world/

[3] Sources : http://www.gapminder.org/world/

The physical vulnerability growth factor, if one takes into account the GDP index, is 89 for the IdF; 91 for London. These huge factors are explained by the comparison between the Information and Communication Technologies (ICT) era and the pre-industrial period. As stated previously, some may note that this period is perhaps too long and contains too many changes to be relevant for vulnerability factor calculations. However, if one takes into account the speed of technological change, this argument does little. Half of technological inventions were invented these past 50 years. Therefore, analyzing the long-term allows us to confront better perhaps "the acceleration of time."

### *3.5 Balancing of the urban growth and GDP factors*

In the Ile-de-France and London examples, there is a correlation between urban growth and GDP. As one of the causes - or consequences ? – of a city development is to produce wealth, the fact that the two factors are in the same order of magnitude may seem normal and even confirm the reasoning and calculation. However, it may be that in a region and at a given time, urban growth goes faster than GDP. The local economy just needs to be based on low added-value production and requires a lot of labor. Thus, in that case, there will be a tendency to see rudimentary dwellings or even slums in a contemporary city. If, however, a city specializes in high technology and financial services, and limits its foreign population to only working people (plus their families if applicable), as is the case for Switzerland or was so for the United Arab Emirates (Dubai) before the crisis of 2008, then the trend will be reversed: the GDP will grow faster than population and urbanization.

In order to calculate the physical vulnerability factor (symbolized by "R€" or "R$" if the GDP are calculated in constant dollars), one takes into account the factor of urban growth and GDP.

$R_{\$} = \sqrt{(f_{urb} \times f_{PIB})}$

In the case of the IdF between 1800 and 2008:

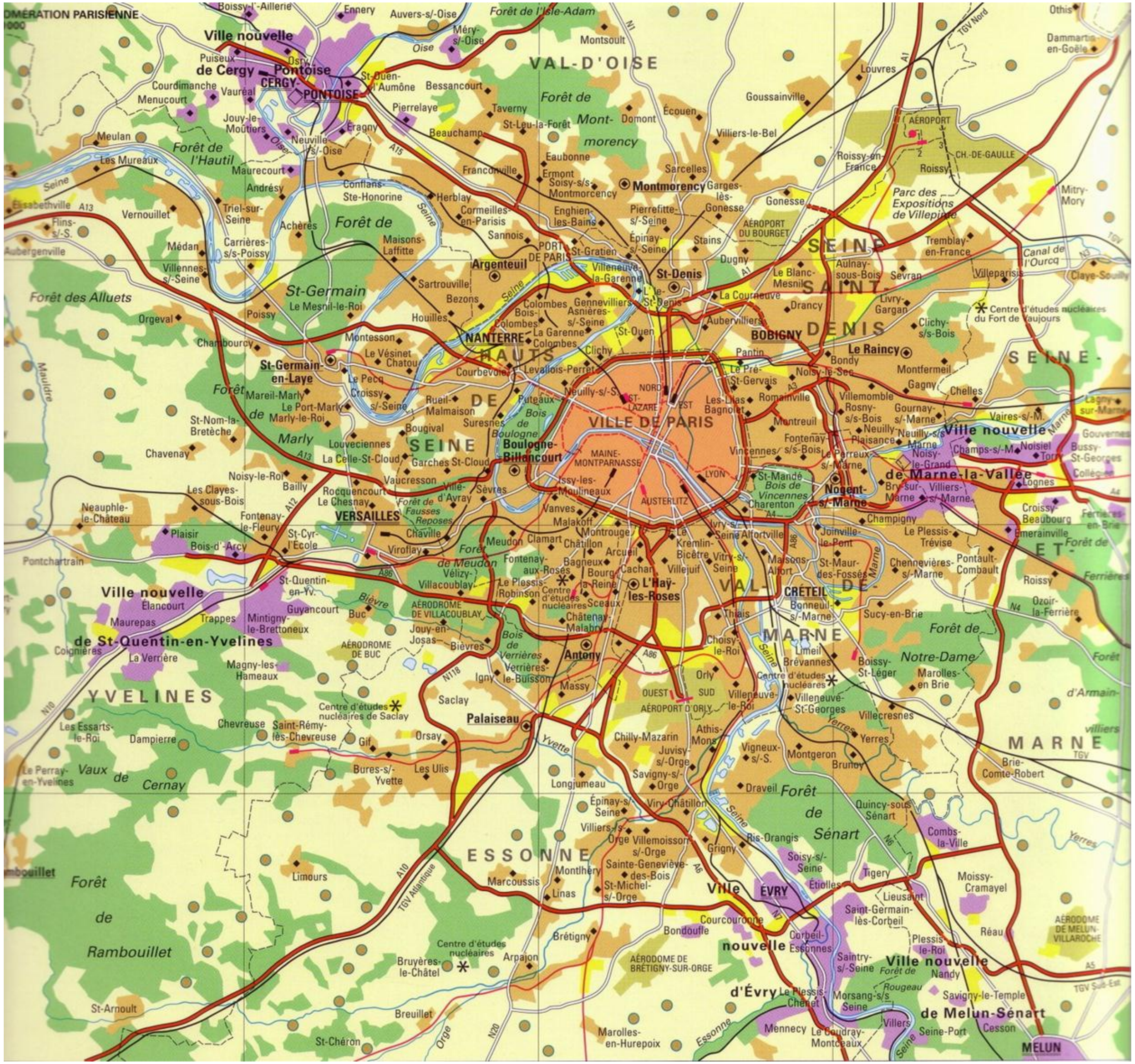
$R_{\$} = \sqrt{(f_{urb} \times f_{PIB})} = \sqrt{(88.27 \times 79.56)} = 83.80$

