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The Torrential Crisis in the European Mountains (14th–19th Centuries)

1.1. Introductory generalities on global fluvial systems

Fluvial systems function according to universal principles, governed by fluid mechanics, while remaining subject to regionalized constraints under climatic control; this provides partially distinct forms to northern, temperate and tropical rivers. In most matters and to stick to the circulation of water and sediment, the scientific literature distinguishes "sediment production" zones* (essentially localized in mountain and hill regions), "sediment transfer" zones* and "sedimentary deposit" zones downstream (alluvial plains, deltas, ocean margins). This longitudinal zonation is also governed all over the globe by secondary processes that nuance the general principle.

First, river styles* are under the control of climate, vegetation that more or less protects slopes, and geology that conditions lithology and the ability to mobilize certain types of soft materials. If the balance or equilibrium between liquid flow (capable of ensuring sediment transport) and solid flow (sediment to be transported) is in favor of the former, the material is easily evacuated and the river presents a simple morphology, demonstrating a single winding channel, sometimes classified as a meandering* channel. These channels are found in regions that produce little sediment (mountains and hills with heavy rainfall, wooded, sparsely populated) and in the transfer zone.

If, on the contrary, the liquid/solid fluxes balance is in favor of the latter, then the flows are not capable of transporting the entire load originating from the

production zone. This situation is very frequently seen in regions with semi-arid climates (the slopes there are badly protected), in regions of the globe with a contrasted relief and a fragile structure, and finally in elevated areas that have been cleared and over-exploited for pastures and agriculture (Figure 1.1).

Figure 1.1. *The Selle torrent in the Massif des Écrins (France); it is fed here by an avalanche cone whose base is eroded by lateral erosion from the torrent. The bed comes loose downstream and adopts a braid style (source: J.-P. Bravard)*

The production zone and sometimes even the transit zone are then saturated with rough material; in response, the river channel adopts a particular shape and mode of functioning, braiding*.

The braid style is classically contrasted with the meander style, even though composite or hybrid styles are frequently seen. The excess sediment therefore has a descriptor, or marker, which is braiding, easy to diagnose and interpret based on the dynamic function of the basin. Without anticipating too much further, we can assume that braided channels reveal crises, which are the subject of the first chapters of this work.

Figure 1.2. *A river in British Colombia, the Squamish River. This wandering gravel-bed river*, with a basin well provided in both water and sediment, meanders and braids at the same time in a former glacial basin [HIC 75] (source: J.-P. Bravard)*

Some further questions have join those stated above, at the forefront of scientific investment. These concern:

1) the precise methods of mobilizing material on slopes until they enter channels (this is slope–river bed coupling* or "decoupling");

2) revealing permanent deposit sites at the foot of eroded slopes far from active channels; these are long-lasting, for they are sheltered from erosion by channels (we generally speak of "colluvia"* to distinguish them from alluvia);

3) the importance of alluvial plains as deposit sites for alluvia brought when channels flood; the question also needs to be asked of these materials being recovered when the river channels move on the plain and recover these deposits to incorporate them into its load;

4) the chronology of sedimentary recovery that can ensure a transfer to the system's traps downstream, even during phases with limited material entry into rivers from production zones. In short, the process chain involving production–transfer–deposit and the morphological "continuum"* involving mountain–piedmont

plain–valley are not sufficient to correctly grasp the load of a river that is building its delta.

Finally, let us observe that the globe's rivers, aside from increasingly rare exceptions, have stopped presenting the "pure" mechanisms, that were briefly described, for more than a century (sometimes longer). Sedimentary traps, the complexity of which was just explained, have moved to the background, behind the reality of artificial traps constituted by dams-reservoirs, the number and capacity of which exploded across the globe in the 20th Century.

However, let us move to the heart of the subject of this first chapter, which is the sedimentary crisis of the Little Ice Age (abbreviated as LIA). The knowledge we have of the LIA is progressing in the fields of both hydrology and sediment transfer and deposit, not to exclude the mechanisms that connect these two components. Let us take the example of hydrology. A very in-depth study of the archives of cities on the Lower Rhone has provided great insight into the hydrological rhythm of the river at the outlet of its basin [PIC 14b]. The study of the floods on the Rhône, spread across decades and four degrees of gravity based on their manifestation in the riverbed and in its floodplain, revealed new elements, particularly their classification into two hydrological "hyperphases," the first dating back to 1450–1599 and the second to 1647–1711. The hyperphases are separated from one another by a period of moderate hydrology (1600–1646). On an even finer level, the decade 1701–1710 was the hardest in the history of the river, and before it, the period from 1481 to 1500. During hyperphase 1, an isolated event, the 1548 flood, would surpass even that of 1856, despite it being considered the most significant flood in the Rhône's history, i.e. the absolute "reference" for risk managers in France. Another discovery is the way in which the contemporary hydrological regime was established, with boosts in strong hydraulicity in the decades 1770–1780, 1801–1810 and 1841–1850. If the floods in 1840 and 1856 do not belong to these sequences, it is because these are isolated manifestations on a foundation of weak hydraulicity (Figure 1.3). This figure is one of the markers of the river's new hydrology according to the authors of the study, G. Pichard and E. Roucaute.

It is possible to evoke the reality and the gravity of the long crisis of the Little Ice Age (LIA), because the proofs of highly active processes that affected the torrents and torrential rivers are numerous enough to be convincing. These manifestations allow us to understand the extent of the means used by the inhabitants of slopes and floodable plains to find initially local and provisional solutions, then more or less definitive ones, occasionally benefitting from the help of the public authorities. We will consider the question of the torrential crisis from the LIA from the perspective of several European mountain ranges.

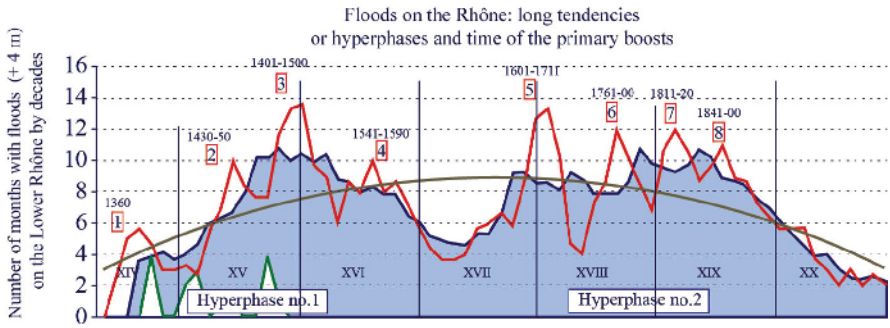


Figure 1.3. *Hydrological hyperphases (black curve) and flood periods (red curve) from the 14th to the 20th Century. The gray line emphasizes the LIA period (source: [PIC 14b]). For full color image see: www.iste.co.uk/bravard/sedimentary1.zip*

1.2. Manifestations of the LIA crisis in the river valleys of Western Europe

1.2.1. *Mountain crises*

Historians have collected testimonies in the high valleys of the Western Alps. Two works are interesting insofar as they pose the question of a change in the torrential and river landscapes during the Middle Ages based on texts and in little-known terms, without being able to reference the later notion of the Little Ice Age, which did not yet exist when they were written. The medievalist historian T. Sclaffert [SCL 26, SCL 59] observes that Seyssins, located near Grenoble, had a port on the Drac, from which, curiously, boats departed, whereas (later) iconography shows us that the Drac was a torrent congested with pebbles in the modern era. The historian hardly goes beyond the 14th Century to find torrential activity in the Northern and Southern Alps, but the crisis (in the broad sense) is indeed present. T. Sclaffert describes valley floors covered in fields, orchards and prairies on riverbanks; later, the rivers become torrential, capable of ravaging the valley floors during floods. The agricultural wealth went along with the existence of numerous mills and “artifices” that have since disappeared. This research provides raw facts that are all the more interesting in that they had no explanatory objective and that no manifestation of the change in landscape is sought to support a theory that did not yet exist.

Here, we will use the great work by forester Paul Mougin (1866–1939). It certainly comes after the laws voted on in France to restore mountain territories (1860 and 1882), but it provides a very interesting historical overview of the causes of deforestation in Savoy.

P. Mougin [MOU 14] adopts the standpoint of his original post when he positively emphasizes the foresight of the mountains' inhabitants (both monks and farmers) but negatively emphasizes their "spirit of profit and plunder" to explain elevated clearings and illegal deforestation as well as pastureland abuses in the forest, not to mention supplying mines, salt manufacturing and glass factories with lumber and fuel, or even the destructive effects of wars. The degradation of forests seems to be attested to in the Ancien Régime in France (1589–1789), but it is not possible to create a hierarchy of these factors. The author dates the first measures to ban deforestation back to the decisions of the Senate in Savoy (the first in 1559, renewed in 1594, 1654, 1666 and 1667); these decisions went into effect through a royal decree in 1723 applicable in the Duchy of Savoy, then by the Royal Constitutions of 1729 and 1770. P. Mougin accuses the confiscation of religious and noble property, following the annexation of the Sardinian province in 1792, of having allowed a loss of all control over the forests to exclusively favor the communes and their inhabitants; the end of the Empire (1815) is also a period considered by P. Mougin to be harmful for afforestation. The period of Sardinian restoration (1816–1860) did not bring about improvements, despite the restoration of the "royal regulations".

