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Streamflow Naturalization Methods: a Review

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1 Streamflow naturalization methods: a review

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9 Abstract

10 Over the past few decades, several naturalization methods have been developed for
11 removing anthropogenic influences from streamflow time series to the point that
12 naturalized flows are often considered as true natural flows in many studies. However,
13 such a trust in a particular naturalization method does not expose the assumptions
14 underlying the method, nor does it quantifies the associated uncertainty.

15 This review provides an overview of streamflow naturalization approaches. The
16 terminology associated with naturalization is discussed and a classification of
17 naturalization methods according to the data requirements and main assumptions is
18 proposed.

19 A large set of studies developing or applying naturalization methods are reviewed and
20 the main challenges associated with the methods applied are assessed. To give a more
21 concrete example, a focus is made on studies conducted in France over the last decade,
22 which applied naturalization methods to estimate water extraction limits in rivers.

23
24 **Keywords:** Naturalization methods; Streamflow; Human influences; Impacted
25 catchments; Uncertainty; Hydrological modelling

1 Introduction

1.1 *Natural, influenced and naturalized flows*

Humans have fundamentally affected the continental hydrological cycle through the impoundment of rivers, land use changes, water extractions and the long-term effect of climate change (Dynesius and Nilsson, 1994; Steffen et al., 2011; Vidal, 2019; Vörösmarty and Sahagian, 2000). Since the 1950s, there has been phenomenal growth of human enterprise, which resulted in an exponential increase in the number of large dams and water consumption (Steffen et al., 2015). These human influences continue to have a significant impact on observed river flows, which will be qualified as "influenced" in the rest of this paper. As highlighted by the Panta Rhei decade launched by the International Association of Hydrological Sciences (IAHS) in 2013, knowledge of the interactions between humans and water remains limited (Montanari et al., 2013). Therefore the natural and anthropogenic parts of the observed flows need to be distinguished (Littlewood and Marsh, 1996). Anthropogenic is understood here as relating to or resulting from the influence of human beings on nature (<https://www.merriam-webster.com/dictionary/anthropogenic>).

In case of existing human influences upstream of a gauging station, observed flows are generated both by natural processes and human activities. Therefore natural flows cannot be directly measured and must be estimated. Two main types of approaches are adopted to get natural flows:

- **Using reference high quality flow observation:** Reference Hydrologic Networks (RHNs) have been established in several countries (Burn et al., 2012; Whitfield et al., 2012). The gauging stations are selected for having stable land-use conditions in upstream catchment, no significant regulation, enough record length, active data collection, high data quality and adequate metadata

1
2
3 51 (Whitfield et al., 2012). They represent how catchments respond to climate
4
5 52 variability and serve as reference to hydrological trends induced by climate-
6
7 53 driven changes and in studies at the regional scale.

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9
10 54 • **Using naturalization methods:** in case there are human influences, dedicated
11
12 55 methods have to be applied to retrieve the natural flow regime from influenced
13
14 56 flow in a target basin. The natural flow estimates are then called naturalized
15
16 57 flows.

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18
19 58 In this article, we will focus on the second type of approach. Naturalization methods use
20
21 59 various sources of information depending on their availability, typically observed
22
23 60 influenced flows, volumes linked to human influences, flows observed before or after
24
25 61 the period of influence, or flows free from influence at the regional scale. Naturalization
26
27 62 methods are all based on models, some of which are very crude (typically a water
28
29 63 balance equation) and others are more complex and comprehensive. Hydrological
30
31 64 models, representing the rainfall-runoff relationship at the catchment scale, or routing
32
33 65 models, representing the upstream-downstream flow propagation, are commonly used in
34
35 66 naturalization methods. In cases of insufficient or too coarse data on influences, models
36
37 67 may be also needed to generate information on these human-induced influences.

38 39 40 41 42 43 68 **1.2 Why do we need natural flows?**

44
45 69 As noted by the Canadian Science Advisory Secretariat (MPO, 2013), the flow of a
46
47 70 river is the main variable that connects eco-system components along a river corridor
48
49 71 via hydrological, biological, geomorphological, and water quality processes. As a result,
50
51 72 natural flow can be typically used as a reference to estimate hydrological response to
52
53 73 climate regime, to evaluate the ecological state of a river (Poff et al., 1997) and to
54
55 74 estimate the quantity of water available. Here we detail three domains for which natural
56
57 75 flows are needed and naturalization methods can therefore be helpful.

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2
3 • **Ecological impact assessment**
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5
6 76 Naturalization methods contribute to the evaluation of anthropogenic impacts on
7
8 77 ecosystems. Comparing naturalized streamflows against influenced streamflows
9
10 78 provides a way to assess the anthropogenic impact on the natural environment (Poff et
11
12 79 al., 1997, Rahman and Bowling, 2018). The degree of alteration corresponds to the
13
14 80 difference between naturalized and observed streamflows (Jacobson and Galat, 2008),
15
16 81 or the difference between indicators computed on these streamflows (Richter et al.,
17
18 82 1996). These indicators include the magnitude of monthly flows, magnitude and
19
20 83 duration of annual extreme floods, timing of annual extreme floods, frequency and
21
22 84 duration of high and low pulses, and rate and frequency of flow changes (Birkel et al.,
23
24 85 2014; De Girolamo et al., 2015; Fantin-Cruz et al., 2015; Fernández et al., 2012; Laizé
25
26 86 et al., 2014; Ryo et al., 2015).

27
28 87 The classical approach to quantify the degree of alteration consists in using the observed
29
30 88 natural flow from a pre-influence period. However, if these observations are not
31
32 89 available or on a too short duration to give a robust estimates of hydrological indicators
33
34 90 (Fantin-Cruz et al., 2015), naturalization methods can provide an estimation of natural
35
36 91 flow based on data from the influenced period only. Moreover, observed natural flows
37
38 92 over the pre-influence period may not be representative of the climate and physical
39
40 93 conditions of the influenced period due to natural evolution and variability.
41
42 94 Consequently they may not be exploitable for human impact studies. Naturalization
43
44 95 methods also make it possible to separate the impact due to anthropogenic pressures
45
46 96 (local or regional) and the impact caused by climate change, and to quantify them. The
47
48 97 anthropogenic impact corresponds to the difference between the naturalized and
49
50 98 observed streamflow during the influenced period. The climatic impact corresponds to a
51
52 99 difference between the naturalized flow over the influenced period and the observed
53
54 100 flow over the influenced period and the observed
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1
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3 101 natural flow of an earlier period. As an example, naturalization has been applied in
4
5 102 China to quantify climatic and anthropogenic impacts: on the Haihe River basin (Bao et
6
7 103 al., 2012; Wang et al., 2013; Zhan et al., 2013), the Yellow River basin (Hu et al., 2015;
8
9 104 Li et al., 2007; Wang et al., 2010), the Miyun reservoir (Ma et al., 2010), the Yangtze
10
11 105 River basin (Li et al., 2013) and Poyang Lake (Gu et al., 2017), the Laohahe River basin
12
13 106 (Jiang et al., 2011) and the Shiyang River basin (Huo et al., 2008). Similarly, in
14
15 107 Australia, the CSIRO (2008) conducted the Sustainable Yields project to assess climate
16
17 108 change impacts on the Murray-Darling basin, at a detailed basin scale.

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19
20
21 109 • **Climate impact issue**

22
23
24 110 In a context of climate change, many studies prefer to focus on projections of "natural
25
26 111 streamflows", even in heavily influenced rivers, because it would be too complex to
27
28 112 address the issues of climate change and water use changes at the same time. Therefore,
29
30 113 flow naturalization becomes necessary to serve as a baseline, as well as to calibrate
31
32 114 hydrological models. For example, in the case study of the Seine River, Dorchies et al.,
33
34 115 (2014) used the naturalized streamflow on the 1990-2011 period to calibrate a model to
35
36 116 estimate the future available water resources for the 2046-2065 period. On a larger
37
38 117 scale, in the SCENES project (water Scenarios for Europe and Neighbouring States),
39
40 118 Laizé et al. (2014) used the naturalized streamflow on the 1961-1990 period as a
41
42 119 baseline to estimate the future of freshwater resources for 2040-2069.

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45
46 120 • **Water resources management**

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48
49 121 In many countries, regulations on the authorization of abstractions and discharges into
50
51 122 rivers, and on the good ecological status of rivers, are based on naturalized hydrological
52
53 123 indicators. The environmental conditions enabling governmental agencies to protect,
54
55 124 restore or rehabilitate rivers, can be linked to components of the natural flow regime
56
57 125 (Poff et al., 1997). Two of the main approaches to obtain an environmental flow regime
58
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1
2
3 126 are linked to the natural flow regime (Acreman and Dunbar, 2004): the look-up tables
4
5 127 approach is based on the statistical properties of the natural flow regime and the desktop
6
7 128 analysis approach is based on the natural seasonality and variability of flows. These
8
9 129 methods, failing to have access to observed natural flow, use a naturalized flow regime.
10
11
12 130 In a regulation context, management of water resources is essential to satisfy the supply
13
14 131 of drinking water, preserve the ecological status of the aquatic environment, limit the
15
16 132 negative consequences of floods and droughts, and provide water for different economic
17
18 133 needs such as industry, agriculture, fishing and electricity (European Commission,
19
20 134 1997). In this perspective, naturalized flow can be used to simulate different water
21
22 135 management scenarios and the impact of these scenarios on the quantity of available
23
24 136 water (Desconnets et al., 1998; Dunn and Ferrier, 1999; Kim and Wurbs, 2011; Maurel
25
26 137 et al., 2008; Wurbs, 2006).
27
28
29 138 Naturalization methods also constitute one of the fundamental element supporting water
30
31 139 management policies. For example, the Water Framework Directive typically appeals to
32
33 140 natural conditions to define the natural status of a river (Bouleau and Pont, 2015). In
34
35 141 France, naturalization methods are used to estimate maximum water extractions
36
37 142 sustaining environmental flows (Fabre et al., 2016). In the UK, the Environmental
38
39 143 Agency developed guidelines to provide naturalized low-flow statistics to enable
40
41 144 regulators to make licensing decisions (Bullock et al., 1991; Holmes et al., 2002; Young
42
43 145 et al., 2003). These results make it possible, in particular, to define the maximum
44
45 146 possible withdrawals to maintain good ecological status (Acreman et al., 2008).
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53 **1.3 Key challenges around naturalization**

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55 148 Flow naturalization faces several challenges. From a theoretical point of view, a
56
57 149 naturalized flow could be defined as a flow observed in the absence of human activities
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59 150 in the catchment upstream of the gauging station. However, the definition of a natural
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3 151 status of a catchment may be difficult for various reasons, e.g. when the catchment
4
5 152 characteristics and the human influences have been co-evolving over a long period.
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7 153 Therefore, there is not always a clear distinction between the influenced period and the
8
9 154 pre- or post-influenced periods, which may limit the naturalization process. Obviously,
10
11 155 this will be hugely dependent on the geographical region, since some have known the
12
13 156 human influence over centuries though others were only influenced over the last few
14
15 157 decades.

16
17 158 Another issue lies in the lack of justification in the choice of naturalization methods in
18
19 159 many studies. The application of naturalization methods raises hypotheses, in particular
20
21 160 in terms of transposition (i.e. transfer of information) in space and time, which seem
22
23 161 rarely verified. This may limit the reliability of naturalized flow estimates.

24
25 162 Finally, naturalized flows are often implicitly considered accurate estimates of natural
26
27 163 flow. In practice, naturalized flows include uncertainties arising from method
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29 164 assumptions, data and models used. It is therefore important to be transparent about
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31 165 these uncertainties to avoid mis-use of natural flows data when uncertainty is large.
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39 166 **1.4 Objectives**

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41 167 The main objective of this article is to provide a review on the issue of flow
42
43 168 naturalization. More specifically, this paper intends to (1) provide an overview of the
44
45 169 naturalization methods, their assumptions and associated tools, and (2) highlight the
46
47 170 scientific issues raised by the application of naturalization methods commonly done in
48
49 171 scientific or operational studies.

50
51 172 Establishing a corpus of studies on naturalization methods is not straightforward.
52
53 173 Indeed, naturalization methods used to estimate flow series free from anthropogenic
54
55 174 influence are rarely the main focus of scientific publications, though they remain a
56
57 175 necessary step for many issues detailed above. In addition, there is a quite large
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3 176 terminology to address naturalization issues (see the discussion in section 3.1).
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5 177 Therefore, the literature review presented in this article is probably not exhaustive
6
7 178 though it encompasses already a wide range of aspects. Selected articles in this review
8
9
10 179 dates back to the 1970s, with a recent increase in publications after 2010, showing a
11
12 180 growing interest in this issue in the water management community.