In the case of London ("Metropolitan Area") between 1800 and 2008:

$R_{\$} = \sqrt{(f_{urb} \times f_{PIB})} = \sqrt{(36.50 \times 81.95)} = 54.69$

In the case of London and Paris, the two mega-cities saw their urban and economic growth advance together. The London urbanization growth factor is lower than that of Paris because of lower urban density in the British capital. Physical vulnerability factors (urbanization and economy) are strong for the two capitals (89 for Paris and 57 for London), since the start of their industrial and financial growth. Any urban project today, which is built inside the urban network of the two capitals, fits in this context of risk.

Below a map shows the historical borders of Paris and of the former “département de la Seine”. This document shows the urbanized area around 1800, at the beginning of industrialization and urbanization development. This map provides an overview of the dense - thus vulnerable to floods - area, on the assumption that the whole dense area is affected by floods; effectively many urban networks are implanted there.




**D12. Ile-de-France urbanization**

The urban and peri-urban areas (represented in brown) of today's Ile-de-France tend to join the "new towns" (purple areas). Those were originally designed well outside the Ile-de-France urban area, so that they could have their own development, and would not be simple dormitory suburbs.

Urbanization has considerably expanded since Haussmann, thus increasing the vulnerability of the region. However, 75% of Ile-de-France territory is still composed of green areas (forests, parks, fields, ponds).

Distance between two vertical lines: 16,8 km.
Sources : *Atlas Nathan*, supervisor: J. Charlier, ed Nathan, Paris, 2006

## 4. The human vulnerability factor

To establish the human vulnerability growth factor (symbolized $fN_p$), it is sufficient to calculate the ratio between the population subject to the risk of flooding in a currently given territory and the one in the same territory at a given past time. For the examples studied here, it is a comparison of the IdF and London number of inhabitants between today and in 1800.

### *4.1 The IdF example*

Ile-de-France population increased from 600,000 inhabitants in 1801 to around 11.8 million today.

We therefore have the following ratio:

$fN_p$ (idf 2009-1801) = 11.8 M.inhab / 0.6 M.hab = ~ 19,67

We have a human vulnerability growth factor of 19.67 between today and 1800 for the Ile-de-France region. As said before, even if the Parisian suburbs were inhabited in 1800, the main density was in “intra-muros” Paris.

### *4.2 The London example*

In 1800, the population of London was 0.96 million people. In 2001, the London Metropolitan area had 13.9 million inhabitants.

