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▶ To cite this version:

Morgane Terrier, Charles Perrin, Alban de Lavenne, Vazken Andréassian, Julien Lerat, et al.. Streamflow naturalization methods: a review. Hydrological Sciences Journal, 2021, 66 (1), pp.12-36. 10.1080/02626667.2020.1839080 . hal-03266329

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Journal:	*Hydrological Sciences Journal*
Manuscript ID	HSJ-2019-0348.R1
Manuscript Type:	Original Article
Date Submitted by the Author:	11-Jun-2020
Complete List of Authors:	Terrier, Morgane; Irstea, Perrin, Charles; Irstea (Cemagref), UR HBAN De Lavenne, Alban; SMHI Andréassian, Vazken; Cemagref, Unité de Recherche HBAN, Groupe Hydrologie Lerat, Julien; Bureau of Meteorology, Environment and Research – Forecast Systems Vaze, Jai; CSIRO, Land and Water
Keywords:	Naturalization methods, Influenced catchments, Impacted catchments, Uncertainty, Hydrological modelling

Streamflow naturalization methods: a review

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Abstract

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

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

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

Keywords: Naturalization methods; Streamflow; Human influences; Impacted 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

(Whitfield et al., 2012). They represent how catchments respond to climate variability and serve as reference to hydrological trends induced by climate-driven changes and in studies at the regional scale.

- **Using naturalization methods:** in case there are human influences, dedicated methods have to be applied to retrieve the natural flow regime from influenced flow in a target basin. The natural flow estimates are then called naturalized flows.

In this article, we will focus on the second type of approach. Naturalization methods use various sources of information depending on their availability, typically observed influenced flows, volumes linked to human influences, flows observed before or after the period of influence, or flows free from influence at the regional scale. Naturalization methods are all based on models, some of which are very crude (typically a water balance equation) and others are more complex and comprehensive. Hydrological models, representing the rainfall-runoff relationship at the catchment scale, or routing models, representing the upstream-downstream flow propagation, are commonly used in naturalization methods. In cases of insufficient or too coarse data on influences, models may be also needed to generate information on these human-induced influences.

1.2 Why do we need natural flows?

As noted by the Canadian Science Advisory Secretariat (MPO, 2013), the flow of a river is the main variable that connects eco-system components along a river corridor via hydrological, biological, geomorphological, and water quality processes. As a result, natural flow can be typically used as a reference to estimate hydrological response to climate regime, to evaluate the ecological state of a river (Poff et al., 1997) and to estimate the quantity of water available. Here we detail three domains for which natural flows are needed and naturalization methods can therefore be helpful.

- **Ecological impact assessment**

Naturalization methods contribute to the evaluation of anthropogenic impacts on ecosystems. Comparing naturalized streamflows against influenced streamflows provides a way to assess the anthropogenic impact on the natural environment (Poff et al., 1997, Rahman and Bowling, 2018). The degree of alteration corresponds to the difference between naturalized and observed streamflows (Jacobson and Galat, 2008), or the difference between indicators computed on these streamflows (Richter et al., 1996). These indicators include the magnitude of monthly flows, magnitude and duration of annual extreme floods, timing of annual extreme floods, frequency and duration of high and low pulses, and rate and frequency of flow changes (Birkel et al., 2014; De Girolamo et al., 2015; Fantin-Cruz et al., 2015; Fernández et al., 2012; Laizé et al., 2014; Ryo et al., 2015).

The classical approach to quantify the degree of alteration consists in using the observed natural flow from a pre-influence period. However, if these observations are not available or on a too short duration to give a robust estimates of hydrological indicators (Fantin-Cruz et al., 2015), naturalization methods can provide an estimation of natural flow based on data from the influenced period only. Moreover, observed natural flows over the pre-influence period may not be representative of the climate and physical conditions of the influenced period due to natural evolution and variability. Consequently they may not be exploitable for human impact studies. Naturalization methods also make it possible to separate the impact due to anthropogenic pressures (local or regional) and the impact caused by climate change, and to quantify them. The anthropogenic impact corresponds to the difference between the naturalized and observed streamflow during the influenced period. The climatic impact corresponds to a difference between the naturalized flow over the influenced period and the observed natural flow of an earlier period. As an example, naturalization has been applied in China to quantify climatic and anthropogenic impacts: on the Haihe River basin (Bao et al., 2012; Wang et al., 2013; Zhan et al., 2013), the Yellow River basin (Hu et al., 2015; Li et al., 2007; Wang et al., 2010), the Miyun reservoir (Ma et al., 2010), the Yangtze River basin (Li et al., 2013) and Poyang Lake (Gu et al., 2017), the Laohahe River basin (Jiang et al., 2011) and the Shiyang River basin (Huo et al., 2008). Similarly, in Australia, the CSIRO (2008) conducted the Sustainable Yields project to assess climate change impacts on the Murray-Darling basin, at a detailed basin scale.

- **Climate impact issue**

In a context of climate change, many studies prefer to focus on projections of "natural streamflows", even in heavily influenced rivers, because it would be too complex to address the issues of climate change and water use changes at the same time. Therefore, flow naturalization becomes necessary to serve as a baseline, as well as to calibrate hydrological models. For example, in the case study of the Seine River, Dorchies et al., (2014) used the naturalized streamflow on the 1990-2011 period to calibrate a model to estimate the future available water resources for the 2046-2065 period. On a larger scale, in the SCENES project (water Scenarios for Europe and Neighbouring States), Laizé et al. (2014) used the naturalized streamflow on the 1961-1990 period as a baseline to estimate the future of freshwater resources for 2040-2069.