For our purposes, it is interesting to see how the Sardinian legislation dealt with the question of defending against torrential rivers. The Royal Constitutions from 1792 were meant to promote measures limiting "corrosion" and the meandering of rivers: it was forbidden to burn and uproot trees in a stretch measuring approximately 6 m wide, and it was necessary to plant them where there were none. The communes and riverside landowners were responsible for this work. A regulation from 1739 states that commune administrators can impose repair work for "washed away or damaged" river bottoms upon riverside inhabitants (at their cost!); this meant facilitating damaged lands to be farmed again in the interest of their owners and the tax authorities. These measures, reestablished in 1816 when Savoy returned to the kingdom of Piedmont-Sardinia, would remain in effect until 1860. It is surprising that these measures only concerned "rivers and torrents", actually torrential rivers, without observing torrents *per se*, i.e. the sources of the denounced damage. One hypothesis would be that the steep slopes leading to the primary branches of the hydrological network provided too little return to be worth attention.

There are also some testimonies – today we would classify them as "geoarcheological" – concerning the medieval and modern eras.

One inhabitant of the Barcelonnette region provided a first-hand account dating back to the period of extensive forest restoration works. He described thick arable soil underneath the torrential blocks, free of stones, that was "certainly cultivated": this soil contained tools and held a rock wall and poplar trunks in place. Fossilized under thick alluvial fans from the torrential cone of the Riou Bourdou measuring 2–8 m, this agricultural landscape dated back to the early 15th Century, at the latest.

Without citing every element published by a wide range of authors, there is abundant proof of a significant rise in rivers due to coarse alluvium deposition: in the bed of the Giffre (Haute-Savoie), where the poles carved in the late 13th Century and sunk into a marsh are fossilized under pebbles [PEI 86]. In the Chautagne marsh, at the edge of the Rhône in Savoy, peat stopped forming around 1170±140 A.D. due to the massive arrival of overflowing silt deposited by the river's flooding [BRA 87]. An attempt to map the first manifestations of alpine torrentiality based on the published literature provided us with the dates included in the range of 1336–1471, but it goes without saying that such a map should be updated using new intensive research in the medieval archives. It would most likely differ from the prototype, with earlier beginnings and thus fewer dates dating back to the 15th Century.

1.2.2. *River crises and metamorphoses of the Drac and the Isère in Grenoble*

In the 1920s, a pioneering work was written by the engineer Bouchayer regarding the lower Drac [BOU 25]. He showed that the floods in 1277, 1373–1377 and possibly 1414 did not change the morphology of the Drac, but rather that the numerous floods occurring between the late 15th Century and 1675, which we know about because Grenoble's city defenses were directly affected before the works organized by Colbert starting in 1683, belong to a long series of floods in the city and stronghold of Grenoble (Figure 1.4). Furthermore, measures were taken against deforestation in the basin starting in 1565, because this was assumed to be responsible for torrentiality. Finally, the dykes on the Drac were extended to the foot of the Chartreuse Mountains in 1771–1782 in order to limit the damming effect produced on flooding Isère (see below) [SAL 91]. This research, using somewhat obsolete methods, was the first in France to pose the question of variations in the hydrology, solid transport and morphology of an important torrential river.

Figure 1.4. *Map of the damage caused on the outskirts of Grenoble by the flooding of the Drac on October 5, 1616. The Drac braided through the pebble banks and threatened Grenoble's fortifications (source: © Grenoble city archives)*

The most convincing example is that of the Isère, upstream from Grenoble. This large river, which receives the Drac immediately downstream from Grenoble, does not seem to have been affected by floods before 1469 [CŒU 03], and the convergence of its flood with that of the Drac is recorded in 1524–1525. The water levels of the Isère (and that of the floods in the city of Grenoble) are affected by the hydraulic damming exercised by the Drac (1604). The writings of engineer Pierre

Rolland (1741) and his son Jacques (1787), as well as a map of the course of the Isère (*Carte du cours de l'Isère*; referenced in Figure 1.5), describe not only the flooding space [BRA 10a] but also the braiding downstream progression of the Isère in the Grésivaudan valley, to the detriment of Grenoble's reach meanders, which were cut off. Also described are the filling of the bed and the reduction of the hydraulic capacity* at the crossing in Grenoble, as well as the aggravation of the overflow and speeds on the alluvial plain. P. Rolland observes that before the cutoff of the meander in Gières in 1731 (C), the riverside plains along the Isère were submerged:

> "[…] long before the territory of Grenoble had suffered the slightest overflow… whereas the plain and the territory of Grenoble, since the era of this cut-off, were covered with water long before those from the parishes below" (1741).

Figure 1.5. *The Isère and the Drac in Grenoble in 1741. The Isère meanders and flows to the west (left); the Drac converges with the Isère downstream from the city (the Drac is dammed, but forms an alluvial fan in the northwest). The green area represents the spread of the flood on December 21, 1740; the outlet channel project bypassing Grenoble is represented (source: © Departmental archives of Isère). For full color image see: www.iste.co.uk/bravard/sedimentary1.zip*

In an essay dating back to 1787, J. Rolland observes that:

> "[…] the floods… pouring over the plain where currents have been established by the height of the overflow fill the old passages with deposits of gravel and open new ones through the best grounds… The river destroying its banks enlarges its bed, divides its waters, and thus no longer has enough strength to carry the matter that the torrents deposit there, its bed rises to the point that the slightest floods will soon form an overflow there."

As for Grenoble:

> "[…] the Isère crosses it through a channel that can only transport about half the volume of water that it provides during floods, such that the insufficiency of the outlet produces cataracts and currents so large in the streets and around the perimeter of the city that there has always been scouring following which the walls were seen falling, the plantations ripped up, and the buildings collapsing…"

This causes "humidity and deadly diseases". The engineer J. Rolland, beyond the simple repetition of the floods and their effects, analyzed river metamorphosis* before his time, although without conceiving the relationship between the changes occurring on the Drac (the earliest of these) and on the Isère afterwards. The time gap between the reaction of one river or another is now explained by the faster spread of alluvia from the Drac downstream due to the proximity of the sedimentary sources from the upper basin, the very steep slope of the river and the limited storage capacity of the gorge sections. The two studies of the case of the Drac and the Isère are even more remarkable given that they are located at the large confluence in Grenoble. The example of the Isère in Grenoble shows the extent to which the knowledge of rivers was concrete; the large mechanisms were well understood and on the right scale in the late 18th Century. The engineers in the 18th Century did not conceptualize, but they acted empirically and intelligently. Today, we know that the recent concept of "river metamorphosis" applied to these alpine rivers where it had been understood.

The Southern Alps were the subject of fewer works, but the testimonies collected by C. de Ribbe [RIB 57] come together to describe rising rivers. According to a manuscript from before the French Revolution, the Bléone rose three feet at the bridge of Digne; other cases of rapid rising are indicated in the Issole, the Asse, the Durance or even the Ubaye in Barcelonnette. Recent works performed on small territories confirm the state of advanced degradation of rural spaces.

1.2.3. *Flooded piedmont plains in Switzerland*

Grenoble's situation in the 18th Century is particular in that the valley floors, formed by glaciers, are broad enough there to store alluvial sediment and waters. This is also the case in Switzerland, when torrential rivers in the Bernese Alps, loaded with gravel and murky waters, took material over once-flat glacial valley floors occupied by lakes and drained by rivers deprived of the energy necessary to evacuate the torrential material.

The diversion of Swiss rivers from the 15th to the 19th Centuries demonstrates the intensity of the conflict between the humanization of the valley floors through clean-up and the growing constraint exercised by the torrents originating in the nearby mountains. Work has been done according to the possibilities, with no particular model (but possibly the Brenta, which drains Veneto, serves as an example) [SCH 92]. The first, modest deviation of a Swiss river took place starting in the 15th Century to protect Buochs, a village threatened by the Engelberger Aa, a tributary of Lake Lucerne, upstream from Lucerne.

The first important correction is located in southeastern Bern. A tributary of Lake Thun, approximately 30 km southeast of Bern, the Kander was born of a glacier under a 3,650 m summit; its heavily loaded floods joined the Semme and flooded the low alluvial plain west of Thun, threatening to flow into the lake and block the course of the Aar downstream from the city. In 1711–1714, under the impulse and management of soldier and surveyor Samuel Bodmer (1652–1724), then Samuel Jenner, the Kander was diverted into two parallel tunnels dug into the rock of the secondary range in Strättligen using rough tools; this work then allows it to flow directly into Lake Thun, thereby relieving the city. The tunnels having collapsed, the river dug its bed in the rock to a depth of 40 m. Regressive erosion up to a depth of 5 m resulted from this; it spanned a length of 4–5 km, bringing about a loose alluvial substrate. Similarly, a delta composed of sand and gravel formed in Lake Thun, with a depth of approximately 60 meters. Nothing was truly regulated by these works, for the heavy inflow raised the level of the lake and threatened the banks due to a failure to enlarge the lake's outlet [VIS 11].