13
14 181 This paper is organized as follows. Section 2 lists the main human influences
15
16 182 considered in this paper and their potential impact on the natural hydrological cycle.
17
18 183 Then section 3 investigates the concept of naturalized flow and how it is interpreted in
19
20 184 the literature reviewed. Section 4 presents the main types of naturalization methods with
21
22 185 their underlying assumptions and uncertainties. Section 5 discusses scientific and
23
24 186 technical issues associated with naturalization methods, with an example in France.
25
26 187 Finally section 6 gives some concluding remarks.

31 32 188 **2 Potential impact of anthropogenic influences on streamflow**

33 34 35 189 **2.1 Human impacts considered**

36
37
38 190 A prerequisite for streamflow naturalization is to identify the nature of human impacts
39
40 191 and quantify them to determine which influences should be considered in the
41
42 192 naturalization process. Figure 1 (Botai et al., 2015) summarizes how human activities
43
44 193 potentially affect the different components of the hydrological cycle. The main
45
46 194 anthropogenic influences are land cover and land use change, streamflow regulation
47
48 195 infrastructure, and withdrawals and discharges associated with different water uses (**we**
49
50 196 **did not consider here the impacts of human activities on climate, which ultimately**
51
52 197 **impact water resources**). Most of these influences potentially impact several
53
54 198 components of the water cycle and so directly or indirectly the observed streamflow.
55
56 199 **We detail their main impacts in the following paragraphs. Some of these impacts may**
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1
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3 200 be interlinked or show counterbalancing effects. For example, in-basin water abstraction
4
5 201 and release may compensate to some extent at the catchment scale, with limited net
6
7 202 impact on mean flow at the yearly scale. However, they may more deeply modify
8
9 203 catchment dynamics at the seasonal or event scale (high or low flows). Other activities
10
11 204 will always strongly impact catchment water yields and hydrological dynamics, e.g.
12
13 205 inter-basin water transfers.
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16
17 206 [Figure 1 near here]
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19

20 207 **2.2 Dams and their associated storage**

21
22
23 208 Among the 62 studies applying naturalization methods we reviewed, 47 are considering
24
25 209 the impact of dams and artificial reservoirs. The hydrological modifications caused by
26
27 210 dams have two origins (McCully, 2001): the impacts due to the management of the dam
28
29 211 (alternating operations of water storage and release) and the impacts stemming from the
30
31 212 ponding effect of the reservoir. The presence of the stagnant water body, created by the
32
33 213 dam, modifies several components of the local hydrological cycle, including
34
35 214 evaporation and infiltration, and local precipitation for large dams (Degu and Hossain,
36
37 215 2012; Haberlie et al., 2016). It may also strongly modify water quality (Winton et al.,
38
39 216 2019). A permanent rise in the water table downstream can be caused by infiltration
40
41 217 from the reservoir. The dam operations, consisting of periods of storage and release,
42
43 218 regulate water flows in a way generally opposite to natural processes (typically flood
44
45 219 alleviation or low-flow augmentation). They also result in various states of the lake
46
47 220 behind the dam: for flood protection, the reservoir should be as empty as possible and
48
49 221 for potable water supply, the reservoir should be as full as possible (Margat and
50
51 222 Andréassian, 2008). From a temporal point of view, dams can cause changes in flow
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53 223 seasonality and temporary fluctuations, especially hydro-power dams. The management
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3 224 of hydro-power reservoirs will depend on the profitability of electricity generation; for
4
5 225 agriculture purposes, it will depend on crop need. Since each dam has specific
6
7 226 management rules, the impacts of the dams and their amplitudes are each time specific.
8
9
10 227 Note that the cumulated effect of dams over a catchment may also be considered. This
11
12 228 is often the case when there are many small farm dams spread over a catchment. In that
13
14 229 case, this is often much more difficult to access data for each dam and a meta-analysis
15
16 230 over all dams may be preferred (Dong et al., 2019; Fowler et al., 2015; Hughes and
17
18 231 Mantel, 2010).

232 **2.3 Water withdrawal**

233 Water withdrawals refer to the amount of freshwater that is artificially extracted from
234 groundwater or surface water resources. The consumptive use of water corresponds to
235 "the part of water withdrawn that is evaporated, transpired, incorporated into products
236 or crops, consumed by humans or livestock, or otherwise not available for immediate
237 use" (USGS and National Water-Use Science Project, 2019). In our case, water returned
238 to a different catchment than the point of withdrawal (interbasin transfer) is considered
239 a consumptive use. Therefore the quantity of water withdrawn from a river cannot be
240 considered a good indicator of the actual quantitative impact of withdrawals, and the
241 consumed water quantity should be used instead. According to the report of the World
242 Water Development Program (WWAP, 2009), agriculture is the largest consumer of
243 water with 90% consumption for drip irrigation and 50-60% for surface irrigation. The
244 energy sector has the smallest consumption ratio on the order of 1-2%. Domestic uses
245 consume between 10 and 20% of the water withdrawn, and industry between 5 and
246 10%. These figures, however, remain overall estimates with large variability between
247 regions. Water withdrawal can have a temporal impact because of the time lag between
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3 248 the time the water is withdrawn and the moment when the amount of water not
4
5 249 consumed returns to the system (Kendy and Bredehoeft, 2006).
6
7 250 Two sources of water are distinguished: water withdrawn from the groundwater and
8
9 251 water abstracted from the surface. Surface water withdrawals have a direct and rapid
10
11 252 impact on streamflow. Groundwater withdrawals have an indirect or **delayed** impact on
12
13 253 river flows. Exchanges between surface water and groundwater can occur in both
14
15 254 directions: a water table lower than the free surface of the river leads to a recharge of
16
17 255 the aquifer by the river; the situation is reversed if the groundwater level is higher.
18
19 256 Disturbance of the river-groundwater table balance can lead to a drop in the water table
20
21 257 and/or an increase in the recharge rate, and so indirectly influences streamflow (Theis,
22
23 258 1941). **With only four articles considering groundwater abstraction**, this type of
24
25 259 withdrawals remains limited in our article database, but it is more widespread in
26
27 260 operational studies to quantify the available water.
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34 261 **2.4 Water release**

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36
37 262 Water releases refer to the amount of water that is artificially brought to rivers. Two
38
39 263 cases of water release can be distinguished: water releases originating from a
40
41 264 withdrawal on the basin and the releases from an inter-basin water transfer. Inter-basin
42
43 265 water transfer corresponds to the artificial withdrawal of water by ditch, canal or
44
45 266 pipeline from its source in one basin for use in another (Slabbert, 2007). The streamflow
46
47 267 of the receiving basin can consequently be artificially increased. It can also impact the
48
49 268 seasonality of river flows. For example, in several rivers in South African, inter-basin
50
51 269 transfers aim to counter temporal variability and reduce the economic impact of a
52
53 270 localised drought (Blanchon, 2005). In the case of a release following a withdrawal
54
55 271 within the catchment, one part of the water withdrawn having been consumed, the
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3 272 release has a reduced impact on the water resource quantity but an impact on the
4
5 273 temporality of observed streamflow. In the case where the release place differs from the
6
7 274 withdrawal place, release can impact the spatial distribution of water resources.
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9

10 11 275 **2.5 Land use and land cover change**

12
13
14 276 Human activities can lead to a change in land use and land cover through urbanization,
15
16 277 agricultural development, afforestation and deforestation. In the article database, human
17
18 278 influences related to land use are taken into account in the naturalization process in only
19
20 279 eleven studies, although they are the most pervasive anthropogenic impact (Pagano and
21
22 280 Sorooshian, 2005). Changes in land use and land cover have an indirect impact on flow.
23
24 281 In modifying the quantity of energy absorbed by the surface, the evaporation rate is
25
26 282 impacted and the precipitation rate can also be modified in changing the temperature
27
28 283 gradient (Giambelluca, 2005). Groundwater recharge and overland flow are also
29
30 284 impacted. Moreover, numerous studies on land use and land cover change and its
31
32 285 impact on the hydrological cycle have been carried out in relatively small paired
33
34 286 catchments (Stednick, 1996), with results that are difficult to generalize to a larger scale
35
36 287 (Siriwardena et al., 2006; Zhang et al., 2018). The particularity of land use change is
37
38 288 that modification of the evapotranspiration-runoff relation at the local scale can impact
39
40 289 the regional water balance because of changes in atmospheric circulation (Bosmans et
41
42 290 al., 2017; Chase et al., 2000; Gash and Nobre, 1997).
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50 291 **2.6 Combination of human impacts**

51
52
53 292 In practice, observed flow at gauging stations is potentially influenced by several
54
55 293 existing human activities in the basin: industries, energy production at the hydroelectric
56
57 294 dam, agriculture, recreational activities (e.g. ski resorts, navigation for pleasure boating)
58
59 295 and cities (see illustration in Figure 2).
60

1
2
3 296 [Figure 2 near here]
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6 297 Flow regulation and direct withdrawal and discharge in rivers lead to a sudden change
7
8 298 (typically on a daily basis) in river streamflow, whereas the impacts on the other
9
10 299 components of the hydrological cycle can take longer to impact the observed
11
12 300 streamflow. The time delay of the impact on the observed flow is also conditioned by
13
14 301 the distance between the source of the influence and the gauging station, and by the
15
16 302 water pathways. For example, in Figure 2, stations A2 and C are both influenced by the
17
18 303 dam's management. The A2 station, directly downstream of the dam, is impacted sooner
19
20 304 than station C due to shorter propagation time.
21
22

23
24 305 The importance of the influenced signal contained in the observed streamflow can be
25
26 306 conditioned by several factors. Distance plays a role because the intermediate
27
28 307 hydrological processes can mitigate the importance of the impact (Mwedzi et al., 2016).
29
30 308 Thus, the influence of the dam at station C is much less than at station A2, because dam
31
32 309 releases will represent a smaller proportion of the total streamflow at station C than at
33
34 310 station A2, due to inflows by the intermediary basin. In the case of basins with multiple
35
36 311 influences, there can be compensations of some impacts: dam releases can be planned
37
38 312 for agricultural withdrawals downstream, and therefore their impact may not be visible
39
40 313 at the catchment outlet, the reservoir can increase groundwater recharge and thus
41
42 314 compensate the effects of underground withdrawals in summer (Constantz and Essaid,
43
44 315 2007).
45
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50
51 316 The impact of human activities on flow therefore depends on several factors specific to
52
53 317 each basin (type of influence and location, basin characteristics). The following sections
54
55 318 present if and how impacts are taken into account in the naturalization process.
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3 Defining the natural state of the flow regime

In naturalization studies, the purpose is to produce a reference flow regime for influenced rivers. First, the question of what the natural regime of a river corresponds to is addressed, followed by the use and identification of the reference period in studies.

3.1 Naturalization terminology

Examples of scientific definitions of "natural streamflow" or "natural regime" are provided in Table 1. For definitions (D1) and (D3), it is possible to have a natural streamflow despite the presence of anthropogenic factors as long as it does not significantly impact streamflow. Moreover, (D1) and (D2) include the notion of runoff, which can be modified by land use change, without specifying whether it is from a natural or anthropic source. Only (D3), which remains quite comprehensive by referring to "human activity", could take into account this notion of land use and land cover change by human intervention. The first three definitions refer to climate as a variable of the natural regime even though climate change is linked to greenhouse gases emitted by humans. Although (D2) does not refer to the catchment in its natural state, it refers to the drainage network, and thus the aspect of the natural geomorphology of the river. (D4) remains quite general by referring to natural conditions without explaining what they are.

[Table 1 near here]

Although there is no common definition of natural streamflow, we summarise the previous definitions as follows: a naturalized streamflow refers to an estimation of the natural flow under specified conditions of river basin development that includes either no human impact or some defined low level of development (Wurbs, 2006).

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2
3 342 In the literature, it appears that the streamflow obtained in naturalization is not
4
5 343 systematically called "naturalized streamflow" and may be designated by other words
6
7 344 which are not necessarily synonymous. We will present the terms by which some
8
9 345 authors refer to naturalized flows and discuss the nuances in the definition of
10
11 346 naturalized flow that these terms imply. First, there are the terms referring to the
12
13 347 influenced state of the basin such as the terms "regulated" or "influenced" streamflow.
14
15 348 Following existing definitions of regulated flow (AFB and Ministère chargé de
16
17 349 l'environnement, 2016a; Bureau of Meteorology, 2012; Environmental Protection
18
19 350 Agency, 2015; WaterNSW, 2015), an unregulated streamflow corresponds to a natural
20
21 351 flow not impacted by artificial flow-regulation structures. The influences of land-use
22
23 352 changes are therefore not included. The terms "uninfluenced" and "unimpaired" flow
24
25 353 refer to the flow of an undisturbed stream caused by human interventions and whose
26
27 354 flows retain their general characteristics (AFB and Ministère chargé de
28
29 355 l'environnement, 2016b). The uninfluenced flow thus takes into account a wider field of
30
31 356 influence such as the change of land use and land cover. Other terms refer to the natural
32
33 357 state of the catchment such as "flow under natural conditions" and "natural flow". The
34
35 358 "simulated natural streamflow" encountered in some studies refers to a naturalized
36
37 359 streamflow obtained using a hydrological model. The terms of "reconstructed or
38
39 360 estimated natural/virgin streamflow" are synonymous with naturalized streamflow.
40
41 361 Although all these terms refer to a naturalized flow, they may not reflect the same
42
43 362 natural reference. So, the nuances between these terms must not be forgotten to avoid
44
45 363 confusion.