- **Water resources management**

In many countries, regulations on the authorization of abstractions and discharges into rivers, and on the good ecological status of rivers, are based on naturalized hydrological indicators. The environmental conditions enabling governmental agencies to protect, restore or rehabilitate rivers, can be linked to components of the natural flow regime (Poff et al., 1997). Two of the main approaches to obtain an environmental flow regime are linked to the natural flow regime (Acreman and Dunbar, 2004): the look-up tables approach is based on the statistical properties of the natural flow regime and the desktop analysis approach is based on the natural seasonality and variability of flows. These methods, failing to have access to observed natural flow, use a naturalized flow regime.

In a regulation context, management of water resources is essential to satisfy the supply of drinking water, preserve the ecological status of the aquatic environment, limit the negative consequences of floods and droughts, and provide water for different economic needs such as industry, agriculture, fishing and electricity (European Commission, 1997). In this perspective, naturalized flow can be used to simulate different water management scenarios and the impact of these scenarios on the quantity of available water (Desconnets et al., 1998; Dunn and Ferrier, 1999; Kim and Wurbs, 2011; Maurel et al., 2008; Wurbs, 2006).

Naturalization methods also constitute one of the fundamental element supporting water management policies. For example, the Water Framework Directive typically appeals to natural conditions to define the natural status of a river (Bouleau and Pont, 2015). In France, naturalization methods are used to estimate maximum water extractions sustaining environmental flows (Fabre et al., 2016). In the UK, the Environmental Agency developed guidelines to provide naturalized low-flow statistics to enable regulators to make licensing decisions (Bullock et al., 1991; Holmes et al., 2002; Young et al., 2003). These results make it possible, in particular, to define the maximum possible withdrawals to maintain good ecological status (Acreman et al., 2008).

1.3 Key challenges around naturalization

Flow naturalization faces several challenges. From a theoretical point of view, a naturalized flow could be defined as a flow observed in the absence of human activities in the catchment upstream of the gauging station. However, the definition of a natural status of a catchment may be difficult for various reasons, e.g. when the catchment characteristics and the human influences have been co-evolving over a long period. Therefore, there is not always a clear distinction between the influenced period and the pre- or post-influenced periods, which may limit the naturalization process. Obviously, this will be hugely dependent on the geographical region, since some have known the human influence over centuries though others were only influenced over the last few decades.

Another issue lies in the lack of justification in the choice of naturalization methods in many studies. The application of naturalization methods raises hypotheses, in particular in terms of transposition (i.e. transfer of information) in space and time, which seem rarely verified. This may limit the reliability of naturalized flow estimates.

Finally, naturalized flows are often implicitly considered accurate estimates of natural flow. In practice, naturalized flows include uncertainties arising from method assumptions, data and models used. It is therefore important to be transparent about these uncertainties to avoid mis-use of natural flows data when uncertainty is large.

1.4 Objectives

The main objective of this article is to provide a review on the issue of flow naturalization. More specifically, this paper intends to (1) provide an overview of the naturalization methods, their assumptions and associated tools, and (2) highlight the scientific issues raised by the application of naturalization methods commonly done in scientific or operational studies.

Establishing a corpus of studies on naturalization methods is not straightforward. Indeed, naturalization methods used to estimate flow series free from anthropogenic influence are rarely the main focus of scientific publications, though they remain a necessary step for many issues detailed above. In addition, there is a quite large terminology to address naturalization issues (see the discussion in section 3.1). Therefore, the literature review presented in this article is probably not exhaustive though it encompasses already a wide range of aspects. Selected articles in this review dates back to the 1970s, with a recent increase in publications after 2010, showing a growing interest in this issue in the water management community.

This paper is organized as follows. Section 2 lists the main human influences considered in this paper and their potential impact on the natural hydrological cycle. Then section 3 investigates the concept of naturalized flow and how it is interpreted in the literature reviewed. Section 4 presents the main types of naturalization methods with their underlying assumptions and uncertainties. Section 5 discusses scientific and technical issues associated with naturalization methods, with an example in France. Finally section 6 gives some concluding remarks.

2 Potential impact of anthropogenic influences on streamflow

2.1 Human impacts considered

A prerequisite for streamflow naturalization is to identify the nature of human impacts and quantify them to determine which influences should be considered in the naturalization process. Figure 1 (Botai et al., 2015) summarizes how human activities potentially affect the different components of the hydrological cycle. The main anthropogenic influences are land cover and land use change, streamflow regulation infrastructure, and withdrawals and discharges associated with different water uses (we did not consider here the impacts of human activities on climate, which ultimately impact water resources). Most of these influences potentially impact several components of the water cycle and so directly or indirectly the observed streamflow. We detail their main impacts in the following paragraphs. Some of these impacts may be interlinked or show counterbalancing effects. For example, in-basin water abstraction and release may compensate to some extent at the catchment scale, with limited net impact on mean flow at the yearly scale. However, they may more deeply modify catchment dynamics at the seasonal or event scale (high or low flows). Other activities will always strongly impact catchment water yields and hydrological dynamics, e.g. inter-basin water transfers.