The last example that we will use is the correction of the Linth, planned in 1784 and successfully executed between 1807 and 1816 according to a plan by the Badish engineer von Tulla, the same man who corrected the Rhine. The plain located between the outlet of Lake Walen and that of Zurich was occupied by a broad river, the Linth, whose floods caused great damage. Under the authority of the engineer Escher, the Linth was the subject of double channelization, one cutting through the river braids over a length of 15 km, the other an upstream derivation through Lake Walen (called the "Escher Canal"). These works were done using piles of fascines capable of holding the sediment percolating through the branches and creating a new

bank downstream step by step. This work was meant to calm the Linth's flooding, before the plain was crossed by the Linth canal, leading to Lake Zurich. This is a great example of hydraulic protection, even though it required several decades of effort to obtain very high efficiency.

1.2.4. *Sedimentation and large works in Italy*

It is undoubtedly in Italy that the problems of torrentiality were the most severe, possibly because the geographical configuration juxtaposes steep mountains (that are also densely populated and thus fragile) and low land with uncertain drainage. It is not excessive to make a comparison between certain alpine configurations and that of the Appennino Tosco-Emiliano, where the torrential rivers drain the mountain towards the Po plain on the one hand and the Tuscan plane on the other hand, the Arno serving as a primary drain there.

In Florence, the rise in the Arno's bed between the Saint Nicolas and Toussaints dykes became concerning in the 16th Century [FRI 74]. Viviani shows that the process takes place up to the sea and is due to the convergence of multiple factors acting in a cumulative way: a context of sedimentary overabundance (and rise) on the tributary branches draining the Apennine, notably on the Bisenzio and the Ombrone; the loss of head caused by mill thresholds; and finally, the narrowing of the bed caused by the arches of bridges. As an example, the large palace of the Uffizzi in Florence had been built in 1560 by Vasari; it had most likely been established above the level of the heavy floods, during an era when rising water levels were still limited, but in 1677, during the restoration of the palace's foundations, Viviani had the low windows of the stables, which water and mud could enter, partially bricked up.

In the late 16th Century, the projects to correct the Arno aimed to no longer leave "such a beautiful, rich and magnificent" city exposed (Figure 1.6). These projects can be divided into three categories:

1) by-passing Florence by digging a new flood bed, fed by a spillway, but with the risk connected to excessive speeds;

2) building up the Arno's parapets in the city by closing all openings, including the drains that would be transferred downstream; it is true that this choice would have caused a "loss of the beautiful view over the Arno" and would have made it "an entire river seemingly suspended in the air between two walls";

3) lowering the Arno's bed as it crossed Florence by eliminating the works raising the shoreline in the city while preserving the large dyke upstream to catch gravel.

In the late 17th Century and after great procrastination, the policy adopted to protect Florence was to catch the alluvia on the mountain. Torrents like the Nievole, the Serchio or the Era were outfitted with "dykes", essentially small river dams built to block rocks and gravel; these works allowed sediment to pass, however, and Viviani recommended constantly raising all the Arno's tributaries as well as the bed of the Arno itself, all while reforesting the tributaries' basins. This example shows that the defense of Florence, initially planned in the 16th Century, adopted in the late 17th Century the principles that have become classics for combatting torrents and, further downstream, classic for protecting against the flooding of torrential rivers. Disputes are therefore lively between the followers of sedimentary retention and those who doubt the ability of dams to efficiently catch material.

The policy adopted in Florence in the early 18th Century confirms the control of the Arno's tributary torrents, but the opposite policy was adopted for the river, in order to improve the conditions for navigation and conquering lands. At great cost, the Arno on both sides of Florence is narrowed between the longitudinal dykes and straightened to reduce its length by 7 or 8 km, at the expense of broad sinuosities earlier on. The result of these works is a several-meter rise in the bed between the dykes and a descent of rocks and gravel further downstream, where they fill a large section that previously had always possessed a sandy bed (Figure 1.6). This policy of cutting sinuosities, pursued downstream between 1740 and 1760 to protect Pisa from the flooding Arno, was harshly condemned by the engineer P. Frisi [FRI 62] on the grounds that it was inefficient and harmful.

Figure 1.6. *The Arno crossing Florence, looking downstream. This "view" of Florence shows the large transversal dyke retaining sediment and the extension of the river immediately upstream from the city; this is due to the erosion of the natural bank and significant deposits (source: Fondazione Cassa di Risparmio, Florence)*

In Emilia-Romagna, the question of alluvium accretion on the Po and its tributaries originating in the Apennines was more serious than in Florence. We will see the way in which the disputes between cities concerning the lower reach of the Reno (this is the "Reno question") were a factor in the progress of Italian hydraulic science (Chapter 2). In the late 18th Century, the bed of the Reno and that of its tributary, the Sammoggia, rose on the gravel descending from the mountain and progressed ever further, as on the Arno. The Po's plain became increasingly marshy between Bologna and Ferrare. There are several competing drainage "lines", from the direct route to the Po Grande, starting towards Ferrare in 1522 and sought after by the Este family who defended the interests of the city of Bologna, to routes leading to the Comacchio lagoon, borrowing the route of old branches of the Po. The definitive route (the *cavo Benedettino*) was created under Pope Benedict XIV in the 1760s. The channel combines several functions: directing the Reno's waters, navigation and on-land deposits. It adopted an artificial route going through Argenta and leading to the Po Morte di Primaro before reaching the Adriatic Sea. Experts who were against the digging of a new straight bed for the Reno towards the Po Grande had claimed that the arrival of gravel from the mountain would make its bed sinuous and rise and threaten the dykes and the surrounding countryside located further down. This was actually the case during the 1648 rupture of the dykes at Cento, after which the plain was ravaged by the flood [LUG 13].

Another "classical" region regarding dangers connected to fluvial alluvium accretion is that of Venice, i.e. the lagoon, port and *grau** through the lido* and thus "la Serenissima" itself, then considered to be threatened by death. The Venice lagoon appeared around 7000–6000 BP*, when the sea level stabilized to be around the current level. The regional coastal rivers brought the sand that the long-shore drift* modeled into an open lido through passes. The site in Venice was chosen in the 5th Century AD due to the protection that the island could ensure in the face of threats coming from both the sea and the continent. To ensure its longevity in the face of river backfilling caused by the coastal tributaries (the most important of which was the Brenta), the lagoon could hardly count solely on the slow tectonic subsidence* experienced by the Po's low plain, to which the compaction of Holocene sediment deposited since the rise in the sea level is added.

The Brenta is a 160 km coastal river that starts in Trentino, drains the Valsugana and leaves the Alps in Bassano; today, it is adopting a piedmont plain route that leads it to the Adriatic Sea south of Chioggia, avoiding the Venice lagoon to the east [BON 03]. A good geomorphological map reveals the spatial scope of the immense alluvial fan of the Brenta, which was noted thanks to old channels still filled with water; they are occupied by the phreatic flows from large sources originating at the edge of Pleistocene gravel from the high plain and fine sediment from the low Holocene plain. The river, random in its movements, has occupied the territory

between the fans of the Sile and the Piave to the northeast and the Euganean Hills and the fan of the Adige to the south [BON 08]. The successive channels of the Brenta River, dated Roman and Medieval, naturally fed the Venice lagoon, where river levees were observed and properly dated. The last natural branch (the *Medoacus Major* in texts) reveals a change in the Brenta on the northern blank of its fan in the 6th Century AD, possibly during catastrophic floods that occurred in the fall of 589, according to the chronicle written by a contemporary.

In the Middle Ages, waterways played a remarkable role in the political, military and economic histories of the large cities of Veneto. In the 14th Century, Venice, a rival of Padua and Treviso, became not only a maritime power but also a land power. The density of the hydrographic network played an essential role in ensuring the economic prosperity of these cities, and Venice could legitimately claim that controlling the water was vital for it, as it was for the prosperity of Padua. The Brenta provided Padua's economic outlet and allowed it to construct its *contado*; it also constituted the hinterland* of Venice, which the river was to provide with food and wood flowing downstream. The Brenta also provided Venice with potable water endowed with excellent organoleptic qualities complementing the scarce water supply provided by polluted wells below city plazas to drain rain waters; in 1425, the Brenta became the only source of water authorized by the city magistrates. If the little river brought prosperity to Venice, it was also the cause of its decline. The city always had to defend itself, but "the most formidable danger was not only the sea and the men it brought, but also powerful, disorganized forces, those of nature, which dominated the continental water, i.e. rivers" [BEV 95].

In 1141, the Paduans rerouted the Brenta directly towards the lagoon using the old route, the branch of the Medoacus Major [RIP 03]. However, the river naturally leads to Venice, which is thus threatened by the construction of an interior delta, by the deposition of sand at this site and by the closing off of access to the sea provided by the *Canale Orfano* through the lido. To ward off these threats weighing over the city, the *Medoacus Major* was closed in 1191 by the Venetians so that the Brenta would flow a bit further to the south. The hydraulic story is then one of debates and conflicts to remove the mouth of the Brenta from the Venice lagoon by constantly moving it further to the south, until the *Brenta nova* was opened in 1540. By proposing a new route for the river, the engineer Marco Cornaro (1412–1464) had thought up several radical solutions meant to stop the accumulation of sand and the paludification* of the lagoon at a time when the excessive deforestation in the Alps was already being denounced. This rerouting risked modifying the lagoon's equilibrium, interrupting navigation and stopping mills and the provision of potable water. Debates were heated, and in 1501, the Republic's Council of Ten named a Magistrate of Water; in 1505, he established a *Collegio Solenne delle Acque*. These measures alone speak to the extreme importance granted to water management. The final decision would be made to ensure the rerouting of the lagoon to the south to

make it operational in 1610. In 1613, to reduce floods and due to the insufficient size of the *Brenta nova*, a water collection channel (the *Taglio nuovissimo*), running north–south, was dug between the *Brenta nova* and the lagoon [BON 12].