$fN_p$ (London 2009-1801) = 13,9 M.inhab / 0,96 M.inhab =~ 14,47

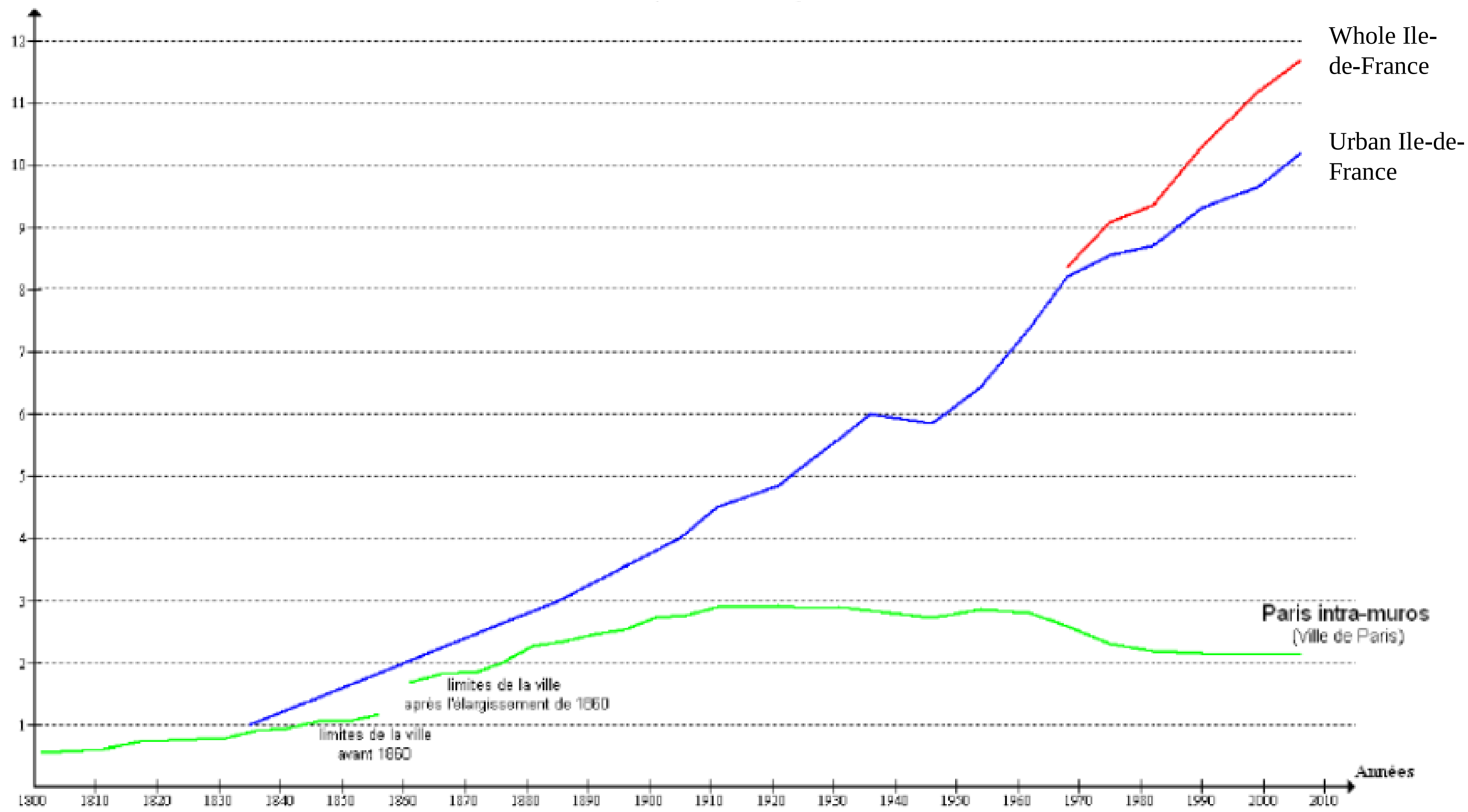
We have a growth factor of human vulnerability of 14.47 between the contemporary and 1800 British capital. Even if the suburbs - Greater London today - were inhabited areas in 1800, the main density was in the center of London (the equivalent of intramural Paris). Today, the LMA corresponds to a wide IdF. The geographical situation is the following one: a larger London territory but with a density lower than the Paris region one.