[Figure 1 near here]

2.2 Dams and their associated storage

Among the 62 studies applying naturalization methods we reviewed, 47 are considering the impact of dams and artificial reservoirs. The hydrological modifications caused by dams have two origins (McCully, 2001): the impacts due to the management of the dam (alternating operations of water storage and release) and the impacts stemming from the ponding effect of the reservoir. The presence of the stagnant water body, created by the dam, modifies several components of the local hydrological cycle, including evaporation and infiltration, and local precipitation for large dams (Degu and Hossain, 2012; Haberlie et al., 2016). It may also strongly modify water quality (Winton et al., 2019). A permanent rise in the water table downstream can be caused by infiltration from the reservoir. The dam operations, consisting of periods of storage and release, regulate water flows in a way generally opposite to natural processes (typically flood alleviation or low-flow augmentation). They also result in various states of the lake behind the dam: for flood protection, the reservoir should be as empty as possible and for potable water supply, the reservoir should be as full as possible (Margat and Andréassian, 2008). From a temporal point of view, dams can cause changes in flow seasonality and temporary fluctuations, especially hydro-power dams. The management of hydro-power reservoirs will depend on the profitability of electricity generation; for agriculture purposes, it will depend on crop need. Since each dam has specific management rules, the impacts of the dams and their amplitudes are each time specific. Note that the cumulated effect of dams over a catchment may also be considered. This is often the case when there are many small farm dams spread over a catchment. In that case, this is often much more difficult to access data for each dam and a meta-analysis over all dams may be preferred (Dong et al., 2019; Fowler et al., 2015; Hughes and Mantel, 2010).

2.3 Water withdrawal

Water withdrawals refer to the amount of freshwater that is artificially extracted from groundwater or surface water resources. The consumptive use of water corresponds to "the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise not available for immediate use" (USGS and National Water-Use Science Project, 2019). In our case, water returned to a different catchment than the point of withdrawal (interbasin transfer) is considered a consumptive use. Therefore the quantity of water withdrawn from a river cannot be considered a good indicator of the actual quantitative impact of withdrawals, and the consumed water quantity should be used instead. According to the report of the World Water Development Program (WWAP, 2009), agriculture is the largest consumer of water with 90% consumption for drip irrigation and 50-60% for surface irrigation. The energy sector has the smallest consumption ratio on the order of 1-2%. Domestic uses consume between 10 and 20% of the water withdrawn, and industry between 5 and 10%. These figures, however, remain overall estimates with large variability between regions. Water withdrawal can have a temporal impact because of the time lag between the time the water is withdrawn and the moment when the amount of water not consumed returns to the system (Kendy and Bredehoeft, 2006).

Two sources of water are distinguished: water withdrawn from the groundwater and water abstracted from the surface. Surface water withdrawals have a direct and rapid impact on streamflow. Groundwater withdrawals have an indirect or delayed impact on river flows. Exchanges between surface water and groundwater can occur in both directions: a water table lower than the free surface of the river leads to a recharge of the aquifer by the river; the situation is reversed if the groundwater level is higher. Disturbance of the river-groundwater table balance can lead to a drop in the water table and/or an increase in the recharge rate, and so indirectly influences streamflow (Theis, 1941). With only four articles considering groundwater abstraction, this type of withdrawals remains limited in our article database, but it is more widespread in operational studies to quantify the available water.

2.4 Water release

Water releases refer to the amount of water that is artificially brought to rivers. Two cases of water release can be distinguished: water releases originating from a withdrawal on the basin and the releases from an inter-basin water transfer. Inter-basin water transfer corresponds to the artificial withdrawal of water by ditch, canal or pipeline from its source in one basin for use in another (Slabbert, 2007). The streamflow of the receiving basin can consequently be artificially increased. It can also impact the seasonality of river flows. For example, in several rivers in South African, inter-basin transfers aim to counter temporal variability and reduce the economic impact of a localised drought (Blanchon, 2005). In the case of a release following a withdrawal within the catchment, one part of the water withdrawn having been consumed, the release has a reduced impact on the water resource quantity but an impact on the temporality of observed streamflow. In the case where the release place differs from the withdrawal place, release can impact the spatial distribution of water resources.

2.5 Land use and land cover change

Human activities can lead to a change in land use and land cover through urbanization, agricultural development, afforestation and deforestation. In the article database, human influences related to land use are taken into account in the naturalization process in only eleven studies, although they are the most pervasive anthropogenic impact (Pagano and Sorooshian, 2005). Changes in land use and land cover have an indirect impact on flow. In modifying the quantity of energy absorbed by the surface, the evaporation rate is impacted and the precipitation rate can also be modified in changing the temperature gradient (Giambelluca, 2005). Groundwater recharge and overland flow are also impacted. Moreover, numerous studies on land use and land cover change and its impact on the hydrological cycle have been carried out in relatively small paired catchments (Stednick, 1996), with results that are difficult to generalize to a larger scale (Siriwardena et al., 2006; Zhang et al., 2018). The particularity of land use change is that modification of the evapotranspiration-runoff relation at the local scale can impact the regional water balance because of changes in atmospheric circulation (Bosmans et al., 2017; Chase et al., 2000; Gash and Nobre, 1997).

2.6 Combination of human impacts

In practice, observed flow at gauging stations is potentially influenced by several existing human activities in the basin: industries, energy production at the hydroelectric dam, agriculture, recreational activities (e.g. ski resorts, navigation for pleasure boating) and cities (see illustration in Figure 2).