A similar, though somewhat more modest story is that of the two other coastal rivers, the Sile and the Piave, that silted up massively in the northern part of the Venice lagoon during the great flood of 1533 [BON 04]. In the 16th Century, the engineers of the Republic of Venice forced the Piave and the Sile rivers to flow to the northeast, into the "old" Piave. In the end, Venice's obsession with protecting itself from river contributions was translated by large works to push the threat of the Po to the south. The downstream course of the large river actually shifted to the north and threatened to capture the Adige and to fill the port of Chioggia. In 1600–1604, Venice rerouted the *Po di Tramontana* towards the south into the *Taglio di Porto Viro* that had just been dug.

At the end of these sometimes-lively debates, an exceptional corpus of hydraulic knowledge concerning the balance between rivers, the lagoon, the wind and the sea ended up being created, taking into consideration the currents of fresh water and the pressure of salt water. Modern water science was established in Venice, as well as other parts of Italy, but like nowhere else in the Western world.

As a partial conclusion concerning mountain regions, the long erosive and river crisis of the Little Ice Age greatly affected Italy starting in the 16th Century and lasting until the mid-19th Century. France was prematurely affected, but the convincing testimonies are only significant in the 17th Century and particularly in the 18th Century. The Mediterranean and Apennine mountain climatic background and high human densities combined to fragilize these mountains. One of the favorite subjects of current research is actually attempting to take human and climatic factors into account for the onset of erosive crises across territories. The range of knowledge in the modern era never mentions the hypothesis of aggravated precipitation nor even natural factors encouraging erosion. Pragmatic solutions dealing with the anthropic causes of erosion result therefrom, but they would be no different if natural causality had played an effective role recognized as such.

In any case, the policy to protect deforested slopes and correct torrents began actively in the late 16th Century in Tuscany, whereas nothing was to be observed in France or in the field (but this would need to be verified with precision, and the discoveries, if they are made one day, will likely be limited) nor in the scientific literature that is well identified. Jean-Antoine Fabre is most likely the first French scientist to tackle the question of torrentiality, both theoretically and practically, if we trust his 1797 treatise. His work comes more than a century after that of Tuscan

Vincenzo Viviani (Chapter 2). Italy was certainly at the forefront, but it is very clear that its cities, in a position of both political and commercial powers, had that ability to kindle the scientific spirit and mobilize it rapidly and intensely; a dense network of wealthy cities located on piedmont plains and near torrential waterways could attract the benefits of active patronage.

Without excluding the ability of these cities to react, the precocity of their responses to crises on the Po's plain and in Tuscany could also be an indication of the premature appearance of serious difficulties that could have made "systematization" necessary on the part of these cities; this was also true, at the level of the drainage basins, since the recommended and implemented measures extend from the high basins to the river, sometimes until the mouth, as can be seen from the example of the Arno. It is at the level of the mountain basin that the constraints are mastered and at the level of the river basin that we can hope to find the responses to the question of floods, drainage and improvement in a period characterized by a growing need for wheat.

1.3. The difficult mastery of the Rhine delta in the modern era

Far from the Alps, whose sediments originating from the alpine Rhine are caught in Lake Constance or drained by the Bavarian upper Danube, the Rhine discharges the waters from a basin measuring 198,000 km^2; as for the Meuse, it drains a surface area of 36,000 km^2. A relief of hills, plateaus and old mountains provides a diversified load that feeds an active delta. The low valleys of the Rhine and the Meuse in their common delta somewhat resemble the fluvial Veneto in that the gentle slopes and high average discharges accommodated heavy floods and significant solid fluxes during the Little Ice Age. We will examine the way in which the dynamics of this climatic period manifested themselves concretely in the preparation of the fluxes into this delta over the last centuries.

1.3.1. *Flow distribution between river branches: an age-old battle against the elements of nature*

The river network in the Netherlands has been organized since the Middle Ages; elevated dykes were built between 1050 and 1350 to set the route of river branches and protect the delta plain against floods. Nothing was gained, however. St. Elizabeth's flood took place on November 18 and 19, 1421, in the regions of Holland and Zeeland, particularly in the Biesbosch, the space located between the Waal and the Meuse, moving through the city of Dordrecht. A storm that built up over the North Sea broke the poorly maintained dykes surrounding the polders, ravaged

dozens of villages and caused the death of thousands of inhabitants all the way up the Waal estuary (the downstream Rhine) affected by the storm surge (Figure 1.7). Although polderized, the Biesbosch remained a wetland after this catastrophe, with 7000 ha of artificial lakes having come into contact with the rising freshwater during high tide until 1970. The Biesbosch has been one of the most beautiful national parks in the Netherlands since 1994.

Figure 1.7. *Extract from a map of Holland representing the downstream course of the Rhine and the Meuse. Drawn by Daniel de la Feuille in 1706, it was republished in 1747 by Paul de la Feuille in J. Ratelband's atlas. The large lake is the Biesbosch, created by the bursting of the dykes on the Rhine in 1421 (source: Wikimedia Commons)*

Since the works of the Medieval era, the course of the Rhine and its branches has been fixed without ever being secured again. Downstream from the city of Lobith, quite close to the modern-day border with Germany, the Rhine extends through its major branch, the Waal, below the village of Nijmegen. Another branch of the Rhine, parallel to the Waal but 10–20 km to the north, takes the name "Nederrijn" (lower Rhine) or "Lek" once it has passed Arnhem; on its right, it has lost the branch of the Ijssel that flows to the north towards the Ijsselmeer. As for the low Meuse, its course is parallel to the Waal, with which its bed is locally anastomosed.

One hydraulic difficulty has shown itself through the centuries, primarily in the 16th Century. This is the relative reinforcement of the flow through the Waal to the detriment of the secondary branches, the Waal having captured 90% of the water

and the other distributary channels only 10%. The strong flow of the overflowing Waal threatened the country with floods, whereas the impoverished branches, notably the Ijssel, saw sedimentary accumulation, the current's low speed no longer allowing the material to be evacuated. It was in 1707 that large works were performed to enlarge the stretch between the Waal and the bifurcation of the Ijssel in order to reinforce the flow leading to the Ijssel, thus to restore the balance of the flow distribution. This was performed through the digging of the Pannerdensch channel, in the bed of the river branch. However, this was also followed (rather logically) by the modification of the Nederrijn, which also reacted to the increase of the flow from the Waal. Next came ruptures of the dykes and serious floods, great instability of the stretches of the river that underwent sedimentation and incessant works to reconfigure the branches and bifurcations. In particular, low dykes and movable partitions were built to keep the low floods in the river channels. In 1745, the goal was set to give two-thirds of the Rhine's water to the Waal, one-third remaining for the Pannerdensch channel and then for the Ijssel and the Nederrijn. This was a long and difficult task [HES 02b]. In 1753, the Dutch Academy of the Sciences in Haarlem proposed responses to the following questions:

> "To what extent have the rivers in the Netherlands risen on their sediment since the turn of the century? By what means can we remove the deposits of sand and mud formed in the river beds and how can we prevent sedimentation?" [MID 97]

These questions show that the problem was very well stated. The later works were crowned an empirical success, which was probably enough for their promoters. The desired result was achieved in the mid-1780s thanks to the placement of a new generation of spurs allowing another water partition, and "normalization" was also obtained in the mid-19th Century, after which harnessing became systematic and led to the definitive fixation of the river branches.

1.3.2. *Returns on destabilization*

Recent research has allowed us to theoretically understand the profound causes of the changes recorded since the Middle Ages and the reasons for the recorded success. The medieval dykes, with their increased height, had not modified the river environment, but the Waal tended to slowly increase its part of the water and sediment flow, while the secondary branches were progressively blocked. The work performed between 1350 and 1707 returned balance to the flow distribution between the branches of the Rhine through the artificial reduction of the width of the branches. The consequence of this heavy modification of the hydraulic geometry

was the modification of the energy applied to the floor of the channels through surface unity, particularly in the annex branches. This work was not sustainable, for the same causes produced the same effects: despite the digging of the Pannerdensch channel, which was in use for a few decades, the Waal maintained its supremacy and its relative excess of energy restored the imbalance to the detriment of the secondary branches, endlessly subject to excessive sedimentation. As we saw above, it is the complete harnessing of the system that allows us to maintain a totally artificial balance, capable of balancing out the natural tendency to create a single bed through the Netherlands [HES 02a].