### *4.3 Perspectives*

Even if the Ile-de-France is more densely populated than the London Metropolitan Area, in both mega-cities, human vulnerability increased by factors of 14 and 20. Any urban infrastructure implementation welcoming the public in the long term (housing, schools and universities, offices, factories) or in a temporary way (exhibition halls) fits into this context of risk. The sustainable development of these two territories requires taking into account their hydrological characteristics, including their extremes having a century time probability, in order to prevent fluvial origin disasters in the long term. This fight takes two forms: on the one hand the prevention of hazard itself (the flood), and on the other the development of the Ile-de-France or London resilience by limiting the consequences where this hazard occurs.


D13. Pictures 1, 2 and 3 (BdF, 6th February 2010): the Thames in Greenwich. The tidal range can reach 10 m. This river is very sensitive to the tides at this location. This territory has become more urbanized, a fact that increased its vulnerability.
Picture 4 (BdF, 6th February 2010): the "eternal" rushes to combat water, especially when the tides are high or when the rains are intense or…when the two events occur simultaneously.
The photos have been taken from a "Transport For London" (TFL) fluvial shuttle.

D14. **Paris and Ile-de-France population growth** (1801 – 2006)




The diagram above shows the IdF demographic evolution, between 1801 and 2006, in the historical centre ("intra-muros" Paris), in the urbanized rings, and finally in the the French capital sphere of influence, at the confines of the periphery and on the rural territories fringe. The blue and red curves indicate the growth of human vulnerability in the respectively peri-urban and "rurban" areas. There is the transfer of population from "intra-muros" Paris to the suburbs, from 1960.

The first green line part represent the Paris limits in 1859, before the annexation of surroundings town. The second part shows the 1860 limits.

D15. **Densities of the territories included in the Ile-de-France in 2007**

| **Territories** | **Population** number of inhabitants census 2007 | **Surface** in $km^2$ | **Density** in $inhab/km^2$ |
|---|---|---|---|
| **Intra-muros Paris** (« département » 75) | 2 193 031 | 105 | 20 807 |
| Little ring (« Depts. » 92, 93, 94) | 4 349 640 | 657 | 6 622 |
| Large ring (« Depts. » 77, 78, 91, 95) | 5 056 173 | 11 250 | 449 |
| **Ile-de-France** (whole région) | 11 598 844 | 12 012 | 966 |
| Bassin Parisien (géologique) | 21 000 000 | 140 000 | 150 |

If one subtracts the woods of Boulogne and Vincennes areas, the density of intramuros Paris passes to approximately 25.200 living (hab) per square kilometre, in 2007. This density is among the highest of the different major political or economic capitals in the world.

Sources: INSEE, 2007. Modifications: BdF.

D16. **South-East England administrative areas densities** (2001)

| **Territoires** | **Population** Number of inhabitants in 2001 | **Surface** in $km^2$ | **Density** in $inhab/km^2$ |
|---|---|---|---|
| **Central London** | 2 766 000 | 305 | 9 054 |
| Greater London | 7 172 000 | 1 610 | 4 454 |
| **Métropolitan area** | 13 945 000 | 16 256 | 858 |
| South-East England | 18 387 000 | 27 473 | 669 |