[Figure 2 near here]

Flow regulation and direct withdrawal and discharge in rivers lead to a sudden change (typically on a daily basis) in river streamflow, whereas the impacts on the other components of the hydrological cycle can take longer to impact the observed streamflow. The time delay of the impact on the observed flow is also conditioned by the distance between the source of the influence and the gauging station, and by the water pathways. For example, in Figure 2, stations A2 and C are both influenced by the dam's management. The A2 station, directly downstream of the dam, is impacted sooner than station C due to shorter propagation time.

The importance of the influenced signal contained in the observed streamflow can be conditioned by several factors. Distance plays a role because the intermediate hydrological processes can mitigate the importance of the impact (Mwedzi et al., 2016). Thus, the influence of the dam at station C is much less than at station A2, because dam releases will represent a smaller proportion of the total streamflow at station C than at station A2, due to inflows by the intermediary basin. In the case of basins with multiple influences, there can be compensations of some impacts: dam releases can be planned for agricultural withdrawals downstream, and therefore their impact may not be visible at the catchment outlet, the reservoir can increase groundwater recharge and thus compensate the effects of underground withdrawals in summer (Constantz and Essaid, 2007).

The impact of human activities on flow therefore depends on several factors specific to each basin (type of influence and location, basin characteristics). The following sections present if and how impacts are taken into account in the naturalization process.

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).

In the literature, it appears that the streamflow obtained in naturalization is not systematically called "naturalized streamflow" and may be designated by other words which are not necessarily synonymous. We will present the terms by which some authors refer to naturalized flows and discuss the nuances in the definition of naturalized flow that these terms imply. First, there are the terms referring to the influenced state of the basin such as the terms "regulated" or "influenced" streamflow. Following existing definitions of regulated flow (AFB and Ministère chargé de l'environnement, 2016a; Bureau of Meteorology, 2012; Environmental Protection Agency, 2015; WaterNSW, 2015), an unregulated streamflow corresponds to a natural flow not impacted by artificial flow-regulation structures. The influences of land-use changes are therefore not included. The terms "uninfluenced" and "unimpaired" flow refer to the flow of an undisturbed stream caused by human interventions and whose flows retain their general characteristics (AFB and Ministère chargé de l'environnement, 2016b). The uninfluenced flow thus takes into account a wider field of influence such as the change of land use and land cover. Other terms refer to the natural state of the catchment such as "flow under natural conditions" and "natural flow". The "simulated natural streamflow" encountered in some studies refers to a naturalized streamflow obtained using a hydrological model. The terms of "reconstructed or estimated natural/virgin streamflow" are synonymous with naturalized streamflow. Although all these terms refer to a naturalized flow, they may not reflect the same natural reference. So, the nuances between these terms must not be forgotten to avoid confusion.

3.2 Determination of the basin's baseline condition

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

[Figure 3 near here]

The pre-influence period serves as the basin's baseline condition and is assumed to correspond to a past period when the observed flow is considered as free of the impact of the anthropogenic influences considered in the naturalization processes. Information from this pre-influence period is used by several naturalization methods. However, in many cases, the influence dates back before flow measurements were made and there is therefore no information on natural flows.

The post-influence period corresponds to the period after the influences considered in the basin has ceased and a return to a natural state, which may be different from the state before the influence. This period is also relevant to serve as a natural reference period if the system has enough time to return to uninfluenced conditions. Obviously, the post-influence period does not exist in catchments under active anthropogenic activities. Studies exploiting the post-influence period mainly focus on sediment dynamics and fauna and flora species after a dam removal (Hart et al., 2002; Kibler et al., 2011; Magirl et al., 2014). Therefore, post-influence periods will not be discussed in this paper, however some comments about the pre-influence period are somewhat transposable to post-influence.

The use of data from the pre-influence and post-influence periods to estimate the natural regime over a later influenced period raises a question about the reversibility of the system: if all activities stopped, would the river be able to return to a natural state that it would have reached if it had never been influenced (Cooper, 2004)? In some cases, the influence of humans is so old that it has shaped the characteristics of the basin and it represents the new natural condition. For example in southern France, the system Neste was created in the 19th century for irrigation purposes. This network of canals strongly impacted the land use of a large number of small catchments, with conditions now that are very different from those that were before (Tardieu, 2008; Villocel, 2002). Still in France, many wetlands were dried out for sanitary of agricultural objectives, like the Marais Poitevin since the beginning of the 18th century, and it would be difficult to come back to the pristine conditions (Godet and Thomas, 2013).

Theoretically, the separation of the pre-influence and influenced periods should match the start of the influence on the basin. In practice, in the case of dam commissioning, as illustrated for the Aube dam (Figure 4), the change on the observed flow time series is abrupt and so the separation is easily identifiable. In other cases, like withdrawals or small farm dams, which may gradually appear in the basin and evolve over time, or in the case of gradual land use and land cover change, the date of implementation of all the influences is rarely accessible and there is generally no abrupt change on the observed flow time series, which complicates the separation dating.