1.4. Observations on the torrentiality of the Southern Alps in the late 18th and 19th Centuries

Until recently, the French Southern Alps had been one of the chosen lands for manifestations of torrential erosion in Europe. They owe this to natural characteristics like the abundance of outcrops made of fragile marly rocks, tectonics disrupted by orogeny and, of course, the characteristics of the Mediterranean climate with strong autumnal water vapor, not forgetting the melting of mountain snow in the spring. These natural traits do not sufficiently explain unbridled torrentiality. In fact, it is best to consider the high human density of these mountains, as well as the methods of exploitation that made the slopes valuable, both for agricultural plowing as multiple forms of pastures. In this regard, transhumance, which involved welcoming large herds from the Provence lowlands in the summer, must have contributed considerably to the weakening of elevated lands leased by these communities. We have decided to consider the way in which the contemporaries, who were eyewitnesses, tackled this question.

1.4.1. *A highly degraded state of affairs in the late 18th Century*

Thanks to Charles de Ribbe (1827–1899), we have a precious and most likely trustworthy work, written in 1857 by a legal expert from Provence [RIB 57]. “Attaching a singular value to tradition on taste and principle”, as he himself maintains, Charles de Ribbe, lawyer in the Imperial Court of Aix and legal historian, familiar with the archives of Provence, was the archetypical conservative legal expert in his youth, partisan to a coercive policy concerning the abuse practiced in the mountains of the Southern Alps. At the end of his life, he had moved towards the social ideas of engineer and sociologist Frédéric Le Play. Struck by the 1856 Rhône floods, the Durance and its tributaries, C. de Ribbe recounts, in detail, the story of the relationships between the mountain communities and the law under the Ancien

Régime, in Provence, which he called the "natural fatherland of torrents" (Figure 1.8). These abuses were followed by the absolute prohibition of deforestation, clearing and thinning or slash-and-burn*, ancestral practices that were motivated by a search for land to plant wheat and that were held responsible for the erosion of the thin, arid soil of the alpine slopes. The resistance of a population that considered itself impoverished and the calamities due to torrents hindered the strict application of the law; today, we would call these "humanitarian reasons". The most serious cases were, according to Charles de Ribbe, those of the villages of the Saint-Laurent-du-Var and Gréolières. However, the law had its say with the royal decree from April 12 1767 authorizing, clearing and even granting premiums; we can also mention the tolerance allowed by the law from Floréal 9, year XI[1], the source of the accusations of laxness made following this period of French history. Charles de Ribbe finally denounced the later insufficiency of the 1827 Forest Code, which gave full liberty to the owners to use and abuse their forests both to collect wood and for pastures and burning. The opinion of this legal expert, who was certainly not an 18th-Century man, but who was capable of understanding the century according to the law that he had put in place, provided a counterpoint that was indispensable for analyses by naturalist foresters.

During the French Revolution, engineer Jean-Antoine Fabre dedicated several pages of a treatise on the means of preventing destruction by torrents and their formation in the department of Basses-Alpes [FAB 97]. With benefit of inventory, it is the oldest published text that we have in France (Figure 1.9. (a)). Fabre recommends avoiding clearing or imposing restrictions on them, such as leaving cleared strips, since the walls (check dams) prescribed by law had not been built; reforesting the mountain by planting acorns and beechnuts to populate these areas with oaks and beeches and grassing over the land by planting the seeds of adapted plants. It is nearly certain that some of the practices recommended by Fabre and commonly used in the 19th Century were already in place. Doesn't this forester report the only means known at the time to "destroy torrents"?

> "This method involves taking them from their origin and barricading the bed at intervals with stakes thrust into the ground, intertwined with trees placed across them and covered with stones. This will form an obstacle that will stop the water during storms and force them to deposit everything they are transporting. As the floor rises due to deposition, these works will also be raised until the torrent bed is entirely filled. Then, to prevent renewed formation, it will be greatly prudent to plant bushes at this site".

1 Floréal, year XI: April, 1802–1803.

Figure 1.8. *Extract from Trudaine's atlas for the generality of Grenoble. Haut-Dauphiné no. 7 (1745–1780). "Path through the Die Gap, Drôme, Hautes-Alpes", along the torrent of the Petit Buëch. The alluvial fans from the mountain chains are very active; note the Buëch's braid style (source: National archives, CP/F/14/8479)*

Fabre does not recommend "walls", for they are costly and responsible for scouring at their feet, creating a cascade. Walls already existed in the Haute-Provence landscape, such as on the Mezel torrents that converge with the Asse; the bed there is large enough for the scour pool at the foot of the wall to be limited. Fabre's negative experience regards the Cébière torrent near Castellane, into which a scoured wall collapsed. Fabre considers any effort to "destroy a torrent"[2] useless and he believed that it is too late once the torrents have already dug deep "valleys" or when they are dug up to the rock. This minimalist position taken by Fabre, who is nevertheless an experienced observer, suggests that the practice of thresholds or dams (his "walls") was still in its infancy, unless they were excessively prudent or the financial means were truly lacking, which is also possible.

2 In the 19th Century, we would speak of the "extinction" of a torrent.

The oldest report we have found on the torrentiality of the Diois (Drôme) dates back to 1860, but it concerns an initiative taken in 1804. In the commune of Menglon, the Boidans torrent threatens to bury the hamlet of Gallands under gravel. The 1860 document[3] demanded urgent action both to reforest the mountain and to build a dam to hold back the alluvia. He mentions a check dam made of dry rocks, measuring 7 m in height, built in 1804 with the same goal (in 1860, vestiges were present). This dam had produced erosion downstream, which destroyed the retaining walls of the village houses. This is only one example, and a systematic search would likely reveal this practice and show its use across the Alps.

1.4.2. *Prefect Pierre-Henri Dugied's project (1819)*

Soon after his arrival in the department of Basses-Alpes, Prefect Pierre-Henri Dugied presented an "afforestation project" to the Interior Minister. As he had just arrived from the subprefecture of Joigny, in Yonne (South of Paris basin), he had no experience with torrential activity, but he learned by taking a tour around his precinct [DUG 19]. The report that he wrote was meant to inform the departmental functionaries and French agricultural societies about the issue. In accordance with what a Restoration prefect was duty-bound to write, it was the Revolution and the laxism of the courts that were responsible for the excessive clearing and deforestation in the mountains. As corrective measures, Dugied proposed planting forest species, premiums to communes, and he showed himself to be very cautious concerning work on the mountain torrents, which he would delay for 20 years in his personal capacity. He was drawn in by techniques used by a landowner (and local representative) with a physiocratic leaning to conquer lands on the Asse River using dykes encouraging deposition. Following this visit, the prefect gladly dedicated more generous state funding, increased through owners' contributions, to conquer 4000 ha of beautiful river land along the Durance, the Bléone and the Verdon. In order to "box in torrents", it was rather a matter of reducing the influence of torrential rivers for the benefit of rich agriculture. Dugied's concerns distanced themselves from the mountain source of the issues; the project is, as we can see, somewhat lacking in orientation.

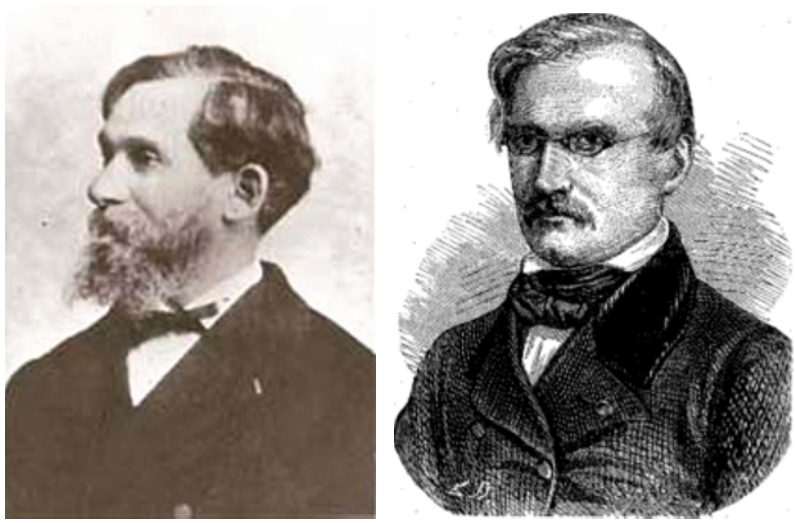
1.4.3. *Alexandre Surell, author of the French policy for restoring mountain territories*

The best-known specialist on alpine torrentiality is Alexandre Charles Surell (1813–1887). A graduate of the *École polytechnique*, he was named bridge and road

3 Archives of the Drôme, 57 S 46.

engineer for the department of the Hautes-Alpes in 1836 (at the age of 23), a position he would stay in for 7 years (Figure 1.9. (b)).

Two years after his arrival, Surell wrote a famous text, the content of which is based on the effects of the floods that occurred in 1837 and 1838 [SUR 41]. This engineer is often presented as a forester due to the orientation of his work and the policy that he brought about, but he did not belong to the forester corps (he would later make a career with the railways). Surell presented himself as a successor to Fabre, with whom he likely shared the same hydraulic culture.



a) b)

Figure 1.9. *a) Photograph of Georges Fabre (1844–1911); b) Etching representing Alexandre Charles Surell (1813–1887) (source: Wikipedia)*

In substance, the work must be merited on the great clarity and its attractive character for the general public, if only through its lack of hydraulic equations in the text. We can find in Fabre's principles, with classical torrential terminology, the notion of the slope of equilibrium*, the definition of torrential lava* and the choice of check dams rather than more or less tightened longitudinal dykes[4]; without further delay, he maintains that the people in the country had long since adopted groynes, but they were rarely followed up on by the Administration. Surell summarized

4 Surell points out that these check dams were very widespread in his department and gave the example of those built under the Empire in the bed of the Romanche in Villars d'Arène.