364 **3.2 Determination of the basin's baseline condition**

365 As illustrated in Figure 3, three periods can be distinguished in naturalization. The
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1
2
3 366 influenced period corresponds to the period when the observed flows are impacted by
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5 367 anthropogenic influences. Over this period, where no observation of the natural flow is
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7
8 368 available, one seeks to estimate natural streamflow using naturalization methods.

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10 369 [Figure 3 near here]

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12
13 370 The pre-influence period serves as the basin's baseline condition and is assumed to
14
15 371 correspond to a past period when the observed flow is considered as free of the impact
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17 372 of the anthropogenic influences **considered in the naturalization processes**. Information
18
19 373 from this pre-influence period is used by several naturalization methods. **However, in**
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21 374 **many cases, the influence dates back before flow measurements were made and there is**
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23 375 **therefore no information on natural flows.**

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28 376 The post-influence period corresponds to the period after the influences **considered in**
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30 377 the basin has ceased and a return to a natural state, which may be different from the
31
32 378 state before the influence. This period is also relevant to serve as a natural reference
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34 379 period if the system has enough time to return to uninfluenced conditions. Obviously,
35
36 380 the post-influence period does not exist in catchments under active anthropogenic
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38 381 activities. Studies exploiting the post-influence period mainly focus on sediment
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40 382 dynamics and fauna and flora species after a dam removal (Hart et al., 2002; Kibler et
41
42 383 al., 2011; Magirl et al., 2014). **Therefore, post-influence periods will not be discussed in**
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44 384 **this paper, however some comments about the pre-influence period are somewhat**
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46 385 **transposable to post-influence.**

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52 386 The use of data from the pre-influence and post-influence periods to estimate the natural
53
54 387 regime over a later influenced period raises a question about the reversibility of the
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56 388 system: if all activities stopped, would the river be able to return to a natural state that it
57
58 389 would have reached if it had never been influenced (Cooper, 2004)? In some cases, the
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60

1
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3 390 influence of humans is so old that it has shaped the characteristics of the basin and it
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5 391 represents the new natural condition. For example in southern France, the system Neste
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7 392 was created in the 19th century for irrigation purposes. This network of canals strongly
8
9 393 impacted the land use of a large number of small catchments, with conditions now that
10
11 394 are very different from those that were before (Tardieu, 2008; Villocel, 2002). Still in
12
13 395 France, many wetlands were dried out for sanitary of agricultural objectives, like the
14
15 396 Marais Poitevin since the beginning of the 18th century, and it would be difficult to
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17 397 come back to the pristine conditions (Godet and Thomas, 2013).

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21
22 398 Theoretically, the separation of the pre-influence and influenced periods should match
23
24 399 the start of the influence on the basin. In practice, in the case of dam commissioning, as
25
26 400 illustrated for the Aube dam (Figure 4), the change on the observed flow time series is
27
28 401 abrupt and so the separation is easily identifiable. In other cases, like withdrawals or
29
30 402 small farm dams, which may gradually appear in the basin and evolve over time, or in
31
32 403 the case of gradual land use and land cover change, the date of implementation of all the
33
34 404 influences is rarely accessible and there is generally no abrupt change on the observed
35
36 405 flow time series, which complicates the separation dating.

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41 406 [Figure 4 near here]

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43
44 407 In naturalization studies, change-point detection tests (Andréassian et al., 2003; Hubert
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46 408 et al., 1989) are mainly used to distinguish the pre-influence and influenced periods
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48 409 (Bao et al., 2012; Gu et al., 2017; Guo et al., 2014; Hu et al., 2015; Jiang et al., 2011;
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50 410 Wang et al., 2009; Wang et al., 2013; Zhan et al., 2013). The identified break point most
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52 411 often corresponds to a statistically significant change in the observed flow time series,
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54 412 but this break can have an anthropogenic origin (dam, urbanization, etc.), be natural
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56 413 (natural change in the morphology of the river) or stem from climatic variability or a
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3 414 data problem (change in data measurement devices, etc.). With this method, it is
4
5 415 important to underline that anthropogenic disturbances can still exist during the period
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7 416 defined as pre-influence (Jiang et al., 2011) and that these influences can therefore
8
9 417 impact the naturalized flows obtained.
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13 418 **4 Methods to naturalize streamflows**

14 419 **4.1 Overview on naturalization methods**

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17 419 We have identified six main naturalization methods in the literature: (1) the
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19 420 reconstitution, (2) water balance, (3) routing, (4) the extension, (5) the paired catchment
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21 421 and (6) regionalization (or neighbourhood) methods. These methods differ mainly by
22
23 422 their input data and the underlying models used.
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28 424 The reconstitution, extension and neighbourhood methods are based on a hydrological
29
30 425 model simulating a naturalized streamflow with an estimated set of parameters
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32 426 reflecting the natural hydrological conditions. In reconstitution, failing to have past
33
34 427 observations, information on the observed influenced streamflow and the anthropogenic
35
36 428 influences are exploited to indirectly estimate the set of parameters representing natural
37
38 429 hydrological conditions. In extension, past observations of natural flows on the target
39
40 430 catchment are used to estimate the set of parameters reflecting the natural hydrological
41
42 431 conditions. In neighbourhood, the observations that exist on neighbouring basins are
43
44 432 exploited to estimate the set of parameters. Although these methods use a hydrological
45
46 433 model, they rely on different assumptions and data to obtain the model parameter set.
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51 434 Figure 5 provides a decision tree for the use of the various methods. The starting key
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53 435 question is generally the availability of input data on influences, followed by the
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55 436 availability of data from pre- or post-influenced period, or of regional data. The use of
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57 437 these different data raises hypotheses for the application of the methods. Figure 5 shows
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3 438 which methods can be applied based on the available data. If all the data are available,
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5 439 all the methods can be applied. If no data is available, one may end up to the conclusion
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7 440 that no flow naturalization is possible (black ellipse on the graph). In that case, one may
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9 441 appeal to hydrological models implemented at the global scale, which do not require
10
11 442 local or regional data. However, the reliability of these models at the local scale remains
12
13 443 limited. That is why this option will not be further discussed in this review.
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16
17 444 In the following sections, an explanation of the main hypotheses raised by the
18
19 445 naturalization methods is provided in order to identify their application conditions.
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21 446 Figure 6 shows which methods are used in our articles database.
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24 447 [Figure 5 near here]

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26 448 [Figure 6 near here]

27 28 29 30 449 **4.2 Methods using data on influences**

31 32 33 450 **4.2.1 Water Balance**

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35 451 The Water Balance method consists in decomposing flow into a natural part and an
36
37 452 influence part at the scale of the influenced system (typically an artificial reservoir), by
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39 453 removing the volume variation in the river induced by the source of influence, ΔV ,
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41 454 during the time interval Δt , from the influenced observed flow, Q_{observed} , to obtain the
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43 455 naturalized flow, $Q_{\text{naturalized}}$ (equation 1). The system studied can be a river reach where
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45 456 there is a water withdrawal or release, or a reach downstream of an influence. By
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47 457 convention, in the case of a water discharge, ΔV will be negative. In the case of a water
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49 458 withdrawal, ΔV will be positive. This method is generally applied at a gauging station
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51 459 located downstream of the influences in the river, although in principle it is also
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53 460 applicable to a fictitious point where flow data obtained through regionalization
54
55 461 methods are available. Hydraulic propagation between the influence and the station can
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3 462 have an impact on the computation of the naturalized streamflow. The ΔV computed at
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5 463 a moment t will not have an immediate impact on the observed streamflow at the
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7 464 downstream station, but will have an impact at the time $t + \Delta p$, where Δp corresponds to
8
9 465 the propagation time. If the propagation time is much lower than the study time step,
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11 466 then the propagation effect can be ignored. Otherwise, it is advisable to use a
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13 467 propagation model. The choice of time step will define the hydrological processes to be
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15 468 taken into account and their influences to be considered.
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20 469
$$Q_{\text{naturalized}} = Q_{\text{observed}} + \frac{\Delta V}{\Delta t} \quad (1)$$

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24 470 The Water Balance method is the most widely used in the studies. Table 2 lists the
25
26 471 studies using this method. It appears that this method, mainly constrained by the
27
28 472 availability of data, is mostly applied to a daily time step over periods ranging from a
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30 473 few months to several decades. However, if the method is applied over a long period of
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32 474 time, there may be disparities in the quality of the naturalized flows obtained over the
33
34 475 entire period. This may be due to the evolution of the quality of the measured flows
35
36 476 (Littlewood and Marsh, 1996). In the studies taking into account the influence of dams,
37
38 477 it appears that, for the most part, only the impact of dam regulation operations is taken
39
40 478 into account (Assani et al., 1999; Kim and Wurbs, 2011; Naik and Jay, 2005; Page et
41
42 479 al., 2005; Peters and Prowse, 2001; Yuan et al., 2017). Some studies also take into
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44 480 account evaporation from the reservoirs (Fantin-Cruz et al., 2015; Tongal et al., 2017)
45
46 481 and precipitation falling on the reservoirs (Gu et al., 2017), but no studies seem to take
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48 482 into account the underground exchanges induced by the reservoir. For studies taking
49
50 483 into account withdrawals, it appears that it is the volume of water consumed that is
51
52 484 taken into account in naturalization and not the volume of water withdrawn (Davtalab et
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54 485 al., 2017; Littlewood and Marsh, 1996; Wallace and Pavvloski, 1988; Wurbs, 2006).
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3 486 [Table 2 near here]
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7 487 *4.2.2 Reconstitution method*
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9 488 The Reconstitution method is based on the exploitation of the influenced observed
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11 489 streamflow and the information available on influences during the influenced period and
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13 490 on the use of hydrological models taking anthropogenic influences explicitly into
14
15 491 account. As illustrated in Figure 7, the Reconstitution method consists first in
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17 492 calibrating the hydrological model on the influenced observed streamflow taking into
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19 493 account the anthropogenic influences. Then the set of parameters obtained is used to
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21 494 simulate a naturalized streamflow without taking into account the anthropogenic
22
23 495 influences. In cases where the signal of influence in the observed flow is predominant
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25 496 over the natural signal, it is important to ensure that the calibrated parameter set is able
26
27 497 to reflect the natural catchment behaviour. Step 1 is common to all studies applying the
28
29 498 Reconstitution method, with more or less complex calibration methods depending on
30
31 499 the model used and the influence considered. There are some variants of step 2, for the
32
33 500 estimation of the naturalized streamflow. One variant corresponds to the case where the
34
35 501 model output considered is the time series of the influences. The second step then
36
37 502 corresponds to the application of the Water Balance method where the volume variation
38
39 503 of the influences is added to the observed streamflow (Dunn and Ferrier, 1999;
40
41 504 Maheshwari et al., 1995; Wurbs, 2006). Another more hydraulics-oriented variant,
42
43 505 relevant for the semi-distributed and distributed models with an in-stream flow routing,
44
45 506 consists at step 2 of propagating the upstream natural streamflow if available (Kim et
46
47 507 al., 2012). In the case of an impact of land use and cover change, in the second step the
48
49 508 parameter and input corresponding to influenced land use are changed to correspond to
50
51 509 the pre-influenced state (Nobert and Jeremiah, 2012; Shi et al., 2013; Yin et al., 2017;
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53 510 Zhang et al., 2016).
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3 511 [Figure 7 near here]
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5 512 Since studies are often not very explicit in terms of the model calibration with
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7 513 anthropogenic influences, it is difficult to clearly identify which studies apply
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10 514 Reconstitution methods. Table 3 presents a synthesis of the models used in studies
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12 515 applying the Reconstitution method, the time step of the naturalized flow, the influence
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14 516 taken into account as input in the studies and the simulated flow. The impact of dams
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16 517 and reservoirs are often the main issue in Reconstitution studies. This can be explained
17
18 518 by the fact that their management can be simulated. The second most studied influence
19
20 519 is land use and land cover changes, which are taken into account by physically based
21
22 520 hydrological models such as SWAT (see Table 3). The semi-distributed spatial
23
24 521 resolution is adopted by most studies. In the case of large catchments, the influences can
25
26 522 be localized in space and attenuation of the influences along the river are more
27
28 523 accurately considered.
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33 524 [Table 3 near here]
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36 37 525 *4.2.3 Comparison*