[Figure 4 near here]

In naturalization studies, change-point detection tests (Andréassian et al., 2003; Hubert et al., 1989) are mainly used to distinguish the pre-influence and influenced periods (Bao et al., 2012; Gu et al., 2017; Guo et al., 2014; Hu et al., 2015; Jiang et al., 2011; Wang et al., 2009; Wang et al., 2013; Zhan et al., 2013). The identified break point most often corresponds to a statistically significant change in the observed flow time series, but this break can have an anthropogenic origin (dam, urbanization, etc.), be natural (natural change in the morphology of the river) or stem from climatic variability or a data problem (change in data measurement devices, etc.). With this method, it is important to underline that anthropogenic disturbances can still exist during the period defined as pre-influence (Jiang et al., 2011) and that these influences can therefore impact the naturalized flows obtained.

4 Methods to naturalize streamflows

4.1 Overview on naturalization methods

We have identified six main naturalization methods in the literature: (1) the reconstitution, (2) water balance, (3) routing, (4) the extension, (5) the paired catchment and (6) regionalization (or neighbourhood) methods. These methods differ mainly by their input data and the underlying models used.

The reconstitution, extension and neighbourhood methods are based on a hydrological model simulating a naturalized streamflow with an estimated set of parameters reflecting the natural hydrological conditions. In reconstitution, failing to have past observations, information on the observed influenced streamflow and the anthropogenic influences are exploited to indirectly estimate the set of parameters representing natural hydrological conditions. In extension, past observations of natural flows on the target catchment are used to estimate the set of parameters reflecting the natural hydrological conditions. In neighbourhood, the observations that exist on neighbouring basins are exploited to estimate the set of parameters. Although these methods use a hydrological model, they rely on different assumptions and data to obtain the model parameter set.

Figure 5 provides a decision tree for the use of the various methods. The starting key question is generally the availability of input data on influences, followed by the availability of data from pre- or post-influenced period, or of regional data. The use of these different data raises hypotheses for the application of the methods. Figure 5 shows which methods can be applied based on the available data. If all the data are available, all the methods can be applied. If no data is available, one may end up to the conclusion that no flow naturalization is possible (black ellipse on the graph). In that case, one may appeal to hydrological models implemented at the global scale, which do not require local or regional data. However, the reliability of these models at the local scale remains limited. That is why this option will not be further discussed in this review.

In the following sections, an explanation of the main hypotheses raised by the naturalization methods is provided in order to identify their application conditions. Figure 6 shows which methods are used in our articles database.

[Figure 5 near here]

[Figure 6 near here]

4.2 Methods using data on influences

4.2.1 Water Balance

The Water Balance method consists in decomposing flow into a natural part and an influence part at the scale of the influenced system (typically an artificial reservoir), by removing the volume variation in the river induced by the source of influence, ΔV, during the time interval Δt, from the influenced observed flow, $Q_{observed}$, to obtain the naturalized flow, $Q_{naturalized}$ (equation 1). The system studied can be a river reach where there is a water withdrawal or release, or a reach downstream of an influence. By convention, in the case of a water discharge, ΔV will be negative. In the case of a water withdrawal, ΔV will be positive. This method is generally applied at a gauging station located downstream of the influences in the river, although in principle it is also applicable to a fictitious point where flow data obtained through regionalization methods are available. Hydraulic propagation between the influence and the station can have an impact on the computation of the naturalized streamflow. The ΔV computed at a moment t will not have an immediate impact on the observed streamflow at the downstream station, but will have an impact at the time t + Δp, where Δp corresponds to the propagation time. If the propagation time is much lower than the study time step, then the propagation effect can be ignored. Otherwise, it is advisable to use a propagation model. The choice of time step will define the hydrological processes to be taken into account and their influences to be considered.

$$Q_{naturalized} = Q_{observed} + \frac{\Delta V}{\Delta t} \qquad (1)$$

The Water Balance method is the most widely used in the studies. Table 2 lists the studies using this method. It appears that this method, mainly constrained by the availability of data, is mostly applied to a daily time step over periods ranging from a few months to several decades. However, if the method is applied over a long period of time, there may be disparities in the quality of the naturalized flows obtained over the entire period. This may be due to the evolution of the quality of the measured flows (Littlewood and Marsh, 1996). In the studies taking into account the influence of dams, it appears that, for the most part, only the impact of dam regulation operations is taken into account (Assani et al., 1999; Kim and Wurbs, 2011; Naik and Jay, 2005; Page et al., 2005; Peters and Prowse, 2001; Yuan et al., 2017). Some studies also take into account evaporation from the reservoirs (Fantin-Cruz et al., 2015; Tongal et al., 2017) and precipitation falling on the reservoirs (Gu et al., 2017), but no studies seem to take into account the underground exchanges induced by the reservoir. For studies taking into account withdrawals, it appears that it is the volume of water consumed that is taken into account in naturalization and not the volume of water withdrawn (Davtalab et al., 2017; Littlewood and Marsh, 1996; Wallace and Pavvloski, 1988; Wurbs, 2006).