Fabre's contributions, but he did not innovate with regard to torrential hydraulics; his contribution was quite different. We will start with his remark that "entire villages are on the verge of being engulfed"; we must admit that "the formation of these torrents came after the establishment of villages" [SUR 41, p. 54].

Herein lies the dynamic aspect of Surell's work, the process being modern in that it had the dual vision of space and time (he was only 25 and this native of Bitche in Lorraine had just gotten to know the Hautes-Alpes!). If Surell placed geological causality ahead of climatic causality in his explanations, his work is full of history in its part dedicated to the formation and violence of torrents. The basic principle of Surell's reflections is that there is a birth, life and death of torrents. In his words, torrents *are born* before inhabitants' eyes (e.g. on the mountain of Orcières), *develop* (as with the mountain of Saint-Sauveur, facing Embrun) and *are extinguished*[5] (like in Savines, where Surell observed evidence of former, contemporary activity of a human establishment). His understanding of phenomena integrates time into a fragmented, multiple space. The extinction of torrents remains to be explained. When the torrent's slope of equilibrium is reached, scouring stops and "everything becomes calm":

> "Nothing will remain standing except solid rocks, everything scourable having been carried away… The torrent will find its origin at the food of a wall of steep rocks" [SUR 41, p. 143].

In the technical terms used by Surell, there are both torrents that are born in an upper valley and others that deviate from their course over alluvial fans in search of their slope of equilibrium, and yet others that have acquired a stable regime. Herein lies the approach that we call "synchronic"* today. From another perspective, known as "diachronic"*, the torrential river seeks a longitudinal profile (through "corrosion", i.e. bed incision or thalweg aggradation), reaches its slope of equilibrium and wanders to finally acquire its stable regime (at the end of an undetermined period). Surell does not employ the term "cycle", which can be found in the works of geographer W.M. Davis [DAV 99], but the concept is implicit in this statement:

> "Each started with a torrential era, and each ends or will end with a stable state" [SUR 41, p. 150].

"Nascent" torrents are attributed to deforestation, as attested to systematically by "the seniors in every commune", but the process is reversible, since afforestation can

5 The volcano metaphor is implicit, as is the term "lava", but Surell's explanation definitely stems from the field of hydraulics.

contribute to their expansion, thanks to roots, to the shelter of canopy*, obstacles and the imbibition of humus. It is indeed the placement into a historic perspective across landscapes and mankind that lends strength to Surell's work. As for the causes of the fragilization of slopes, Surell does not innovate and returns to Dugied's ideas: the local farming community had cleared steep slopes covered with pastures despite the prohibition by Colbert's 1669 ruling, and they were spared by the courts; the Revolution and the Empire were also responsible, starting with the spread of the law from Floréal 9, year XI, which only punished the clearing of wooded areas. Surell concludes: "after the plows come the herds", both local and transhumant ones. An unpopulated mountain like the Dévoluy "abandons the plow" and "bases all of its resources on herds" that "hasten the ruination of the nation, which will perish at the hands of this very resource" [SUR 41, p. 185]. We could be tempted to see the parallel to the torrential cycle in this history of the humanized landscape. The logical consequence implemented by the Administration would be the policy to evict inhabitants from threatened slopes.

To the number of solutions, Surell proposed creating reservations, even "no-go areas" on eroded slopes in order to allow the forest to rebuild itself; he advocated planting grass, with rapid effects, when afforestation was not possible, notably at higher altitudes. In the face of the opposition that manifested itself in the mountain inhabitants, the Administration would impose its views and hasten the process by protecting these spaces and planting them. Even though his discourse was more favorable to local farmers than to transhumant herders, Surell recommended recognizing the public utility of reforestation and practicing the seizure of property. One of his key statements is the following:

> "We must ask for help from living forces rather than fight the torrents by building up stone and earthworks at high costs" [SUR 41, p. 161].

Surell's plan is thus to implement biological engineering and not to continue treating torrential beds, which he judges to be expensive and pointless.

Alexandre Surell was not the only specialist in alpine torrentiality. Two names emerge from the period between 1850 and 1860, which was crucial for the maturation of the ideas that led to the law on the restoration of mountain lands (*restauration des terrains de montagne*, RTM): Auguste Blanqui in the political field [PON 95] and Joseph Scipion Gras in the technical domain.

Auguste Blanqui (1805–1881) went down in history for his socialist, utopian ideas as well as his revolutionary stances [BLA 46]. A native of Puget-Théniers in the department of Alpes-Maritimes and therefore familiar with torrential matters,

Blanqui chose to support taking rights of ownership away from individuals using and abusing their freedom; this position is in line with his views on social equality:

> "What could be wrong with the owner of abandoned lands whose sterility he continues to maintain being bound to reforest them or concede the pointless possession thereof to the State, thereby acting for himself and all others?"

Blanqui likely led a role in preparing people for the principle of expropriation that would be upheld in the RTM's policy, launched by an 1860 law.

Joseph Scipion Gras (1806–1873), born in Grenoble and a graduate of the *École polytechnique*, was named the engineer-in-chief of the mines in his hometown, where he was responsible for geological and meteorological studies on alpine torrents [GRA 50].

J.S. Gras published two important studies that led to progress in the understanding of solid transport in saturated flow and rehabilitated the principle of check dams; he made a case for high-altitude check dams capable of stopping "pebble fans" in a manner all the more stable as the deposition has gained vegetation. He also made a case for the creation of devices allowing sediment deposition at the top of alluvial fans.

J.S. Gras applied his principles to the confluence of the Vénéon and the Romanche, in the upper part of the Bourg-d'Oisans basin; the Romanche actually aggraded notably between the dykes in the 1840s and caused increasingly serious floods. His 1850 work contains an appendix on the torrents that descend from the eastern flank of the Chartreuse Mountain upstream from Grenoble in a very particular geological and climatic context. The solution lies in the construction of stone or wooden dams capable of containing the pebbles descending from the mountain walls inside the upper catchments. His 1857 work expands these perspectives and presents very concrete solutions for building efficient dams (partial and complete containment, containment mazes, check dams) [GRA 57]. It is very likely that Joseph Scipion Gras's notoriety weighed heavily on the decision to build torrential dams to complement the more "biological" choices that Alexandre Surell had defended earlier. The conceptual and technical tools were ready to implement the restoration of mountain land (RTM).

1.4.4. *The restoration of mountain land (RTM)*

The State's position, when it came to implementing generalized measures, was to negotiate with the general councils of the departments in question, these being divided between the support provided by its "elite", on the one hand, at the recommendation of government functionaries, and the reluctance of elected officials not wishing to lose the votes of rural inhabitants threatened with the loss of their range areas and the benefits of transhumance, on the other hand. The 1927 Forest Code had freely allowed pasturelands on non-forested areas, and the doxa of the era was "for the progress of agriculture", including in communities on slopes, judged to be capable of producing grains. Ministerial measures in the late 1830s, inspired by the ideas of the Restoration, invited the general councils to vote in favor of agriculture, and it was not a question of reforestation this time. The elected officials were in sync with the government's position, since the Southern Alps had experienced a series of drought years between 1825 and 1840 that caused them to forget the torrential danger.

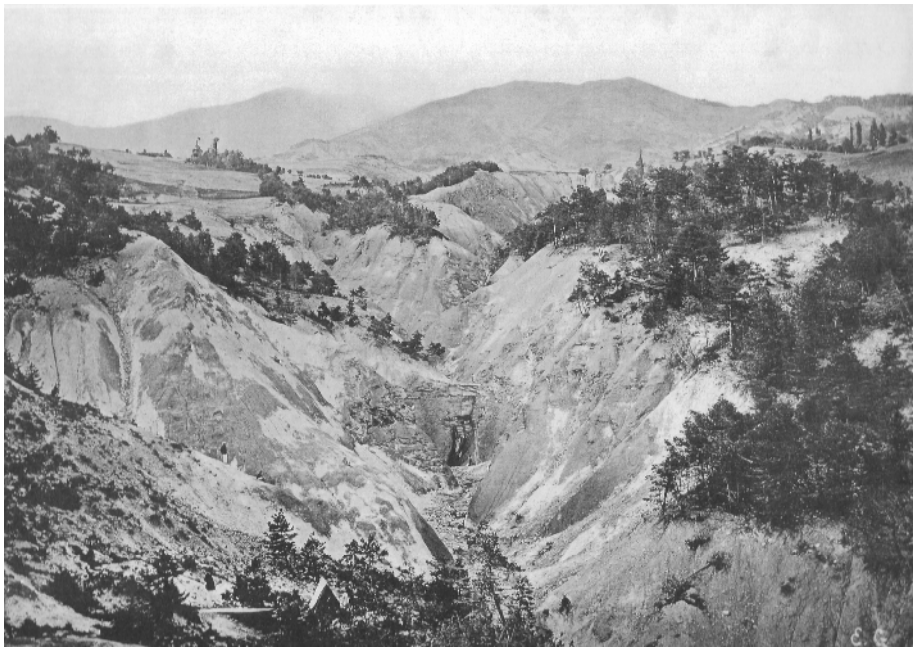


Figure 1.10. *The state of very advanced degradation of a small basin in Basses-Alpes: the Valette torrent in the "Saint-Pons perimeter" around 1880 (source: [GAY 82], Archives RTM)*