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39 526 The Reconstitution and Water Balance methods are based on the hypothesis that by
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41 527 knowing the impacts of the various influences on the observed flow, it is possible to
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43 528 have a naturalized flow free from these influences. As no study has made a comparison
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45 529 between the Reconstitution method and the Water Balance method, it is not possible to
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47 530 know which one is the most suitable. However, here are a few elements that
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49 531 differentiate these methods and may guide their choice:
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- 51
52
53 532 • **Data availability.** The Water Balance method requires time series data on the
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55 533 entire period to naturalize. The advantage of the Reconstitution method is that
56
57 534 once the parameter set has been obtained, it is theoretically applicable to other
58
59 535 periods.
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3 536 • **Setting up the model.** The Water Balance method seems to be easier to apply
4
5 537 than the Reconstitution method which requires the implementation of a
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7 538 hydrological model on the basin. However, the use of a hydrological model can
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9 539 facilitate several steps such as estimating the volumes of influences that can be
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11 540 incorporated into the model or estimating travel time. It is difficult to say a priori
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13 541 which method will be easier to apply. This depends primarily on the catchment
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15 542 area and the influences considered.
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21 543 **4.3 Methods using observation from the pre-influenced period**

22 23 24 544 **4.3.1 Extension method**

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26 545 The Extension method is based on the exploitation of observed data of the target
27
28 546 catchment from the pre-influence period and on the use of a hydrological model able to
29
30 547 simulate the natural streamflow of the target catchment. The required data for the pre-
31
32 548 influence period are at least the natural observed streamflow and the input data required
33
34 549 by the model. On the influenced period, the input data required to use the model are
35
36 550 necessary. The Extension method consists in calibrating the hydrological model on the
37
38 551 natural observed streamflow of the pre-influence period and then in using the set of
39
40 552 parameters obtained on the influenced period to simulate a naturalized streamflow
41
42 553 (Figure 8).
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47 554 [Figure 8 near here]

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49 555 Table 4 presents an overview of the studies applying the Extension method and the
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51 556 hydrological models used. The common point of the models is their ability to simulate a
52
53 557 natural flow. The models used in these studies show differences in terms of the type and
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55 558 level of complexity. Some studies used empirical models which establish a purely
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57 559 mathematical relationship between natural flow and weather variables over the pre-
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3 560 influence period. Wen (2009) established a multi-regression model with the
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5 561 precipitation and the maximum temperature data at the monthly time step; Jiang et al.
6
7 562 (2011) built a multi-regression model with the precipitation and the potential
8
9 563 evapotranspiration; Ahn and Merwade (2014) also take into account the drainage area.
10
11 564 Other studies applied more complex models such as conceptual hydrological models
12
13 565 (Chang et al., 2015; Guo et al., 2014; Wang et al., 2013; Zhan et al., 2013), or physical
14
15 566 models (Bao et al., 2012; Chang, Zhang, et al., 2015; Jiang et al., 2011; Ma et al., 2010;
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17 567 Wang et al., 2010). Jiang et al. (2011) and Chang et al. (2015), who used models of
18
19 568 different types, showed that the results obtained with the two models are comparable.
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24 569 [Table 4 near here]

27 570 4.3.2 Paired catchment method

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29 571 This method is explained here but also partly belongs to the family of methods
30
31 572 exploiting regional information (see Figure 5). This method is based on the
32
33 573 implementation of a statistical flow-rate relationship between the target station to
34
35 574 naturalize and natural donor stations over the pre-influence period. The natural donor
36
37 575 catchment is generally a catchment that is spatially close to (but not nested in) the target
38
39 576 catchment, with similar size. There is no hydrological model involved in this method.
40
41 577 This approach is not limited to cases of experimental basins to evaluate land use and
42
43 578 land cover changes (Brown et al., 2005). To naturalize the flows of La Grande Rivière
44
45 579 in Canada, Hernández-Henríquez et al. (2010) established a flow-rate relation over the
46
47 580 pre-influence period by applying a variant of the Hirsh MOVE I method (Hirsch, 1982).
48
49 581 On the Lena River in the Arctic, influenced by a reservoir dam, Ye et al. (2003)
50
51 582 established a regression on the pre-influence period between a station downstream of
52
53 583 the dam and five natural upstream uninfluenced stations. Smakhtin, (1999) proposed the
54
55 584 same principle for catchments in South Africa. In China, Huo et al. (2008) established
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3 585 flow-rate relationships, including climatic variables (precipitation and temperature),
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5 586 between the uninfluenced upstream and downstream stations. The relation proposed by
6
7 587 Huo et al. (2008) differs from the conventional paired basin methods (Andréassian et
8
9 588 al., 2012) because they also use climatic information. Other variants exploiting the
10
11 589 paired catchment relationship can be applied without parameter calibration. The
12
13 590 drainage area ratio method (Hirsch, 1979) and different variants, requiring only an
14
15 591 access to the catchment's area value, are applied in many naturalization studies (Kim,
16
17 592 2015; Rahman and Bowling, 2018; Wurbs, 2006). In any case, these approaches make
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19 593 the strong assumption that the departure of observed influenced flows from the
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21 594 relationship with paired catchment flow would be due to the influence only, which may
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23 595 not be always the case.
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30 596 *4.3.3 Comparison*

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32 597 Extension and Paired catchment methods are based on the hypothesis that relations
33
34 598 established over the pre-influence period are stationary and remain valid over the
35
36 599 influenced period. For the Extension method, running a hydrological model under
37
38 600 climatic conditions that are different for the calibration period can generate uncertainties
39
40 601 (Coron et al., 2012). The source of these uncertainties can be partly explained by the
41
42 602 fact that, in the models, several physical parameters (soil, vegetation, etc.) are related to
43
44 603 climatic conditions. The calibration of the model creates an interaction between the
45
46 604 parameters and the climatic characteristics of the calibration period. The robustness of
47
48 605 the model is usually tested on the pre-influence period by calibrating the model on a
49
50 606 sub-period and validating it on another one (Bao et al., 2012; Guo et al., 2014; Jiang et
51
52 607 al., 2011; Wang et al., 2010; Wang et al., 2013). For the Paired Catchment method, the
53
54 608 limitation is the climatic gradient between the basins, which could lead to the two basins
55
56 609 evolving differently. On the pre-influenced period, similar climatic conditions,
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3 610 landforms, soils, vegetation and hydrological processes between the basins can reduce
4
5 611 the uncertainties associated with the natural evolution state of the target catchment
6
7 612 (Hernández-Henríquez et al., 2010). These two methods can be distinguished by their
8
9 613 level of complexity. The Extension method requires a rainfall-runoff model and
10
11 614 meteorological data as input, whereas the paired basins method is simpler because it
12
13 615 consists in establishing a relationship between two neighbouring catchments and only
14
15 616 requires streamflow measurements. Despite these differences in complexity,
16
17 617 Andréassian et al. (2012) showed that the paired basin methods can give better
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19 618 performance than the use of a rainfall-runoff model when the density of gauging
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21 619 stations is quite high.
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28 620 **4.4 Methods using regional information**

30 621 *4.4.1 Routing modelling*

32 622 Routing models can propagate the observed streamflow from upstream to downstream.
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34 623 In the case where the upstream recorded streamflow is uninfluenced, it can be
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36 624 propagated by a hydraulic model (or other simpler propagation or statistical methods) to
37
38 625 obtain a naturalized downstream streamflow.
39
40 626 Table 5 presents studies applying Routing modelling methods to naturalize. The
41
42 627 influences taken into account in these studies directly affect flows due to infrastructures
43
44 628 built in the river. In these studies, the hydraulic models used assume that the river bed
45
46 629 topography is still the same without the dams or levees. The implementation of Routing
47
48 630 modelling methods is often time consuming and requires many data to calibrate the
49
50 631 hydraulic model (Shiklomanov and Lammers, 2009). This is especially the case when
51
52 632 important transmission losses occur and must be accounted for (Hughes, 2019;
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54 633 Pacheco-Guerrero et al., 2017). When the upstream flows are influenced, the flow can
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3 634 be naturalized and then propagated using a hydraulic model (Peters and Prowse, 2001).
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5 635 Another variant consists in using a hydraulic model that explicitly takes into account the
6
7 636 different structures (dam, weir, levee, etc.) that may alter streamflow. The model is first
8
9 637 calibrated on the flow conditions of the influenced period. Then, to obtain a naturalized
10
11 638 flow, the various obstacles are removed from the propagation model (Ahn et al., 2006;
12
13 639 Peters et al., 2006; Wyrick et al., 2009). Wu et al. (2015) assume that the hydraulic
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15 640 propagation has no impact and sum the natural upstream flows to naturalize.
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19 641 [Table 5 near here]
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23 642 *4.4.2 Regionalization*

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25 643 Regionalization methods exploit the similarity between catchments to estimate
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27 644 streamflow. Although mainly used for ungauged or poorly gauged basins, their
28
29 645 application in naturalization studies is an interesting option for several reasons. First,
30
31 646 the Water Balance and Reconstitution methods require good knowledge and an access
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33 647 to the data used to characterize the influences, whereas regionalization methods are
34
35 648 usable on a basin with limited data (Hernández-Henríquez et al., 2010; Ye et al., 2003).
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38 649 Secondly, the principle of the Extension methods is based on the temporal
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40 650 transposability of streamflow. Regionalisation methods can be viewed as a variant
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42 651 based on spatial transposability.
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45 652 Regionalization of the hydrological regimes and flow duration curves. In the case where
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47 653 only the flow characteristics of the natural basin's behaviour are investigated and not
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49 654 complete time series are sought, the regionalization of a hydrological regime can be
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51 655 used. For example, in Switzerland, the natural monthly regimes of Alpine basins have
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53 656 been classified into six groups according to the average altitude of the catchments and
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55 657 the proportion of their glacier-covered area. Therefore, due to the physical
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57 658 characteristics of the influenced catchments and an estimate of the average annual flow,
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3 659 Weingartner and Aschwanden (1994) estimated their natural monthly regime, with an
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5 660 uncertainty ranging from 10 to 20%. In Spanish basins, Fernández et al. (2012)
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7 661 estimated the naturalized monthly flow with a hydrological model at the influenced
8
9 662 stations. Then, to estimate the naturalized regime at a daily time step, they calculated
10
11 663 daily distribution coefficients on neighbouring natural stations. These distribution
12
13 664 coefficients were then applied to the naturalized monthly flows that had a naturalized
14
15 665 daily regime. Here, since the focus is on methods for obtaining naturalized flow time
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17 666 series, the methods of this subsection will not be further discussed. However, they
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19 667 remain used operationally in many countries, in cases where only synthetic streamflow
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21 668 descriptors are needed.
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25
26 669 Neighbourhood method. The Neighbourhood method consists in estimating the
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28 670 hydrological model parameters on natural neighbouring basins. The selection criteria for
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30 671 natural neighbouring basins are related to geographical distance or the physical
31
32 672 characteristics of the basins (Hrachowitz et al., 2013). This method is not currently used
33
34 673 on gauged stations in naturalization studies. However, like the Extension and
35
36 674 Reconstitution methods it uses a hydrological model with an alternative approach to
37
38 675 estimate the model parameter. It may be of particular interest when there are no existing
39
40 676 natural flow data on the pre-influence period nor on the influences themselves during
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42 677 the influenced period.
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48 678 4.4.3 Comparison

49
50 679 In this family, the Routing method seems to be a priori the method giving the best
51
52 680 estimate of natural flow since it directly exploits measurements of natural flows
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54 681 upstream of the basins. However, in the case where the intermediate basin has a
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56 682 significant influence on the flow, it may be necessary to also use a hydrological model
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58 683 to simulate the contribution of the intermediate flow (Wyrick et al., 2009). It is also a
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3 684 complex method to use in the case of large transmission losses between the upstream
4
5 685 and downstream station (e.g. in arid regions) (Schreiner-McGraw and Vivoni, 2018).
6
7 686 The Paired catchment method can also be applied in cases where upstream uninfluenced
8
9 687 flow measurements are available. What differentiates it from the Routing method is that
10
11 688 it is based on a flow rate relationship that can indirectly take into account the inflows
12
13 689 from the intermediate basin. Like the Paired Catchment method, the Neighbourhood
14
15 690 method also exploits information from basins with a natural regime. The significant
16
17 691 difference between these two methods is that Neighbourhood is primarily aimed at
18
19 692 transferring parameter sets from a natural catchment to the influenced catchment. The
20
21 693 assumptions involved in these methods, and their strengths and weaknesses, have been
22
23 694 the topic of several studies within the framework of the IAHS decade on Prediction in
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25 695 Ungauged Basins (Hrachowitz et al., 2013; Sivapalan et al., 2003).
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32 696 **5 Discussion**

33 34 35 697 **5.1 Defining naturalized streamflow**

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38 698 When discussing the definition of a natural regime, we showed that there is no
39
40 699 consensus on what a naturalized flow and the natural state of a basin should exactly
41
42 700 refer to. This impacts the choice of the reference period in the various studies. In
43
44 701 practice, the definition of naturalized streamflow should be a compromise between:

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47
48 702 • Our knowledge of the interactions between human activities and the water cycle
49
50 703 and the limit of the definition to be adopted. Since the water cycle is linked to
51
52 704 several other environmental cycles (energy, chemistry, sedimentation, etc.), this
53
54 705 raises the question of the natural state of these other environmental cycles and
55
56 706 their interactions with the water cycle. Typically, the issue of defining a natural
57
58 707 reference in the climate or ecological domains has been discussed and results
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3 708 from a compromise between knowledge, data availability and objectives in the
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5 709 use of the reference (Brázdil et al., 2005; Davis, 2015; Gatti et al., 2015;
6
7 710 Roubicek, 2010).