[Table 2 near here]

4.2.2 Reconstitution method

The Reconstitution method is based on the exploitation of the influenced observed streamflow and the information available on influences during the influenced period and on the use of hydrological models taking anthropogenic influences explicitly into account. As illustrated in Figure 7, the Reconstitution method consists first in calibrating the hydrological model on the influenced observed streamflow taking into account the anthropogenic influences. Then the set of parameters obtained is used to simulate a naturalized streamflow without taking into account the anthropogenic influences. In cases where the signal of influence in the observed flow is predominant over the natural signal, it is important to ensure that the calibrated parameter set is able to reflect the natural catchment behaviour. Step 1 is common to all studies applying the Reconstitution method, with more or less complex calibration methods depending on the model used and the influence considered. There are some variants of step 2, for the estimation of the naturalized streamflow. One variant corresponds to the case where the model output considered is the time series of the influences. The second step then corresponds to the application of the Water Balance method where the volume variation of the influences is added to the observed streamflow (Dunn and Ferrier, 1999; Maheshwari et al., 1995; Wurbs, 2006). Another more hydraulics-oriented variant, relevant for the semi-distributed and distributed models with an in-stream flow routing, consists at step 2 of propagating the upstream natural streamflow if available (Kim et al., 2012). In the case of an impact of land use and cover change, in the second step the parameter and input corresponding to influenced land use are changed to correspond to the pre-influenced state (Nobert and Jeremiah, 2012; Shi et al., 2013; Yin et al., 2017; Zhang et al., 2016).

[Figure 7 near here]

Since studies are often not very explicit in terms of the model calibration with anthropogenic influences, it is difficult to clearly identify which studies apply Reconstitution methods. Table 3 presents a synthesis of the models used in studies applying the Reconstitution method, the time step of the naturalized flow, the influence taken into account as input in the studies and the simulated flow. The impact of dams and reservoirs are often the main issue in Reconstitution studies. This can be explained by the fact that their management can be simulated. The second most studied influence is land use and land cover changes, which are taken into account by physically based hydrological models such as SWAT (see Table 3). The semi-distributed spatial resolution is adopted by most studies. In the case of large catchments, the influences can be localized in space and attenuation of the influences along the river are more accurately considered.

[Table 3 near here]

4.2.3 Comparison

The Reconstitution and Water Balance methods are based on the hypothesis that by knowing the impacts of the various influences on the observed flow, it is possible to have a naturalized flow free from these influences. As no study has made a comparison between the Reconstitution method and the Water Balance method, it is not possible to know which one is the most suitable. However, here are a few elements that differentiate these methods and may guide their choice:

- **Data availability.** The Water Balance method requires time series data on the entire period to naturalize. The advantage of the Reconstitution method is that once the parameter set has been obtained, it is theoretically applicable to other periods.

- **Setting up the model.** The Water Balance method seems to be easier to apply than the Reconstitution method which requires the implementation of a hydrological model on the basin. However, the use of a hydrological model can facilitate several steps such as estimating the volumes of influences that can be incorporated into the model or estimating travel time. It is difficult to say a priori which method will be easier to apply. This depends primarily on the catchment area and the influences considered.

4.3 Methods using observation from the pre-influenced period

4.3.1 Extension method

The Extension method is based on the exploitation of observed data of the target catchment from the pre-influence period and on the use of a hydrological model able to simulate the natural streamflow of the target catchment. The required data for the pre-influence period are at least the natural observed streamflow and the input data required by the model. On the influenced period, the input data required to use the model are necessary. The Extension method consists in calibrating the hydrological model on the natural observed streamflow of the pre-influence period and then in using the set of parameters obtained on the influenced period to simulate a naturalized streamflow (Figure 8).

[Figure 8 near here]

Table 4 presents an overview of the studies applying the Extension method and the hydrological models used. The common point of the models is their ability to simulate a natural flow. The models used in these studies show differences in terms of the type and level of complexity. Some studies used empirical models which establish a purely mathematical relationship between natural flow and weather variables over the pre-influence period. Wen (2009) established a multi-regression model with the precipitation and the maximum temperature data at the monthly time step; Jiang et al. (2011) built a multi-regression model with the precipitation and the potential evapotranspiration; Ahn and Merwade (2014) also take into account the drainage area. Other studies applied more complex models such as conceptual hydrological models (Chang et al., 2015; Guo et al., 2014; Wang et al., 2013; Zhan et al., 2013), or physical models (Bao et al., 2012; Chang, Zhang, et al., 2015; Jiang et al., 2011; Ma et al., 2010; Wang et al., 2010). Jiang et al. (2011) and Chang et al. (2015), who used models of different types, showed that the results obtained with the two models are comparable.

[Table 4 near here]

4.3.2 Paired catchment method

This method is explained here but also partly belongs to the family of methods exploiting regional information (see Figure 5). This method is based on the implementation of a statistical flow-rate relationship between the target station to naturalize and natural donor stations over the pre-influence period. The natural donor catchment is generally a catchment that is spatially close to (but not nested in) the target catchment, with similar size. There is no hydrological model involved in this method. This approach is not limited to cases of experimental basins to evaluate land use and land cover changes (Brown et al., 2005). To naturalize the flows of La Grande Rivière in Canada, Hernández-Henríquez et al. (2010) established a flow-rate relation over the pre-influence period by applying a variant of the Hirsh MOVE I method (Hirsch, 1982). On the Lena River in the Arctic, influenced by a reservoir dam, Ye et al. (2003) established a regression on the pre-influence period between a station downstream of the dam and five natural upstream uninfluenced stations. Smakhtin, (1999) proposed the same principle for catchments in South Africa. In China, Huo et al. (2008) established flow-rate relationships, including climatic variables (precipitation and temperature), between the uninfluenced upstream and downstream stations. The relation proposed by Huo et al. (2008) differs from the conventional paired basin methods (Andréassian et al., 2012) because they also use climatic information. Other variants exploiting the paired catchment relationship can be applied without parameter calibration. The drainage area ratio method (Hirsch, 1979) and different variants, requiring only an access to the catchment's area value, are applied in many naturalization studies (Kim, 2015; Rahman and Bowling, 2018; Wurbs, 2006). In any case, these approaches make the strong assumption that the departure of observed influenced flows from the relationship with paired catchment flow would be due to the influence only, which may not be always the case.