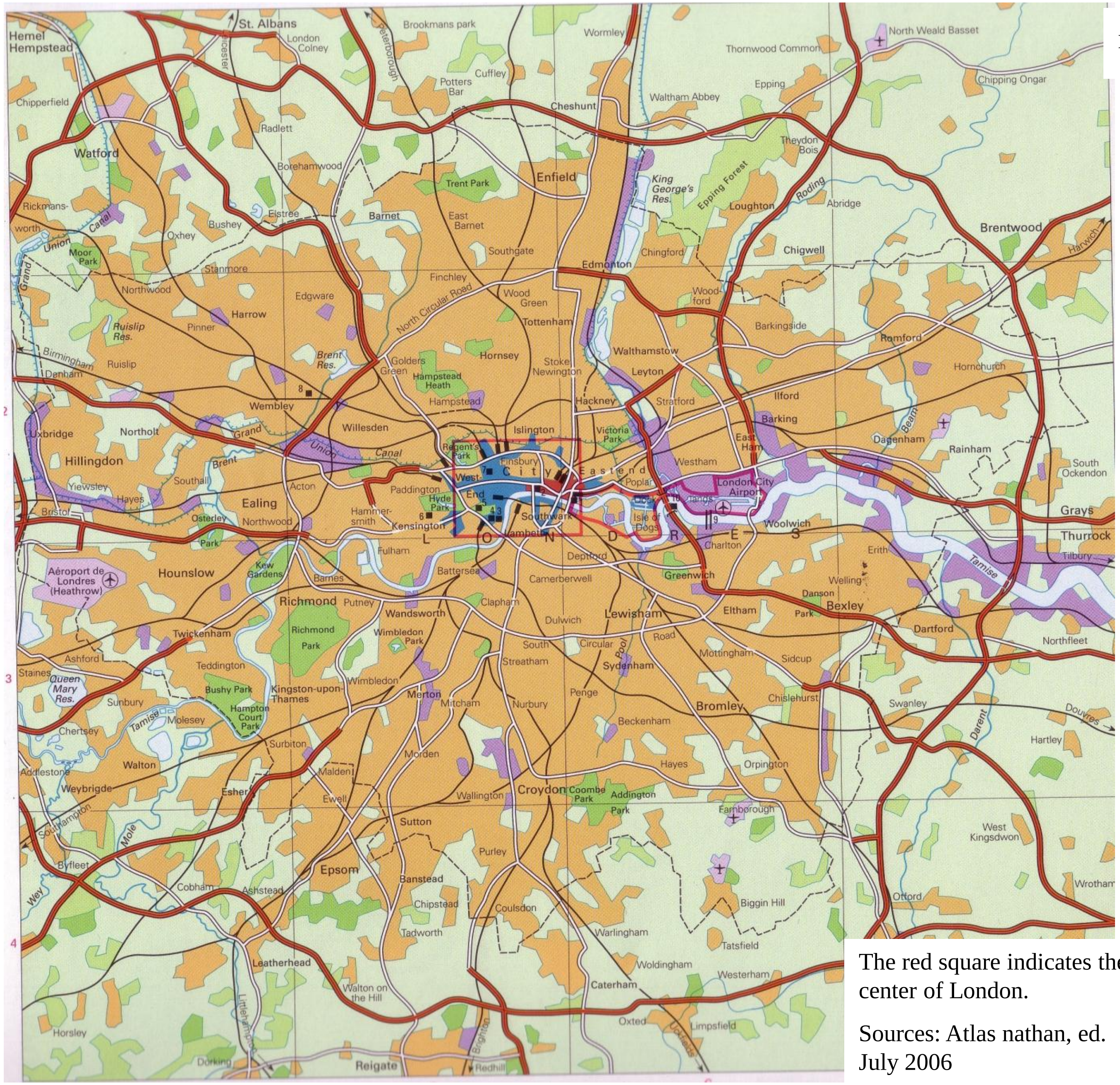
D17. **Historical estimates of the population and density in the London urban area**