8
9
10 711 • A definition not too restrictive to be applicable to a large number of case studies.
11
12 712 Ideally, the reference conditions should correspond to minimally disturbed
13
14 713 conditions (Stoddard et al., 2006), i.e. conditions where there is no significant
15
16 714 anthropogenic disturbance. In practice this would be very constraining because it
17
18 715 is difficult nowadays to access data from basins that are not disturbed by human
19
20 716 activities. In Europe, there are no data on the natural state of a catchment
21
22 717 because the continent has long been densely populated, and the landscapes and
23
24 718 land use have been modified by human presence (Stahl et al., 2010). Moreover,
25
26 719 in some studies, only the naturalization of major influences is desired. In some
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28 720 cases, the naturalized flow can be obtained by removing a single influence to
29
30 721 quantify the role of the influence in the observed flow.
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36 722 The summary of previous definitions we gave in section 3.1 may meet this compromise.
37
38 723 This is actually a key issue when establishing hydrometric reference networks. Since
39
40 724 they should be representative of natural flow conditions, the question of the criteria to
41
42 725 be met in order to consider the corresponding catchments as natural references is raised
43
44 726 (Whitfield et al., 2012). It appears that the definition of conditions vary between
45
46 727 national networks. In Canada, where there are many catchments in pristine conditions,
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48 728 criteria are more rigorous whereas the impact of influences on natural flow regimes is
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50 729 visible across much of the UK rivers for instance.
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56 730 The current perspectives would be to define the naturalized flow as corresponding to a
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58 731 more or less natural state of the basin and to express which influences and associated
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3 732 impacts are considered in each study. Another perspective is to use a more
4
5 733 comprehensive approach, consistent with the definition of naturalized flow chosen, to
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7 734 identify the pre-influence period. In the reviewed studies applying naturalization
8
9 735 methods, the methods to identify the reference period are currently limited to change-
10
11 736 point detection tests, which raise several issues concerning the origin of the change-
12
13 737 point. It would also be interesting to have methods to detect a certain level of influence
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15 738 on the basin.

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20 739 Although defining terms appears essential to understand and compare studies, the
21
22 740 definition process can lead to a reflection on the role of the influences in the methods
23
24 741 and the hypotheses raised. For example, in the case of the Extension method, setting it
25
26 742 at a pre-influence period may imply to account for change in land use to obtain the
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28 743 naturalized flow.

31 744 **5.2 Choice of naturalization methods**

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36 745 By comparing the characteristics of the studies with the choice of the naturalization
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38 746 methods applied, it appears that the same methods are applied on basins with different
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40 747 areas, from the basin scale (100 - 10,000 km²) to the regional scale (100,000 - 1,000,000
41
42 748 km²), and with different influences. Methodological aspects of the studies such as the
43
44 749 time step and the length of the available time series to naturalize do not seem to play a
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46 750 major role in the choice. This raises the question of the criteria that can motivate authors
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48 751 to choose one method over another.

52 752 **5.2.1 Data availability**

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56 753 From a practical point of view, data availability is the first selection criterion (Table 6),
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58 754 which is also reflected in the decision tree illustrated in Figure 5. Thus, the Water
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3 755 Balance and Reconstitution methods use data on influences. The Paired Catchment and
4
5 756 Neighbourhood methods need data on non-influenced catchments. The Routing
6
7 757 modelling method requires a natural upstream flow to propagate it downstream. The
8
9 758 Extension and Paired Catchment methods need data on the past observed natural
10
11 759 streamflow. It is clear that several of these methods are relatively similar and that they
12
13 760 differ only in the tools used. In this section, we will discuss the aspects that can
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15 761 influence the choice of the applied methods.
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19 762 [Table 6 near here]
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23 763 *5.2.2 Distance between the source of influence and the gauging station*

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25 764 Distance is taken into account by the Water Balance and the Routing modelling
26
27 765 methods with the propagation time, and by the Reconstitution methods, which take it
28
29 766 into account according to the structure of the model used and the parameters. For the
30
31 767 transfer modelling family methods, in the case where intermediate hydrological
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33 768 phenomena such as runoff or river-groundwater exchange have a potential impact on
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35 769 the routed flow, a hydrological model should be used to simulate them.
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40 41 770 *5.2.3 Type of influences*

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44 771 In the transfer modelling family, Routing modelling methods are used only to take into
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46 772 account influences that directly impact the flow, as is the case for dams and
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48 773 withdrawals. For the Water Balance method, all the influences and their associated
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50 774 impact on the hydrological cycle could theoretically be taken into account via the ΔV .
51
52 775 In practice, indirect impacts on river streamflow are easier to take into account with a
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54 776 hydrological model family method.
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57
58 777 In the hydrological method family, theoretically the entire impact on the hydrological
59
60 778 cycle could be considered. In practice, the type of influences present in the basin seem

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3 779 to impact the choice of method. In studies that take into account land use and land cover
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5 780 changes in their naturalization process, only Extension and Reconstitution methods are
6
7 781 used. The Extension method is calibrated on the basin conditions before the evolution of
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9 782 the cover. The Reconstitution method makes it possible to take the land cover directly
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11 783 into account during the calibration and then modify it. As land use changes indirectly
12
13 784 modify the flow, it is easier to take these interactions into account with a hydrological
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15 785 model. For the Regionalization methods, this would require a neighbouring basin with a
16
17 786 land cover similar to the influenced basin in its natural state. These methods could be
18
19 787 applied on small experimental Paired Catchments (Brown et al., 2005) but do not seem
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21 788 to be applicable to large catchments.
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25
26 789 Regionalization methods are applied on catchments which are strongly influenced by
27
28 790 dams and other influences. This can be explained by the fact that it is now difficult to
29
30 791 access databases with completely uninfluenced catchments. Weingartner and
31
32 792 Aschwanden (1994) explain that Regionalization methods are easier to apply in cases
33
34 793 where the hydrological conditions encountered are very complex, as in multi-influenced
35
36 794 basins. The complexity of the influences and their impact on the catchment could be a
37
38 795 limit of the Reconstitution method. For example, in the case where irrigation return flow
39
40 796 is taken into account, the difficulty in quantifying them (Dewandel et al., 2008) may
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42 797 lead to eliminating the choice of Reconstitution method.
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48 798 ***5.3 Operational implementation of naturalization methods: the case study on*** 49 50 799 ***the Rhône basin (France)***

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53 800 From theory to practice, it is always useful to see the way practitioners implement
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55 801 methods proposed in the scientific literature. We describe a case study from France. In
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57 802 France, one of the objectives of the Law on Water and Aquatic Environments (LEMA
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59 803 in French) of 30 December 2006 is to restore the balance between water supply and
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3 804 demand. Consequently, studies of “withdrawable” water volumes (i.e. water available
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5 805 for withdraw/human-use) were carried out at the catchment scale in order to determine
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7 806 the quantitative state of water resources and then to propose a preservation strategy of
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9 807 the existing balance or reduce the deficit. These studies include several phases,
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11 808 including an important phase on the identification and quantification of anthropogenic
12
13 809 influences and a phase on the estimation of the water resource using naturalization
14
15 810 methods. The reports produced at the end of these studies are a useful source of
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17 811 information on the application of naturalization methods in operational contexts.
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19 812 Because low-flow periods are of particular concern, naturalized flows are preferentially
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21 813 obtained at a daily scale to calculate drought indicators.
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27 814 Among the many reports available, we made a selection over 20 basins in the the
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29 815 Rhône-Mediterranean Water Agency district (Appendix 1, figure 9). These reports were
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31 816 generally produced by consulting firms and were chosen here in order to have the
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33 817 widest possible panorama (Appendix 1, Table 7). Naturalization methods were applied
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35 818 on sub-basins from a few dozen to several hundreds of square kilometres.
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39 819 With regard to the choice of methods, the most widely used methods are the Water
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41 820 Balance and the Reconstitution methods. The choice of the methods is not clearly
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43 821 justified but can be explained by several factors. First, all influences in the basin are
44
45 822 taken into account. This excludes the Extension method where it is almost impossible to
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47 823 have a period when there is no withdrawal, and the Regionalization method where it is
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49 824 also complicated to have neighbouring basins with no withdrawals. However, a variant
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51 825 of the Neighbourhood method used in an operational context consists in calibrating the
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53 826 hydrological model on the naturalized flow of the upstream influenced sub-basins, and
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55 827 then to use the set of parameters obtained on the influenced downstream basin (CEREG
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57 828 Ingénierie, 2011). Moreover, in these studies considerable preliminary work is
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2
3 829 undertaken to identify and quantify the anthropogenic influences present in the basins.
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5 830 This facilitates the application of the Water Balance and Reconstitution methods.
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7 831 The synthesis of these reports also highlights the implementation of hybrid
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9 832 naturalization methods to address data gaps. Given that hydrological indicators are
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11 833 calculated on the naturalized flow series, the times series must be long enough. These
12
13 834 hybrid versions are presented as a solution in cases where the observational data on
14
15 835 influence and streamflow are too short. One version is to first naturalize the streamflow
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17 836 with the Water Balance method and then to apply the Extension method in calibrating
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19 837 the hydrological model on these naturalized flows. Inversely, the influenced flow time
20
21 838 series can be extended with a hydrological model and then be naturalized with the
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23 839 Water Balance method. It should be noted that each addition of steps in the
24
25 840 naturalization process is a potential source of uncertainty.

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31 841 In the terms of reference of these studies, authors were requested to clarify the limits
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33 842 and uncertainties related to the naturalization process. The level of reflection is very
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35 843 heterogeneous depending on the studies. It appears that most of the authors were able to
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37 844 identify sources of uncertainty. The main sources of uncertainties cited were the
38
39 845 streamflow data, the data on the influence and the climatic data used as model input and
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41 846 model calibration. No study has clearly quantified the global uncertainty of the
42
43 847 naturalized streamflow obtained. In the Les Gardons catchment, it was highlighted that
44
45 848 a 7% error on the naturalized flow had an impact on the study conclusions.

51 849 ***5.4 Level of confidence associated with naturalized streamflow***

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54 850 The previous section on the operational application of naturalization methods in France
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56 851 showed that there is a request on how to assign a level of confidence to naturalized
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58 852 flow. **Because naturalized streamflow is used as a reference for many applications (as**
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2
3 853 discussed in section 1.2), it is important to quantify the associated uncertainties in order
4
5 854 to make robust decisions (Refsgaard et al., 2007). The error associated with naturalized
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7 855 flows is not directly quantifiable because there is no observation of natural flows over
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9 856 the influenced period. The estimation of the confidence in the methods can therefore
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11 857 only be done indirectly. Among the articles analysed, there does not currently seem to
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13 858 be a methodology to evaluate the naturalization process. In this part, we discuss how to
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15 859 indirectly estimate the confidence in results.
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21 860 5.4.1 *Uncertainties in data*

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23 861 To estimate which method is the most appropriate, a first reflection can be carried out
24
25 862 on the quality of the input data (McMillan et al., 2012). As shown in part 5.2,
26
27 863 naturalization methods use different input data which can generate different levels of
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29 864 uncertainty. The main categories of input data are:

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31 865 • Streamflow time series. We distinguish the streamflow time series
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33 866 corresponding to an observed natural flow and the time series corresponding to
34
35 867 an influenced observed flow. The main uncertainties come from the
36
37 868 measurement system in place, the operational conditions and the post-processing
38
39 869 step to estimate the flow (e.g. the stage-discharge relationship). Usually a post-
40
41 870 processing step corrects the occasional errors. In case of a direct impact, the
42
43 871 influenced series can be distinguished from the natural series by the presence of
44
45 872 sudden changes in the time series. This implies a more thorough post-treatment
46
47 873 to distinguish changes due to measurement errors from those due to
48
49 874 anthropogenic influences. Ideally, the measurement system should not change in
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51 875 time. Naik and Jay (2005) pointed out that flow errors can be much more
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53 876 important at the beginning of the period of record. When choosing a method
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3 877 from the hydrological modelling family, questions should be raised on the
4
5 878 confidence placed in the natural flow in the past and the observed flow in the
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7
8 879 present. When the observed data appear uncertain in both cases, it may be
9
10 880 beneficial to use the Neighbouring basin method.