4.3.3 Comparison

Extension and Paired catchment methods are based on the hypothesis that relations established over the pre-influence period are stationary and remain valid over the influenced period. For the Extension method, running a hydrological model under climatic conditions that are different for the calibration period can generate uncertainties (Coron et al., 2012). The source of these uncertainties can be partly explained by the fact that, in the models, several physical parameters (soil, vegetation, etc.) are related to climatic conditions. The calibration of the model creates an interaction between the parameters and the climatic characteristics of the calibration period. The robustness of the model is usually tested on the pre-influence period by calibrating the model on a sub-period and validating it on another one (Bao et al., 2012; Guo et al., 2014; Jiang et al., 2011; Wang et al., 2010; Wang et al., 2013). For the Paired Catchment method, the limitation is the climatic gradient between the basins, which could lead to the two basins evolving differently. On the pre-influenced period, similar climatic conditions, landforms, soils, vegetation and hydrological processes between the basins can reduce the uncertainties associated with the natural evolution state of the target catchment (Hernández-Henríquez et al., 2010). These two methods can be distinguished by their level of complexity. The Extension method requires a rainfall-runoff model and meteorological data as input, whereas the paired basins method is simpler because it consists in establishing a relationship between two neighbouring catchments and only requires streamflow measurements. Despite these differences in complexity, Andréassian et al. (2012) showed that the paired basin methods can give better performance than the use of a rainfall-runoff model when the density of gauging stations is quite high.

4.4 Methods using regional information

4.4.1 Routing modelling

Routing models can propagate the observed streamflow from upstream to downstream. In the case where the upstream recorded streamflow is uninfluenced, it can be propagated by a hydraulic model (or other simpler propagation or statistical methods) to obtain a naturalized downstream streamflow.

Table 5 presents studies applying Routing modelling methods to naturalize. The influences taken into account in these studies directly affect flows due to infrastructures built in the river. In these studies, the hydraulic models used assume that the river bed topography is still the same without the dams or levees. The implementation of Routing modelling methods is often time consuming and requires many data to calibrate the hydraulic model (Shiklomanov and Lammers, 2009). This is especially the case when important transmission losses occur and must be accounted for (Hughes, 2019; Pacheco-Guerrero et al., 2017). When the upstream flows are influenced, the flow can be naturalized and then propagated using a hydraulic model (Peters and Prowse, 2001). Another variant consists in using a hydraulic model that explicitly takes into account the different structures (dam, weir, levee, etc.) that may alter streamflow. The model is first calibrated on the flow conditions of the influenced period. Then, to obtain a naturalized flow, the various obstacles are removed from the propagation model (Ahn et al., 2006; Peters et al., 2006; Wyrick et al., 2009). Wu et al. (2015) assume that the hydraulic propagation has no impact and sum the natural upstream flows to naturalize.

[Table 5 near here]

4.4.2 Regionalization

Regionalization methods exploit the similarity between catchments to estimate streamflow. Although mainly used for ungauged or poorly gauged basins, their application in naturalization studies is an interesting option for several reasons. First, the Water Balance and Reconstitution methods require good knowledge and an access to the data used to characterize the influences, whereas regionalization methods are usable on a basin with limited data (Hernández-Henríquez et al., 2010; Ye et al., 2003). Secondly, the principle of the Extension methods is based on the temporal transposability of streamflow. Regionalisation methods can be viewed as a variant based on spatial transposability.

<u>Regionalization of the hydrological regimes and flow duration curves</u>. In the case where only the flow characteristics of the natural basin's behaviour are investigated and not complete time series are sought, the regionalization of a hydrological regime can be used. For example, in Switzerland, the natural monthly regimes of Alpine basins have been classified into six groups according to the average altitude of the catchments and the proportion of their glacier-covered area. Therefore, due to the physical characteristics of the influenced catchments and an estimate of the average annual flow,

Weingartner and Aschwanden (1994) estimated their natural monthly regime, with an uncertainty ranging from 10 to 20%. In Spanish basins, Fernández et al. (2012) estimated the naturalized monthly flow with a hydrological model at the influenced stations. Then, to estimate the naturalized regime at a daily time step, they calculated daily distribution coefficients on neighbouring natural stations. These distribution coefficients were then applied to the naturalized monthly flows that had a naturalized daily regime. Here, since the focus is on methods for obtaining naturalized flow time series, the methods of this subsection will not be further discussed. However, they remain used operationally in many countries, in cases where only synthetic streamflow descriptors are needed.

Neighbourhood method. The Neighbourhood method consists in estimating the hydrological model parameters on natural neighbouring basins. The selection criteria for natural neighbouring basins are related to geographical distance or the physical characteristics of the basins (Hrachowitz et al., 2013). This method is not currently used on gauged stations in naturalization studies. However, like the Extension and Reconstitution methods it uses a hydrological model with an alternative approach to estimate the model parameter. It may be of particular interest when there are no existing natural flow data on the pre-influence period nor on the influences themselves during the influenced period.