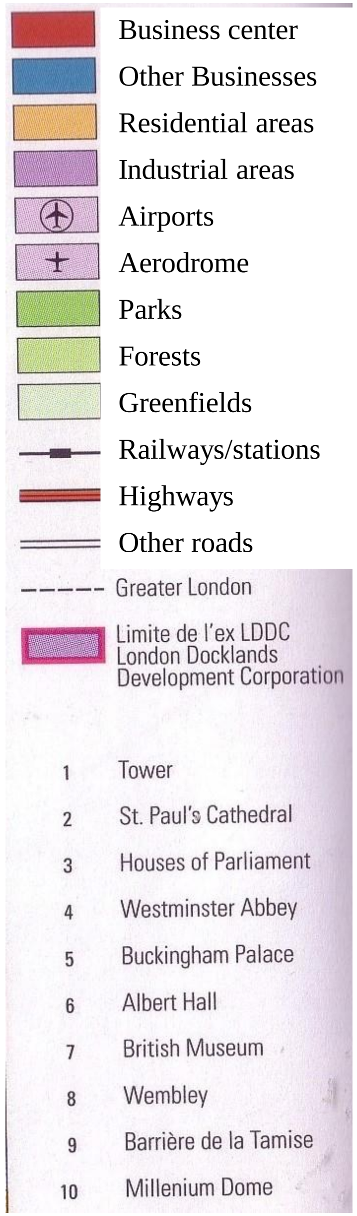
| **London urban zone** at a given time | **Population** (inhabitants) | **Area** in $km^2$ | **Density** in $hab/km^2$ |
|---|---|---|---|
| 1680 | 450 000 | 10 | 43 436 |
| 1720 | 600 000 | 14 | 42 120 |
| 1770 | 700 000 | 18 | 38 610 |
| 1801 | 950 000 | 25 | 38 610 |
| 1821 | 1 350 000 | 39 | 34 749 |
| 1841 | 1 900 000 | 62 | 30 566 |
| 1901 | 5 000 000 | 285 | 17 550 |
| 1951 | 8 100 000 | 1 186 | 6 828 |
| 2001 | 8 279 000 | 1 624 | 5 098 |

The estimates between 1720 and 1901 were made from streets plans.

Sources: Office of National Statistics.

D18. **London urbanization**




The red square indicates the center of London.

Sources: Atlas nathan, ed. July 2006

## 5. The « total » vulnerability factor

This factor, symbolized "$f_{Vul}$", is the result of material and human vulnerabilities combination.

$$fVul = fR_{\$} \times f\ N_p$$

This factor is analyzed under three aspects: geographical, historical and urban.

All urban areas within London and Paris regions are not prone to flooding. In “intra-muros” Paris, the hills of Chaillot, Montmartre, Belleville, Ménilmontant, Butte-aux-Cailles, Montagne-Sainte-Geneviève, and finally Montparnasse, are certainly not concerned by flooding; neither the Valérien Mount and the Saint-Germain-en-Laye terrace, in the peripheral zone. In London, if the "Docklands" are prone to flooding, the "City" is not. But the goal is to calculate a human vulnerability growth order of magnitude to flooding. The banks have always been inhabited and were often the location of industry: easy access to water (historic means of transport), low altitude, enjoyment of a beautiful and calm landscape and the coolness in summer.

Calculating a human vulnerability growth factor to flooding over a period of two centuries may seem impertinent given the needs and development projects that are required to be built immediately. Let one think about the 150,000 missing Ile-de-France dwellings (Serafini, 2009; Ciuch, 2011)! But the time unit for an urban development is a half-century: it is the needed time between the design of a technology, the manufacturing on a large scale, the constitution of its possibly necessary network, and the beginning of the operated project results assessment. Automotive and road networks, the artificial concrete and social housing are examples among others.

Urbanization progresses more and more quickly, notably thanks to new credit, communication and construction techniques. What required before several decades to be built may now be done more quickly, given the increasing demand (75% of the French live in urban areas today) and thanks to the engineering means. Again, the long-term approach allows - perhaps – to adapt better to "time acceleration ".

The development of waterways regulation tools can limit the flood risk, to some extent. However, the more these developments are built, the more extended are the building areas, i.e. officially little or not liable to flooding. The banks of the Seine in Paris became building zones, even if the cellars in these zones are to be flooded. Those located to the West of the capital, in the Yvelines, became building zones in the second half of the 20th century, even if in some buildings, ground floors are garages (Chatou), instead of apartments, as with other housing units on upper land; or even if, as in the plains of Montesson, urban villas estates have been built on areas which have been dedicated to market gardening for centuries. However, on these market garden lands, groundwater can come back to the soil level and cause damage to the urbanized areas.

The Seine river regional developments can fight floods when precipitations are average or intense. However, if they are unusually intense, happen during winter (low evaporation), occur in a way so that the Seine River basin flows, upstream from Paris, accumulate in the capital (instead of being spread out in time), a 1910-type centennial flood will exceed the retention capacities of the dams and dikes and reservoirs. This all the more since the distances between the dams/reservoirs and “intra-muros” Paris are long: fallen rains over this basin portion are not stored and will swell the Seine flows in Paris. If the large Seine lakes had been built before 1910, they could have reduced the level of the Seine in Paris (8.62 m on January 28, 1910) by only 70 cm.