This political choice could only be provisional as long as the positions of some remained unstable. Multiple consecutive years with heavy precipitation ended the short dry period with violent storms between 1840 and 1842. In this short period, two notions immediately opposed one another in the department of the Drôme with regard to how destructive torrents were to be handled [BRA 02]: one involved "enclosing" rivers, the other "treating" slopes. The former option was preferred by landowners on the plain and the prefecture, which was in favor of dyke construction, whereas the latter option found significant support among the General Council. The Drôme's prefecture then changed its position and hoped to solve the issue at the source, "in accordance with the suggestions of the engineer Surell". Once the hydrological crisis had occurred, the General Council returned to its original position, despite the damage caused by a new, small torrential crisis in 1850–1852, and it was content with the State's policy in favor of agriculture. Everything changed once again after the extreme damage brought about by the general flood in May 1856 and the heavy summer storms in the mountain (Figure 1.10). The general councils definitely pronounced their positions in favor of reforestation and the government prepared the 1860 law with a rather general consensus.

The law from July 28, 1860 and that from June 8, 1864 are the legislative tools of the policy for the "restoration of mountain lands" [COR 87]. These laws emphasized planting grass and reforestation, in accordance with Surell's recommendations[6]. They were met with varied opinions by mountain communes, which lost range areas, but benefitted from the jobs on construction sites. Ten years after the 1860 law, the results were clear to see and the administration considered them to be fixed, but later reports would show that the new practices were not actually respected. The law from April 4, 1882 would be necessary for the Administration and the communes to progressively reach a better agreement, thanks to the compensation for expropriated lands and because depopulation had already strongly affected the mountains and reduced opposition. The 1882 law proved to be more flexible than the previous one in that the "obligatory" areas of the 1860 law were restricted to sectors in "actual and current" danger, which is clearly less restrictive [LAN 99]. The Southern Alps were the subject of more significant works than the Northern Alps, where the problems were less severe; furthermore, the altitudes there were too high to allow reforestation and pastoral activity still too excessive for the communes to accept RTM control of their pastoral space (Figures 1.11 and 1.12).

6 Numerous works and updates were carried out by the RTM [DEM 82, GAY 82, KAL 85].

Figure 1.11. *Stabilization of a basin head with a substrate composed of marl and limestone through the riverbanks' shaping and the fixation of "living fascinings" (bundles of sticks meant to take root), the area of the Curusquet in Basses-Alpes (source: Archives RTM)*

Figure 1.12. *Dam no. 1 on the Pravert torrent, built in 1894 in Tréminis (Dévoluy, Southern Alps) (source: RTM 38)*

The alpine policy concerning the control of eroded slopes, as well as mastery of mountain torrents and torrential rivers, came about following the foundation of hydraulics knowledge acquired in the 18th Century, as they were summarized in J.-A. Fabre's treatise. It was Alexandre Surell, however, who first figured out how to combine the dynamic understanding of the mountain space through the integration of societal pressure on slopes, the history of forest loss and the formation of torrents and finally, biological restoration methods. The 1860 law on the restoration of mountain territories led to the complementarity of Fabre's civil engineering methods (torrential check dams built of fascines) and Surell's biological methods (grass and tree seedling, planting of young trees). The implementation of these measures, more or less coercive depending on the location and time period, was the job of the RTM.

1.4.5. *The Southern Prealps (Drôme): what kind of balance in torrential milieus?*

Ongoing research has been conducted in the Diois and the Baronnies on the impact of the measures implemented by the RTM [LIE 03]. In the Drôme basin, which was the most restored in the Southern Alps after 1860, 23 national forests were created and categorized into six large areas, managed by the *Office national des forêts* (French national office of forests), such that 80% of the basin was concerned. The torrential beds were stabilized between 1863 and 1887, and the low-order ravines were "filled" between 1887 and 1914 (all in all, more than 200 dams and more than 200 check dams were built); regarding the afforestation rates, it went from 30% (in poor forests) in 1830 to nearly 60% in 2000 (in well-managed forests).

A large-scale approach was used in the eastern part of the Drôme basin by combining the archives, the analyses of fluvial landforms and their dating based on the rings of forest pines present in the thalwegs. The forest colonization of the torrential beds started in the 1860s and extended downstream following the incision of the channels, which dried out the stony substrates. Climatic change, notably with the disappearance of summer floods, likely played an early role, at least prior to the major effects of the RTM's campaigns [AST 11]. However, it is not possible to determine the respective role of those campaigns, of land abandonment related to depopulation (through the near elimination of pasturing) and of natural regeneration (or "spontaneous" reforestation) following the abandonment of slopes.

Further downstream in the fluvial system and starting in the early 20th Century, the torrential rivers narrowed; their incision on the spot was greatly marked starting in the 1950s. At the same time, the torrential rivers on plains experienced significant contraction of their braids under the effect of the stabilization of sedimentary delivery areas and the incision of riverbeds descending from upstream, the effect of a sedimentary deficit and a rarification of heavy floods. In general, the transit of

course load in torrential rivers diminished less than could be expected, for the materials originating from the incision of tributaries continued to flow [PIÉ 04].

1.5. The sediment conveyor belt, from torrents to outlets

1.5.1. *The forester Georges Fabre, from the Aigoual to the Gironde*

We started with the principle of sediment continuity from sources to the outlet, a founding principle stated by J.-A. Fabre [FAB 97], even though it remains rather implicit in his treatise. What was the fate awaiting this principle in late 19th Century France? We must turn to a man with the same name, Georges Fabre (1844–1911), to find it in its original form. From 1868 to 1900, G. Fabre, a graduate from the *École polytechnique* and a forester, was the director of the Gard's Reforestation Service, working in the Mont Aigoual range. Wishing to tackle the issue of erosion in ranges rather than in individual catchments, G. Fabre made a case for favoring the concept of "extended area" to seriously regulate the problems of excessive erosion and river load. In a report from 1895 [FRA 85], G. Fabre thus demanded an area of the Dourbie (tributary to the Tarn) on the grounds that the sand of the Aigoual, brought downstream, "fatally" obstructed the port in Bordeaux, in the Gironde estuary, at a rate of 600,000 m^3/year (thus, 1/7 of the solid flow from the Garonne would come from this sector of the basin).

> "The forest restoration in the Hautes Cévennes of the Dourbie basin can only be truly efficient and useful through the extinguishing of the thousand ramifications above the large torrential rivers one by one […]. This result can only be obtained by covering all of the craggy slopes with a continuous forest layer".

By highlighting the threats weighing on the port of Bordeaux, G. Fabre would have masked his true goal, which was to create a production forest on the ruins of the old agrarian system of the Cévennes, but this forester knew how to perform a successful "state intervention with a human face" [NOU 88]. The extensive areas created in the Aigoual were likely examples of this without respecting the 1882 law (they went beyond it) and they were validated by the law of August 16, 1913, 2 years after G. Fabre's death. Thus, we see that the implicit principle of continuity between the Aigoual and the outlet of the Gironde was an image meant to convince the central administration; this image does not seem to have been founded on scientific bases, but this point remains to be seen. Regardless of the case, the fact that this image had political power means that continuity was on the legislator's mind.

1.5.2. *The Rhône river trough*

Around 1860, the Little Ice Age (LIA) reached its end and the restoration of mountain territories had not yet begun; land abandonment was too recent for these effects to be felt. Furthermore, considering the downstream transfer time of gravel sediment, the river received material that had left the mountain years, even decades before that date. How did the Rhône react to the crisis of the LIA throughout its course? Homogeneously or heterogeneously? This provides an opportunity for us to observe a river in its continuity, from the mountain to the delta, at a time when this approach was still relevant. The analysis of an atlas at a 1/10,000 scale allowed us to get an exact idea of the river's upstream–downstream diversity [PON 57–66]. Three stretches were therefore highlighted (Figure 1.13).

– The Upper Rhône[7], from the Fier confluence to Vienna, braids intensely, except in two sections where it is closed in and constrained by its limestone surroundings. The bed load had been completely blocked for millennia in the Basses Terres basin, carved out by the last quaternary glacier at the foot of the Jura, unable to feed downstream; it was renewed by contributions from the Ain, after the interruption of transit for about 40 km. The tributaries (the Arve, Fier, Guiers and Ain, as well as the limited contribution of the Gier between Lyon and Vienna) played an important role in this procedure, because they contributed a significant volume of materials, but it was the Ain that was the sole sedimentary supplier between the bend of the Jura and Lyon.

– The Middle Rhône, between Lyon and the confluence with the Isère, does not braid or at least very little so, because its bed load is greatly reduced; the influence of the Ain cannot be felt past Vienna, because all the material that comes from it is deposited in the river bed and on the alluvial plain. In this second portion, the Rhône carries pebbles, but not enough for this to translate into a braid style.