11
12 881 • Climatic time series. The main climatic variables used in the studies are
13
14 882 precipitation and evapotranspiration. Precipitation estimation at the catchment
15
16 883 scale is carried out using interpolation methods of local rainfall measurements.
17
18 884 The measurement system put in place must therefore be adapted to the spatial
19
20 885 and temporal variability of rainfall events in the basin (Lebecherel, 2015). Since
21
22 886 actual evapotranspiration is not measurable at the catchment scale, point
23
24 887 evapotranspiration is used most of the time in the studies. However, this
25
26 888 potential evapotranspiration corresponds to a model output (Oudin et al., 2005),
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28 889 and therefore includes uncertainties. Precipitation can also be estimated by radar
29
30 890 data. In contrast to the raingauge, it is an indirect measurement which is also
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32 891 uncertain.

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36
37 892 • Volume time series of human influences. Since the influence measurements are
38
39 893 not always available, different techniques and assumptions are used to estimate
40
41 894 influence time series. For example, in the naturalization studies examining
42
43 895 agricultural withdrawals, the volume time series are estimated based on data
44
45 896 reported by farmers (Irwin et al., 1975) or models based on cropping patterns,
46
47 897 irrigation water needs and irrigation efficiency (Davtalab et al., 2017; Wallace
48
49 898 and Pavvloski, 1988). Uncertainties associated with these processes seem not to
50
51 899 be quantified, but it can be assumed that these uncertainties could be greater
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53 900 than for the other input data. It is also difficult in naturalization studies to get
54
55 901 sufficient data to characterize all the influences at play on the catchment. Often
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3 902 one has data on the major influences (typically dams, abstractions in rivers), but
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5 903 it is harder to quantify the impact of other influences on flows (land use change,
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7 904 groundwater abstractions). This may leave a level of uncertainty difficult to
8
9 905 remove in naturalized flow estimates.
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12

13 906 A first perspective would be to assess the impact of the quality of these data on the
14
15 907 naturalized flow obtained in a sensitivity study (Devak and Dhanya, 2017). Model
16
17 908 parameters are sensitive to the errors contained in input data. Several studies have
18
19 909 already shown the sensitivity of the models to climate variables (Andréassian et al.,
20
21 910 2004; Oudin et al., 2006). For example, Andréassian et al. (2004) showed that having a
22
23 911 better estimate of potential evapotranspiration does not give better results. In the case of
24
25 912 withdrawable water volume studies in France, there are often strong uncertainties on the
26
27 913 influence data, especially on irrigation data. It would therefore have been interesting to
28
29 914 see the sensitivity of the calculated hydrological indicators to influence data.
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35 915 5.4.2 *Uncertainties in model structure*

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38 916 Model structures can be a source of uncertainties if they are not in line with reality
39
40 917 (Pechlivanidis et al., 2011). The model is a simplification of reality and it may be that
41
42 918 not all processes are represented. In the Reconstitution method, where the model takes
43
44 919 anthropogenic influences into account in the model, it is important to ensure that the
45
46 920 structure of the model is adapted to represent the potential impacts of the human
47
48 921 activities on the different components of the hydrological cycle. The structure of the
49
50 922 Water Balance method can be attractive because of its simplicity, but, during low-flow
51
52 923 periods, errors can lead to obtaining abnormally low or even negative flow rates
53
54 924 (Agosta, 2007; Littlewood and Marsh, 1996). With the Reconstitution method, the
55
56 925 simulated streamflow can be extremely low, which raises questions about its
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3 926 interpretability, especially in intermittent rivers (De Girolamo et al., 2015).
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7 927 *5.4.3 Validation of the method's hypothesis*
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10 928 Each naturalization method is based on different assumptions (see section 4). One key
11
12 929 issue in all methods is the uncertainty linked to the transfer of information in space and
13
14 930 time. This aspect is however not so easy to quantify in the case of naturalization since
15
16 931 no natural flow observation is available on the influenced period and standard split
17
18 932 sample or proxy-basin approaches (Klemes, 1986) cannot be directly applied.
19

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22 933 To assess if the method and tools used are appropriate and thus reinforce our confidence
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24 934 in the results, several methods applied in the literature can be used.

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26 935 In the case of the hydrological modelling family, methods are based on the
27
28 936 transferability of the parameter set. In fact, there is no single set of parameters that can
29
30 937 perfectly reproduce the uninfluenced flow (Beven, 2000). The problem in naturalization
31
32 938 is to know which method makes it possible to transfer the parameter sets with the least
33
34 939 possible uncertainty. With a temporal transposition, robustness can be assessed using
35
36 940 the split-sample test (Coron et al., 2012; Klemes, 1986). This method consists of
37
38 941 evaluating the performance obtained over a subperiod different from the calibration
39
40 942 period. In the case of a spatial-proximity-transposition, robustness can be assessed using
41
42 943 the hydrometrical desert method (Lebecherel et al., 2016). For the Reconstitution
43
44 944 method, the uncertainty obtained at calibration on the simulated influenced streamflow
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46 945 can be transferred to the simulated naturalized streamflow.
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53 946 **6 Conclusion**
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56 947 Human activities can directly impact the observed flow or several components of the
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58 948 hydrological cycle. These human influences can have an impact at the catchment,
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3 949 regional or global levels. Consequently, most of the observed flows are influenced. To
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5 950 have a reference to the natural regime of influenced rivers, an increasing number of
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7 951 studies apply different naturalization methods. However, no state of the art on the topic
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9 952 has yet been made. The inventory of the terms to designate a naturalized streamflow
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11 953 shows that there are several definitions considering different human influences. We
12
13 954 believe that it would currently be too restrictive to propose a single definition of the
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15 955 naturalized flow. We advise that studies propose a clear definition of the influences and
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17 956 impacts considered by the naturalization process.
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22 957 The main naturalization methods were presented and a classification **into three families**
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24 958 **based on the information they used**. Although data availability appears to be the main
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26 959 constraint in the choice of methods to be applied, other criteria play an important role.
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28 960 When intermediate phenomena such as runoff impact the water flow from upstream to
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30 961 downstream, a method from the hydrological modelling family will be more
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32 962 appropriate. The influences and their impacts considered in the naturalization process
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34 963 also lead to questioning the choice of methods and tools used.
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39 964 The example of the application of operational methods shows that the most commonly
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41 965 applied methods for estimating water resources are the Water Balance and
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43 966 Reconstitution methods. This choice is explained by the fact that the authors' goal is to
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45 967 take into account all the influences of the basins and by the difficulty of having access
46
47 968 at a completely natural reference over an earlier period or a neighbouring basin. The
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49 969 development of hybrid methods is a consequence of the difficulty of having both an
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51 970 estimate of the natural flow without any influence and a sufficiently long series to
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53 971 calculate robust hydrological indicators.
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3 972 In these studies of withdrawable water volumes, the uncertainties associated with the
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5 973 naturalization procedure were investigated. It appeared that the authors could identify
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7 974 most sources of uncertainty, but did not quantify the total uncertainty of the naturalized
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9 975 flow obtained. The difficulty in estimating the error associated with naturalized flows is
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11 976 that this can only be done indirectly because the naturalized flow is obtained over a
12
13 977 period when there is no direct observation of the natural flow. A first perspective to
14
15 978 estimate the confidence of the naturalized flow would be to assess their sensitivity to the
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17 979 input data, knowing that very often these inputs do not correspond to observations. A
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19 980 second perspective would be to indirectly assess the assumptions raised by the methods.
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21 981 Methodologies have been established in the literature to assess the ability of models to
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23 982 transfer a set of parameters spatially or temporally.
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40
41 989 submission.
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1645 **10 Appendix 1: Operational implementation of naturalization methods**

1646 [Figure 9 here]

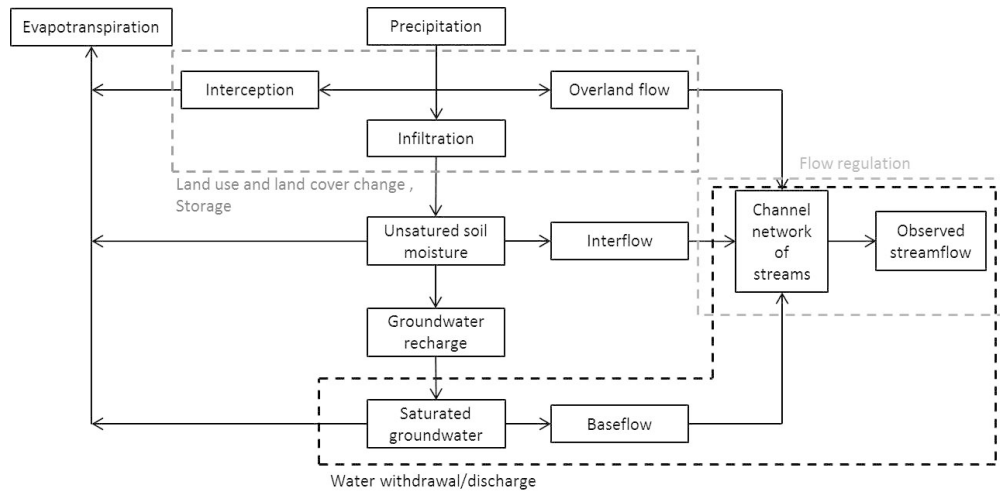
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4 1651 Table 1. Definitions of "natural streamflow" and "natural regime" found in the
5 literature.
6 1652
7 1653 Table 2. Synthesis of studies applying Water Balance methods.
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10 1654 Table 3. Synthesis of studies applying Reconstitution methods.
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12 1655 Table 4. Synthesis of studies applying Extension methods.
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14 1656 Table 5. Synthesis of models used in studies applying Routing modelling methods.
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16 1657 Table 6. Synthesis of input data and tools used by each of the naturalization methods.
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18 1658 Table 7. Synthesis of withdrawable water volume studies. WB corresponds to the Water
19 Balance method, R to the Reconstitution method, E to the Extension method and N to
20 the Neighbourhood method.
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26 1661 Figure 1. Schematic representation of the impacts of human activities and the water
27 cycle components they may directly impact (derived from Botai et al., 2015).
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30 1663 Figure 2. A catchment impacted by human activities: gauging stations A1 and B1 are
31 uninfluenced, gauging stations A2, B2 and C are candidates for naturalization
32 procedures (Source: INRAE).
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37 1666 Figure 3. Diagram of the three periods distinguished in naturalization.
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40 1667 Figure 4. Hydrograph at logarithmic scale of the daily observed streamflow of the Aube
41 River at Arcis-sur-Aube (France, 3560 km²). The red line corresponds to the upstream
42 dam's commissioning in 1990.
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46 1670 Figure 5. Diagram of the choice of naturalization according to the available data.
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49 1671 Figure 6. Naturalization methods applied in the studies reviewed.
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52 1672 Figure 7. Illustration of the two application steps of the Reconstitution method.
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54 1673 Figure 8. Illustration of the two application steps of the Extension method.
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57 1674 Figure 9. Map of the withdrawable water volumes in the catchments studied (Rhône-
58 Mediterranean district).
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Schematic representation of the impacts of human activities and the water cycle components they may directly impact (derived from Botai et al., 2015)

218x108mm (150 x 150 DPI)



A catchment impacted by human activities: gauging stations A1 and B1 are uninfluenced, gauging stations A2, B2 and C are candidates for naturalization procedures (Source: INRAE)

162x110mm (150 x 150 DPI)

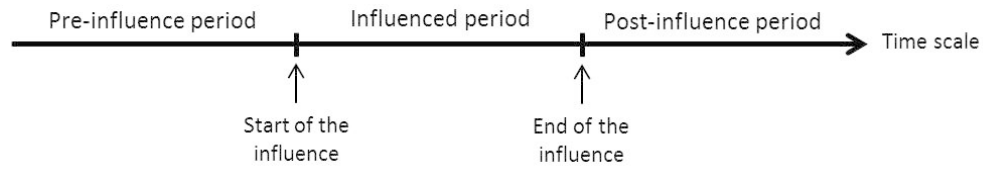
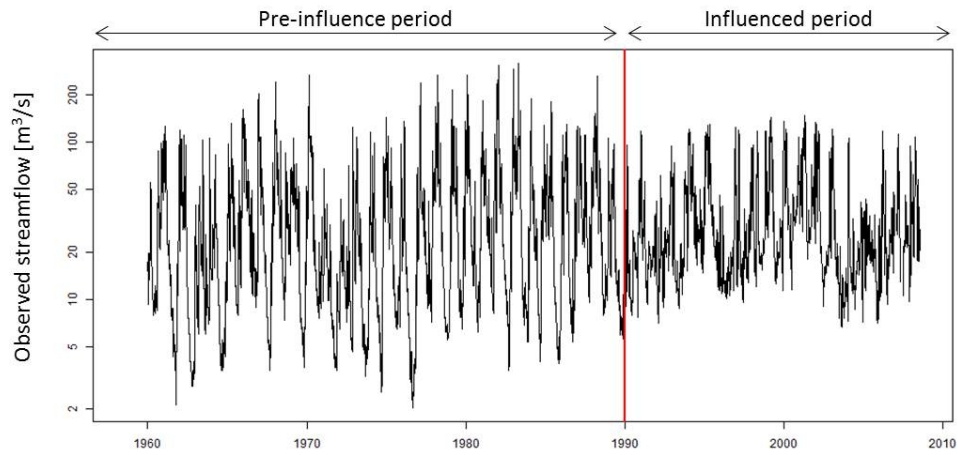


Diagram of the three periods distinguished in naturalization.