D19. **The Seine river watershed, and its reservoir-dams**[1]


The Seine basin reservoirs/dams are:

- Panesière, on the Yonne river, built in 1949, with a maximum capacity of 82 million cubic meters ($Mm^3$)
- la Forêt d'orient (2), on the Seine River, built in 1966, 205 $Mm^3$
- Der-Chantecoq (4), on the Marne River, built in 1974, with a capacity of 365 $Mm^3$
- Lake Amance and Lake of the Temple, on the Aube River, built between 1989 and 1990, with a cumulative 175 $Mm^3$ capacity
- les Côtes de Champagne, on the Ornain River (100 $Mm^3$), in project

These dams are not only designed to flatten the Seine River basin floods upstream from Paris. Indeed, local and national authorities expect from these facilities several functions: support of flows during periods of low flow, irrigation of farmland and touristic activities (boating, fishing and walking). These other three functions imply keeping these retention lakes partly filled. But to prevent a flood better, those reservoirs should be emptied. Conflicts between water users play a role in flood control policies.

The increasing of security equipment – dams/reservoirs, dams/watergates, dykes - is counterbalanced by a strong rise in risk-taking, because of real-estate speculation; the river shores are actually sought by the populations. River developments give a false sense of security. This tendency to risk taking decreases, in the long term, the Paris and London basins resilience to the risks of major floods.

It is appropriate, secondly, to introduce vulnerability in the hydrological risk formula ($fq_{max}$ x $V_{max}$ x f'q = $f_{hydraulic}$).

Two components of the vulnerability (Vul) can be considered: population living in the area affected by the flood and likely to be injured or killed ($N_p$) and the wealth exposed to this risk ($R_€$).

If the hydrological risk factor is multiplied by the increased vulnerability, it gives the total risk factor, which is called "Fluvial risk factor" (F).

$(f_{hydraulics}) \times (fVul) = F$

or

$(f'q_{flood} \times S_{max} \times f'Q) \times (f N_p \times fR_€) = F$

Insurance companies reflect human vulnerability in financial terms. According to the legislation of each country and to the templates used by airlines, such death will amount to such compensation and such bodily or psychological injury to such other allowance. From this point of view, $N_p$ can be transformed into a simple factor of wealth calculation and thus turned into $R_€$. However one must beware: regional development is also a political - and not only a financial – action, and a hazard (flood) realization has an impact on the way to live, to think and to organize. Development managers – the elected politicians - can rather use, for assessing vulnerability, the initial formula ($N_p$ x $R_€$). The human part is the F calculation axis, and all other factors are aid to do the total fluvial risk factor assessment.

A rain-fed flood arriving on a basin watershed at a time where the flow is low (for example, August for the Seine in Paris and January for the Isère in Val d 'Isère) will strongly increase river flows in comparison to the low regime of the season. This factor is interesting: local authorities – confronted with, for example, an authorization application for a campsite on a river floodplain in summer in the Alps or in the Mediterranean basin - may better understand the risk. A rain flood, notably in low flow season, will not attain a flood level, but may very well reach the major bed - and quickly - as long as the watershed (or part of it) is strongly mineralized (mountains) or urbanized.

For periods of high normal flows, a "rain-fed flood" may result in an ephemeral "flood" i.e. an short-time exceeding of the usual High Water Mark (HWM). If this limited rain recurs or lasts - as in 1910 – one will not talk at all about rainflood but about "flood" and exceptionnaly high flows. In Paris, if the river risk factor ($f_{hydraulics}$) is multiplied by the vulnerability one ($N_p$ x $R_€$), it produces the following formula:

Ile-de-France:
$F_{idf}$ = 54 x $fN_p$ (Idf 2009/1801) x $R_\$$ (Idf 2009/1801) =
54 x 19.67 x 83.80 = 89 011 = $10^{4.95}$

London (« Metropolitan Area »):
$F_{London}$ = 54 x $fN_p$ (London 2001/1801) x (GDP $_{London\ 2009}$ / GDP $_{London\ 1800}$) =
54 x 14.47 x 54.69 = 42 734 = $10^{4.63}$