– Finally, from the Isère to the sea, the braiding is moderate, fed by the tributaries thanks to Mediterranean rain (the Drôme, Ardèche, Durance and Gard). The river flows on a rocky floor inclined by tectonic tipping, which gives it great energy, both on the slope and in its flow [BRA 10b].

In 1860, the French Rhône was therefore a source of discontinuous bed load transport along its axis, contrary to what we might think. However, all in all, it is a braided river, contrary to its medieval functioning, which was characterized by meandering, as was proven by the paleo-environmental studies conducted on the alluvial plain. The Rhône transformed during the Little Ice Age, and we can assume that this change took place first downstream from the primary sources of pebbles and that it then moved downstream, although without the continuity having time to

7 The Upper Rhône extends officially from Switzerland to Lyon.

be fully ensured. If we must seek perfect continuity, this must be on the side of the suspended load, made of sand, silt and clay, because these types of material travel quickly and, even though they are deposited, significant quantities were able to reach the sea throughout the periods in question.

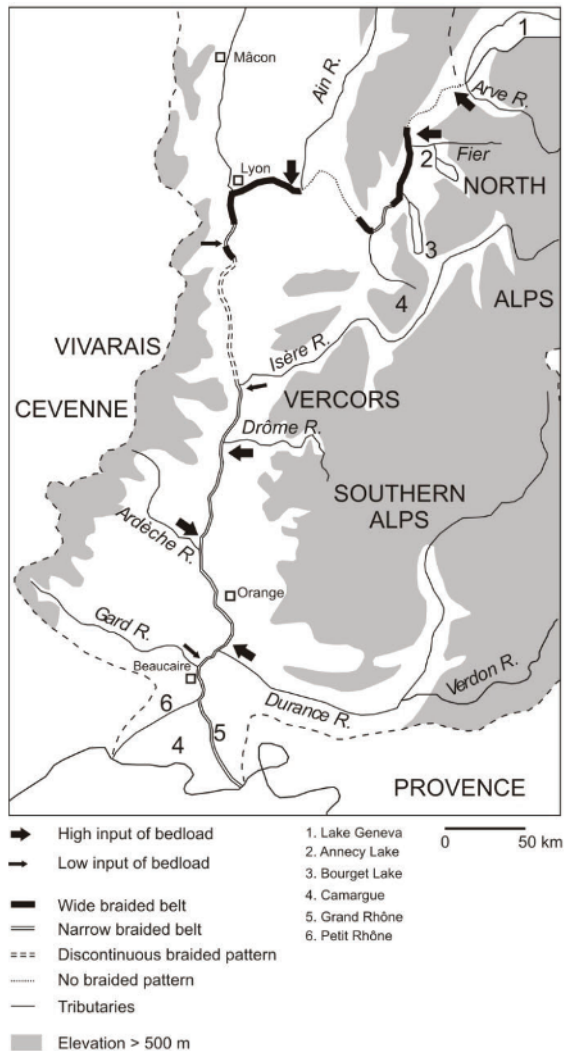


Figure 1.13. *Longitudinal discontinuity of the Rhône around 1860. Discontinuous braiding developed downstream from the injections of gravel bed load by the tributaries (source: [BRA 10b])*

1.5.3. *The redistribution of alluvia in the upper delta of the Rhône*

The territory of an active delta generally starts at a point upstream of the space where the water divides into two or more channels distributing the water. The Rhône delta began at the Tarascon and Beaucaire, even though the diffluence has now moved downstream. The dykes built following the great flood of May–June 1856 no longer allow river construction to be observed across the entire Camargue region. Localized flooding takes place when breaches open in the levees. The observations reported by the Marquis A. de Roys are therefore even more remarkable.

In 1851, A. de Roys measured the volume of alluvia deposited on the delta plain by the Rhône's flooding in November 1840 [NOU 88]. He estimated a 6,000,000 m^3 deposit of fertile silt over 20 days on the Tarascon plain and in the Bellegarde marshes to the west, over an area of 4,000 ha. The thickness of the deposition could have reached a depth of 1 m near the river bulge close to the river and was as thin as 1 mm on the land far from the Rhône (the concentration of suspended material* in the Rhône's water was 4 g/liter, a high value so far downstream).

De Roys claimed that the "fatal dyke construction" on the Rhône, performed 800 years earlier, slowed down the rise of the plain in the Languedoc to the benefit of the narrow strip of alluvial belt within the dykes, such that these dykes burst more frequently. Sand invaded the plain beyond the dykes, and is piled by the action of the north wind into "small mountains" measuring 7–8 m, fixed on obstacles (with a local height of 15–20 m). The thickness of the alluvia and their size reduce downstream as the slope of the plain decreases. However, as noted by M. Pardé [PAR 25], the Rhône channel had also risen between 1842 and 1886. Everything downstream of the Rhône fluvial system reacted to the sediment production of the Alps and the Massif Central; here, we can emphasize the importance then assumed by sand in the river load arriving to the sea.

1.5.4. *Solid contributions to the Rhône outlet and progression of the Camargue delta*

During the LIA, the Rhône's solid flux to its outlet was made up of the suspended load from the entire basin, with contributions from the tributary basins, whose volume depended on the geography and intensity of precipitation. The solid flux also incorporated a bed load* component originating less from the Upper Rhône than from the large tributaries along its southern course. Several studies have been devoted to this issue.

The information concerning the Holocene past is archived in the delta's sediment. A core sampling in the Bras de Fer reveals that it was active as a distributary* of the Rhône between 1586 and 1712. Analyses allowed the hydrology and transport rhythm towards the sea to be reconstructed. The floods and sediment contributions were elevated and frequent, leading to a certain instability of the Rhône, since its bed was in braids at the very heart of the delta. Their heavy mineral composition shows that the majority of the sand came from the nearby and steep Cévennes tributaries. The basin's upstream portion and the Durance provided their load to the delta with a certain delay. The hydrological history of the Rhône in Arles and a series of bathymetric maps showing sedimentary accumulations off the coast of the outlet speak to the great instability of the flood's flow and the solid transport [PIC 95]. Surveys taken on the Bras de Fer's backfill and its former banks showed the role played by coarse sand in a morphology of "delta braids", highlighting the reality of metamorphosis of the Rhône channels in the Camargue region between 1700 and 1710. This example materializes and validates the observations made in the 18th Century, which bore witness to extensive activity at the Rhône outlets.

The progression of the Bras de Fer's outlet was, on average, 80 m/year between 1680 and 1710, and it reached its record of 180 m/year between 1700 and 1710, before the diffluence* that took place starting in 1711 towards the actual outlet. How did the distribution on the coast of material arriving to the sea in the Rhône's unchanged delta take place? Pierre-Jean Bompar's old map (1591) represents the mouths of the river and their entry into the sea, loaded with alluvia. The period 1580–1590 is considered to have experienced a "significant geomorphological crisis" in response to the torrentiality of the Southern Alps; the period 1601–1646 is alleged to have experienced a relative hydrological calm, favorable to the congestion of the river mouths before two new crises, dating back to 1651–1710, 1771–1780 and 1801–1810 and finally, the 1840s allowed sediment to be expelled under hydrological pressure from upstream. The desire to correct the Rhône had been manifest since 1587, when the river was put back into its former bed after the avulsion* of Fumemorte, and it would continue growing in the 18th and 19th Centuries [PIC 95].

The mouths of the river moved laterally along the coast due to changes in the inland routes, connected to the aggradation of the branches built above the delta plain. On the occasions of floods, the aggraded channel swung from one side to the other and opened a new outlet (the so-called *grau*, from the Latin *gradus*, "passage"). A lobe was built at the new outlet, and it was then destroyed by the action of long-shore drift; the long-term equilibrium of the coastline* was thus ensured [MAI 06]. In the early 18th Century, the meandering Bras de Fer, nearly filled, only progressed 50 m/year; the fluxes swung towards the current outlet, the Bras de Pégoulier. The new primary lobe progressed 150 m/year, before experiencing a decrease to 30 m/year between 1765 and 1840.

During the period of strong bed load contribution in the late LIA, the speed of coastline growth was 10 times greater than it is today. Progression owed very little to the Rhône, contrary to intuitive logic. The greater part of the river contributions were collected in the delta lobe*, situated at the current outlet of the Great Rhône, without lateral redistribution. How, then, can we explain the progression experienced by the coast? If the sea provided shelly sand with a biological origin (20–30% of the volume), most of this came from erosion by the long-short drift of old delta lobes (the lobes of the Bras de Fer, closed in 1711, and the Grau d'Orgon, before the Petit Rhône, etc.).

In the first two chapters of this study, we insisted on the period of the Little Ice Age, which extended from the 15th Century to the 19th Century in Western Europe, affecting in particular mountains subject to growing human pressure at the same time. On site, we were able to follow the torrential and river responses to the mountain erosion crisis. In the Alps and the Apennines, this response was expressed from the mountain drainage basins to the sea, but with complex spatial and temporal nuances under the influence of secondary climatic fluctuations and the particularities of the piedmont plains. The concrete effects of the crisis are a discontinuous but sustained feeding of the river outlets, which is translated by limited control of the excessive sediment on the part of society.

In the scientific literature, the gravity of the questions posed to urban societies has led to considerable progress, notably in Italy. This will be the subject of Chapter 2.