168x31mm (150 x 150 DPI)



Hydrograph at logarithmic scale of the daily observed streamflow of the Aube River at Arcis-sur-Aube (France, 3560 km²). The red line corresponds to the upstream dam's commissioning in 1990.

180x88mm (150 x 150 DPI)

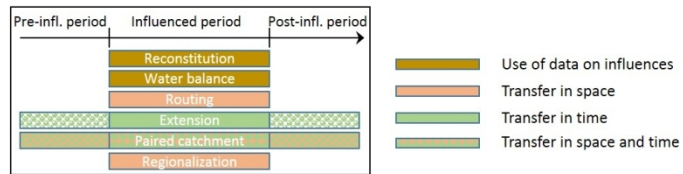
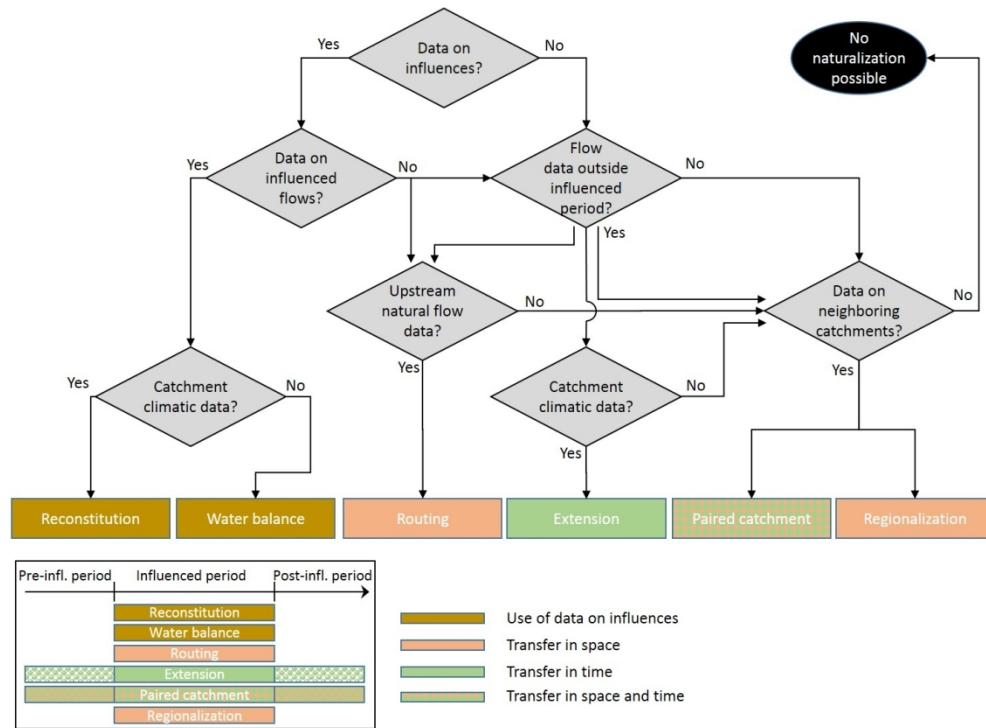
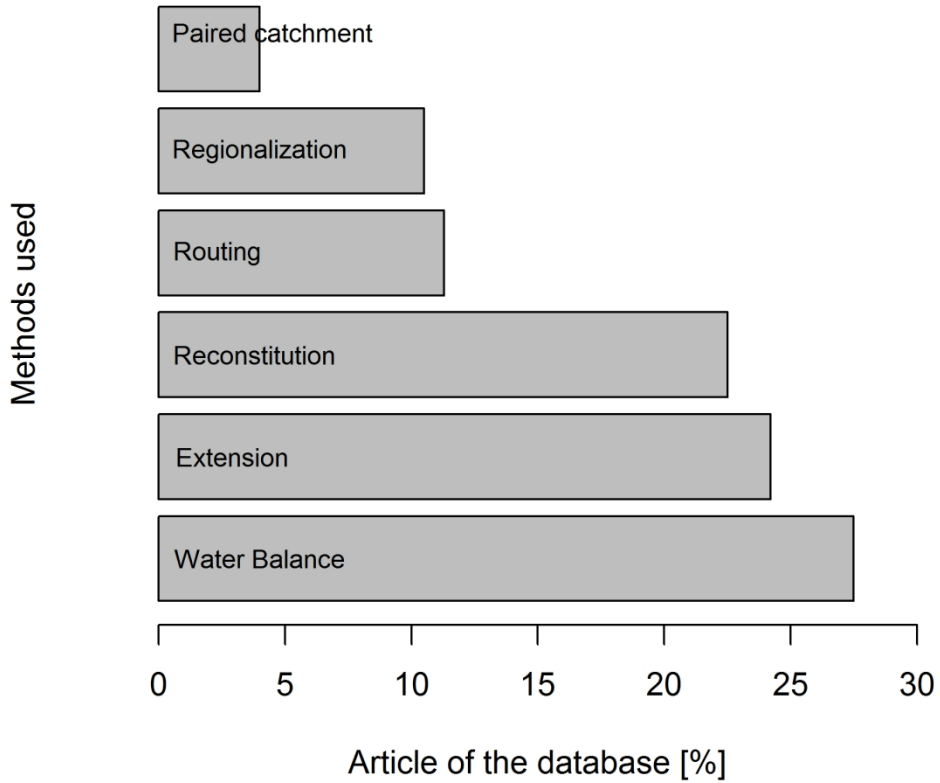


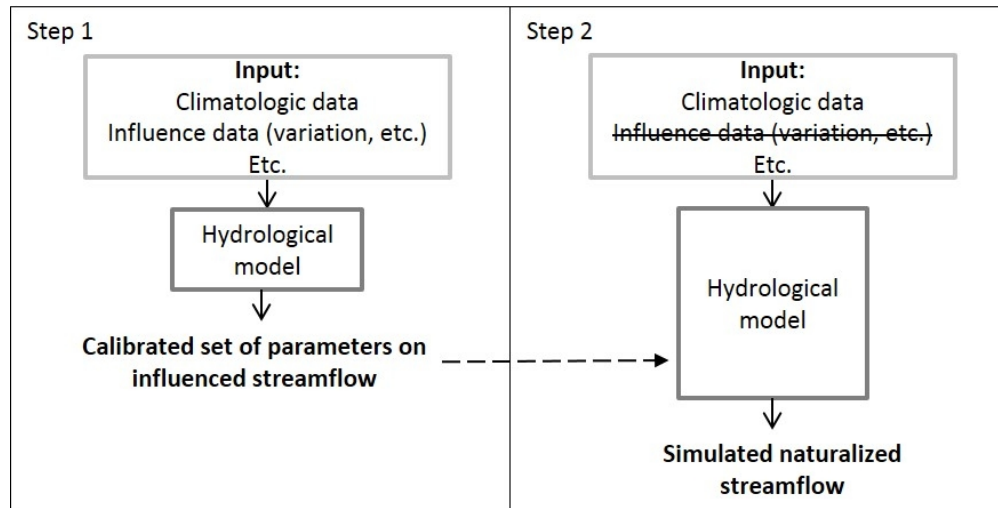
Diagram of the choice of naturalization according to the available data.

252x183mm (150 x 150 DPI)

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Naturalization methods applied in the studies reviewed.



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24 Illustration of the two application steps of the Reconstitution method.

25 148x76mm (150 x 150 DPI)

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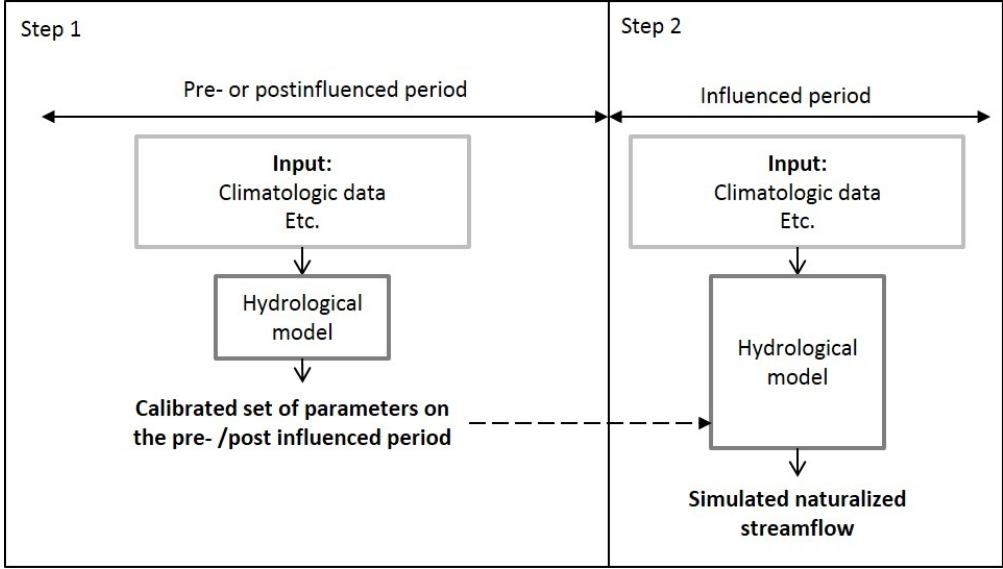
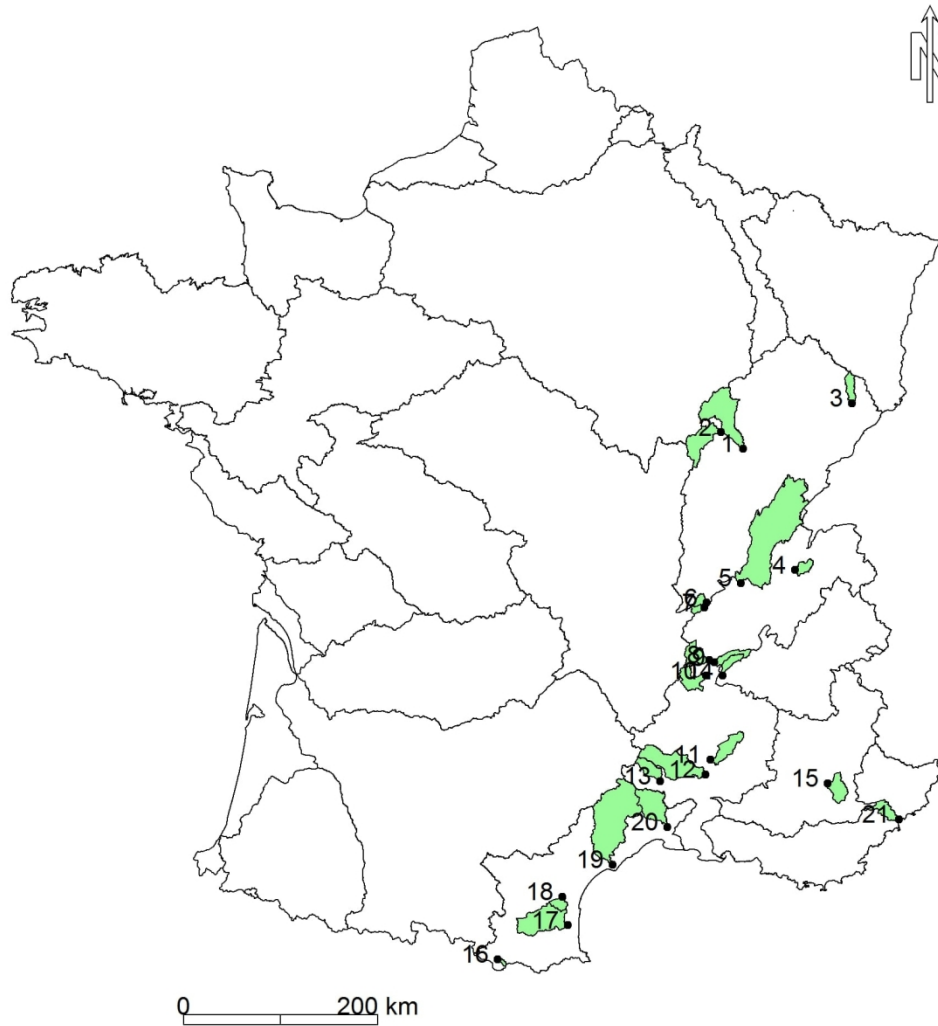


Illustration of the two application steps of the Extension method.