D20. **Fluvial risk components**

| | Factors (Risks/dates) Ile de France | 1800 | 2001/09 |
|---|---|---|---|
| | Hydrologic hazards $f_{hydraulics}$ | 54 | 54 |
| | Human vulnerability $fN_p$ | 1 | 19.67 |
| Physical vulnerability ($R_\$$) $R_\$ = \sqrt{(f_{urb} \times f_{PIB})}$ | Urban growth $\sqrt{(f_{urb})}$ | 1 | $\sqrt{88.27}$ |
| | GDP growth $\sqrt{(f_{PIB})}$ | 1 | $\sqrt{79.56}$ |

| | Factors (Risks/dates) London | 1800 | 2001/09 |
|---|---|---|---|
| | Hydrologic hazards $f_{hydraulics}$ | 54 | 54 |
| | Human vulnerability $fN_p$ | 1 | 14.47 |
| Physical vulnerability $R_\$$ $R_\$ = \sqrt{(f_{urb} \times f_{PIB})}$ | Urban growth $\sqrt{(f_{urb})}$ | 1 | $\sqrt{36.5}$ |
| | GDP growth $\sqrt{(f_{PIB})}$ | 1 | $\sqrt{81.95}$ |

| | f hydraulics | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Territory | f'q $_{flood}$ | V $_{max}$ | f'Q | fNp (2009) | √ (furb) | √ (fPIB) | **F** | **Log F** 10$^{x}$ |
| Ile-de-France | 3 | 3 | 6 | 19.67 | 9.40 | 8.92 | 89 011 | **4.95** |
| London | 3 | 3 | 6 | 14.47 | 6.04 | 9.05 | 42 734 | **4.63** |

These results show the exponential vulnerability growth of these two urban areas. Whether one be in a period of low or high waters, the total fluvial risk factor is a tool to calculate the overall risk of a development near a river bed. This factor allows to estimate - and thus prevent - potential human and material damage likely to appear as long as a watershed (or part of it) gets urbanized, particularly when the latter occurs at an exponential speed, i.e. in an "acceleration of time" context.

## 6. Conclusion

In Paris, the 1910 flood caused substantial material damage, but less than ten human victims. The risk of flooding throughout the Ile-de-France region is civil: it can involve a part of its economy but not its immediate safety. However, the risk of flooding in London is military: in case of a hazard realization (the reason may be of either climatic and/or anthropogenic origin), the extent of the damage would be such that the security of the region could be challenged.

Flood areas in Ile-de-France or Greater London are in a (per)urban fabric and in a systemic functioning. If a part of this set is affected by a flood, the whole system may be affected. The failure of a central node in a rail or telephone network can interfere with the whole networks. If a flood reaches the 6.20 m level in Paris, a significant part of the underground commuter train (RER) network will be invaded by water.

Any development in the basins downstream of Paris or London fit into a context of vulnerability. Beyond the apparent security of the means of protection against the flooding risk, placing a particular regional development in its context of local economic and population growth allows us to take into account better the material and human stakes of these territories. A better understanding of hazards and risks facilitates choices to increase the resilience of the areas likely to be directly or indirectly affected by floods. These vulnerabilities can be calculated generally (calculation of all of the damages that might be caused by a flood) or in a more detailed manner: analysis of only "flood" hazards as the urbanization of a zone grows, or calculation of only human or only physical weaknesses. This formula fits into an interdisciplinary dynamic, which is a major feature of national and regional development. It takes into account the "natural" (flood hazards), built (urban planning), financial (local GDP), demographic and psychological (mental suffering) aspects of the concerned territories.

A substantive debate would be useful in exploiting existing tools for viable projects in the long term. The artificialization of banks - and especially their concreting - was probably an interesting engineering work but has moved the problem of flooding downstream of these works; it contributed sometimes to make it worse by retaining water, once receding had started. The traditional planning solution for natural (overflow ponds) or artificial flooding zones allows to slow the flood and to divide it into the scheduled areas. "It is better to seek to spread the flood than to contain it (Salomon, 1997)".

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