162x92mm (150 x 150 DPI)



Map of the withdrawable water volumes in the catchments studied (Rhône-Mediterranean district).

638x718mm (72 x 72 DPI)

Source	Definition
New South Wales Scientific Committee in Australia, 2002	(D1) Natural flow regimes are determined by the climate, run-off, catchment size and geomorphology without the impacts of dams, weirs, extraction and river management (NSW Scientific Committee, 2002).
Environmental Protection Agency in the USA, 2015	(D2) A stream's natural flow regime is a function of the climate and physical properties of its unique upstream drainage area (Novak et al., 2015).
Canadian Science Advisory Secretariat, 2013	(D3) A "natural flow regime" can be defined as a flow regime that is only affected by the variability in hydrological inputs and outputs (precipitation, evaporation) and natural water storage (such as groundwater) and for which the response in terms of amplitude, timing, duration and frequency of events is unaltered by human impacts (DFO, 2013).
World Meteorological Organization, 2012	(D4) Natural flow corresponds to flow in a stream that would occur under natural conditions (WMO, 2012).

Authors	Basins	Size of the catchments	Influence	Time step	Period	Length[year]
Irwin et al., 1975	Venison Creek, Canada	90	Irrigation abstraction	Daily	July and August from 1967 to 1969	0.3
Wallace et Pawloski, 1988	Small stream in central Michigan	78	Irrigation abstraction	Monthly	From June to August 1983	0.3
Littlewood et Marsh, 1996	Thames basin to Kingston, United Kingdom	9,950	Reservoirs and abstraction	Monthly	1883-1992	99
Assani et al., 1999	La Wache river, Belgium	118	Two dams	Daily	1930-1995	65
Peters et Prowse, 2001	Lower Peace River, Canada	293,000	Hydroelectric dam	Daily	1972-1996	24
Wurbs, 2006	23 basins in Texas, USA	648 to 685 000		Monthly		
Page et al., 2005	Murrumbidgee river, Murray-Darling river system, Australia	84,000	26 dams, weir, and irrigation canals	Daily	1970-1998	28
Jiongxin, 2005	Lijin station (outlet of the river), Yellow river, China		Diversions	Annual	1952-1996	44
Naik et Jay, 2005	Columbia river at the Dalles	660,480	Irrigation abstraction and dam	Daily	1879-1928	49
Agosta, 2007	Ariege river at Foix, Garonne, France	1,360	Hydroelectric dams	Daily	1990-2004	14
Maurel et al., 2008	Seine basins, France	78,000	Industrial, agricultural and drinking water abstraction	Daily	1975-2004	29
Kim et Wurbs, 2011	Brazos river basin	115,565	Dam and diversions	Monthly	1998-2007	9
Fantin-Cruz et al., 2015	Correntes river, Brazil	3,898	Hydroelectric dam	Daily	2005-2012	7
Tongal et al., 2016	South Fork Flathead river	4,248	Dam	Daily	1953-2000	47
Davtalab et al., 2017	Karkheh river, Iran	50,000	Withdrawal for irrigation and canals	Daily		
Gu et al., 2017	Poyang Lake, China	162,200	14 reservoirs		1961-2013	52
Yuan et al., 2017	Yellow river, China	752,000	Irrigation, diversion, reservoirs, withdrawal for industry and civil sectors	Monthly	1961-2010	49

Study	Name	Spatial resolution	Temporal scale	Reservoirs and associated withdrawals in input	Reservoirs and associated withdrawals model	Irrigation in input	Crop model	Land use and land cover	Withdrawal for domestic and industrial purpose
Mareshwari et al. (1995)	Model of the Murray-Darling Commission	Semi-distributed	Monthly	Yes	No	No	No	No	No
Gosain et al. (2005)	SWAT	Semi-distributed	Daily	Yes	No	Yes	No	Yes	No
Kim et al. (2012)	SWAT	Semi-distributed	Daily	Yes	Yes	No	No	No	No
Nobert and Jeremiah (2012)	SWAT	Semi-distributed	Daily	No	No	No	No	Yes	No
Shi et al. (2013)	SWAT	Semi-distributed	Daily	No	No	No	No	Yes	No
De Girolamo et al. (2015)	SWAT	Semi-distributed	Daily	No	No	Yes	Yes	No	Yes
Zhang et al. (2016)	SWAT	Semi-distributed	Daily	No	No	No	No	Yes	No
Yin et al. (2017)		Semi-distributed	Daily	No	No	No	Yes	No	No
Morin et al. (1975)	CEQUEAU	Distributed	Daily	Yes	Yes	No	No	No	No
Desconnets et al. (1998)	CEQUEAU-ONU	Distributed	Daily	Yes	Yes	No	No	No	No

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Authors	Catchment	Country	Influence	Model	Time step	Calibration period	Naturalization period
Siriwardena et al. (2006)	Comet River basin (1 400 km ²)	Australia	Land use and land cover change	SIMHYD (Chiew et al., 2008)	Daily	1970-2000	1970-2000
Wen (2009)	Murrumbidgee river (84,000 km ²)	Australia	Fourteen dams and eight large weirs	Regressive model	Monthly	1889-1920	1921-2007
Ma et al.(2010)	Junction of Chao and Bai River basin (15,800 km ²)	China	Direct withdrawal for irrigation and land use changes	GBHM (Yang et al. 2002, 1998)	Hourly	1956-1965	1984-2005
Wang et al. (2010)	Baimasi basin (13,915 km ²), Yellow River	China	River water withdrawals for irrigation, land use changes	VIC model (Liang et al., 1994)	Daily	1961-1970	1971-2000
Jiang et al. (2011)	Laohahe basin (18,112 km ²)	China	Agricultural and industrial withdrawals, dams and reservoirs	1. Multi-regression 2. VIC model	1. Monthly 2. Daily	1964-1979	1980-2008
Bao et al. (2012)	Three catchments of the Haihe River (from 1,800 to 24,000 km ²)	China	Surface water and groundwater withdrawals for farm, industry and population and land use changes	VIC model (Liang et al., 1994)	Daily	11/16 years in the 1952-1972 period	5/40 years in the 1965-2004 period
Wang et al. (2013)	Haihe River basin (189,000 km ²)	China	Surface water and groundwater withdrawals for farming, industry and population and land use changes	Two-parameter monthly hydrological model (Xiong and Guo, 1999)	Monthly	1957-1978	1978/1980-2000
Zhan et al. (2013)	Bai River (9,228 km ²)	China	Dams, farmland	SIMHYD (Chiew et al., 2008)	Daily	1986-1990	1991-1998
Ahn and Merwade (2014)	103 Stations in New York, Indiana, Arizona and Georgia	USA		Regression (Jiang et al., 2011)	Monthly	1950-1979	1981-2010
Guo et al. (2014)	Weihe River (30,661 km ²)	China	Agricultural irrigation, industrial development, dam construction	HBV model	Daily	1972/1975-19	1985-2007
Chang et al. (2015)	Jinghe River basin (45,400 km ²)	China	Withdrawals	1.TOPMODEL 2.VIC model (Liang et al., 1994)	1. Monthly 2. Daily	1960-1970	1971-2010

Authors	Catchment	Country	Influence	Model
Peters and Prowse (2011)	Lower Peace River (293 000 km ²)	Canada	Hydroelectric dam	Hydraulic: one-dimensional hydraulic flood routing model
Ahn et al. (2006)	Illinois river	United States	Seven locks and dams, 36 levees	Hydraulic (UNET)
Peters et al. (2006)	Peace-Athabasca Delta (6000 km ²)	Canada	Hydroelectric dam	Hydraulic: one-dimensional hydrodynamic model
Shiklomanov and Lammers (2009)	Large Russian Arctic rivers	Russia	Reservoirs	Hydraulic: hydrograph routing model
Wyrick et al. (2009)	Mantua Creek (19 km ²), New Jersey	United States	Two small dams	Hydraulic (HEC-RAS) + Hydrology (HEC-HMS)
Wu et al. (2015)	Taiwan (680 km ²)	Taiwan	Reservoirs and diversions	

	Data required	Water Balance	Reconstitution	Extension	Paired Catchment	Neighbourhood	Routing modelling
Based on access to	Influenced period information: _ Influenced observed streamflow	X	X				
	_ Influence volume time series	X	X				
	Uninfluenced period information: Natural observed streamflow on a pre- or postinfluence period			X	X		
	Regional information: _ Upstream natural flow				X	X	X
	_ Natural observed streamflow on neighborhood catchment				X	X	
Tool used	Hydrological model		X	X	X	X	
	Hydraulic model	X					X
	Mass balance method (catchment area scaling, equipercetile methods, etc.)	X					

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Index	Catchments	Area [km ²]	Influences	Naturalization method				Models	Reference
				WB	R	E	N		
1	La Cance	From 11 to 380	Withdrawals and discharges, and farm dams	X			X	GR2M	BRL Ingénierie (2014)
2	Le Loup	283	Dam and withdrawals	X			X	Grloieau-pixel monthly model	Département des Alpes-Maritimes (2013)
3	Les Gardons	From 69 to 2034	Withdrawal for water supply, agriculture and industry, and dam	X			X	GR4J	BRL Ingénierie (2015)
4	Basse vallée de l'Ain	3630	Five dams and, surface and groundwater withdrawals		X			Modflow	SOGREAH Consultants et EPTEAU (2012)
5	Drôme des collines	470	Withdrawals		X			Conceptual semi-distributed daily model	Artelia Eau et Environnement et Maison régionale de l'Eau (2012a)
6	Hérault	2622	Withdrawals		X			ATHYS and hydrogeological model with withdrawal module	CEREG Ingénierie et Berga Sud (2015)
7	La Galaure	240	Withdrawals		X			Conceptual semi-distributed daily model	Artelia Eau et Environnement et Maison régionale de l'Eau (2012b)
8	Lez provençal	From 110 to 455	Surface and groundwater withdrawals for irrigation and water supply		X			Hydrological model (ATHYS) and hydrogeological model (MODFLOW) with withdrawal module	CEREG Ingénierie et al. (2013)
9	Ouche	916	Surface and groundwater withdrawals		X			Semi-distributed model	SOGREAH et al. (2011)
10	Tille	1300	Surface and groundwater withdrawals		X			NAM (MIKE11)	SAFEGE Ingénieurs Conseils (2011)
11	L'Asse	692	Withdrawals		X		X	ATHYS with withdrawal module	CEREG Ingénierie (2011)
12	La Berre drômoise	138	Withdrawals	X					Société du Canal de Provence et ASCONIT Consultants (2012)
13	L'Agly	From 157 to 1100	Surface and groundwater withdrawals, and dam	X					GINGER Environnement & Infrastructures (2012a)
14	Le Sègre		Withdrawals for irrigation, water supply, industry and artificial snow, and hydroelectric dam	X					SOGREAH (2012)
15	Le Vidourle	800	Surface and groundwater withdrawals, and dams	X					GINGER Environnement & Infrastructures (2012b)
16	Les Usses	310	Withdrawals	X					Risques et Développement et Maison régionale de l'Eau (2012)
17	Savoireuse	235	Withdrawals and farm dams	X					Cabinet Reilé (2012)
18	Le Garon	208	Groundwater withdrawals, farm reservoirs, inter-basin transferts, dam, irrigation	X		X		GR2M	BRL Ingénierie (2013)
19	Yzeron	150	130 farm dams, inter-basin transfert, irrigation	X		X		GR2M	BRL Ingénierie (2012)
20	Le Doux	630	Withdrawals and discharges, dams and farm reservoirs	X		X		GR4J	ISL (2011)
21	La Cèze	1359	Withdrawal for water supply, agriculture and industry, and dam	X		X		GR2M	BRL Ingénierie (2011)