4.4.3 Comparison

In this family, the Routing method seems to be a priori the method giving the best estimate of natural flow since it directly exploits measurements of natural flows upstream of the basins. However, in the case where the intermediate basin has a significant influence on the flow, it may be necessary to also use a hydrological model to simulate the contribution of the intermediate flow (Wyrick et al., 2009). It is also a complex method to use in the case of large transmission losses between the upstream and downstream station (e.g. in arid regions) (Schreiner-McGraw and Vivoni, 2018). The Paired catchment method can also be applied in cases where upstream uninfluenced flow measurements are available. What differentiates it from the Routing method is that it is based on a flow rate relationship that can indirectly take into account the inflows from the intermediate basin. Like the Paired Catchment method, the Neighbourhood method also exploits information from basins with a natural regime. The significant difference between these two methods is that Neighbourhood is primarily aimed at transferring parameter sets from a natural catchment to the influenced catchment. The assumptions involved in these methods, and their strengths and weaknesses, have been the topic of several studies within the framework of the IAHS decade on Prediction in Ungauged Basins (Hrachowitz et al., 2013; Sivapalan et al., 2003).

5 Discussion

5.1 Defining naturalized streamflow

When discussing the definition of a natural regime, we showed that there is no consensus on what a naturalized flow and the natural state of a basin should exactly refer to. This impacts the choice of the reference period in the various studies. In practice, the definition of naturalized streamflow should be a compromise between:

- Our knowledge of the interactions between human activities and the water cycle and the limit of the definition to be adopted. Since the water cycle is linked to several other environmental cycles (energy, chemistry, sedimentation, etc.), this raises the question of the natural state of these other environmental cycles and their interactions with the water cycle. Typically, the issue of defining a natural reference in the climate or ecological domains has been discussed and results from a compromise between knowledge, data availability and objectives in the use of the reference (Brázdil et al., 2005; Davis, 2015; Gatti et al., 2015; Roubicek, 2010).

- A definition not too restrictive to be applicable to a large number of case studies. Ideally, the reference conditions should correspond to minimally disturbed conditions (Stoddard et al., 2006), i.e. conditions where there is no significant anthropogenic disturbance. In practice this would be very constraining because it is difficult nowadays to access data from basins that are not disturbed by human activities. In Europe, there are no data on the natural state of a catchment because the continent has long been densely populated, and the landscapes and land use have been modified by human presence (Stahl et al., 2010). Moreover, in some studies, only the naturalization of major influences is desired. In some cases, the naturalized flow can be obtained by removing a single influence to quantify the role of the influence in the observed flow.

The summary of previous definitions we gave in section 3.1 may meet this compromise. This is actually a key issue when establishing hydrometric reference networks. Since they should be representative of natural flow conditions, the question of the criteria to be met in order to consider the corresponding catchments as natural references is raised (Whitfield et al., 2012). It appears that the definition of conditions vary between national networks. In Canada, where there are many catchments in pristine conditions, criteria are more rigorous whereas the impact of influences on natural flow regimes is visible across much of the UK rivers for instance.

The current perspectives would be to define the naturalized flow as corresponding to a more or less natural state of the basin and to express which influences and associated impacts are considered in each study. Another perspective is to use a more comprehensive approach, consistent with the definition of naturalized flow chosen, to identify the pre-influence period. In the reviewed studies applying naturalization methods, the methods to identify the reference period are currently limited to change-point detection tests, which raise several issues concerning the origin of the change-point. It would also be interesting to have methods to detect a certain level of influence on the basin.

Although defining terms appears essential to understand and compare studies, the definition process can lead to a reflection on the role of the influences in the methods and the hypotheses raised. For example, in the case of the Extension method, setting it at a pre-influence period may imply to account for change in land use to obtain the naturalized flow.

5.2 Choice of naturalization methods

By comparing the characteristics of the studies with the choice of the naturalization methods applied, it appears that the same methods are applied on basins with different areas, from the basin scale (100 - 10,000 km^2) to the regional scale (100,000 - 1,000,000 km^2), and with different influences. Methodological aspects of the studies such as the time step and the length of the available time series to naturalize do not seem to play a major role in the choice. This raises the question of the criteria that can motivate authors to choose one method over another.

5.2.1 Data availability

From a practical point of view, data availability is the first selection criterion (Table 6), which is also reflected in the decision tree illustrated in Figure 5. Thus, the Water

Balance and Reconstitution methods use data on influences. The Paired Catchment and Neighbourhood methods need data on non-influenced catchments. The Routing modelling method requires a natural upstream flow to propagate it downstream. The Extension and Paired Catchment methods need data on the past observed natural streamflow. It is clear that several of these methods are relatively similar and that they differ only in the tools used. In this section, we will discuss the aspects that can influence the choice of the applied methods.

[Table 6 near here]

5.2.2 Distance between the source of influence and the gauging station

Distance is taken into account by the Water Balance and the Routing modelling methods with the propagation time, and by the Reconstitution methods, which take it into account according to the structure of the model used and the parameters. For the transfer modelling family methods, in the case where intermediate hydrological phenomena such as runoff or river-groundwater exchange have a potential impact on the routed flow, a hydrological model should be used to simulate them.

5.2.3 Type of influences

In the transfer modelling family, Routing modelling methods are used only to take into account influences that directly impact the flow, as is the case for dams and withdrawals. For the Water Balance method, all the influences and their associated impact on the hydrological cycle could theoretically be taken into account via the ΔV. In practice, indirect impacts on river streamflow are easier to take into account with a hydrological model family method.

In the hydrological method family, theoretically the entire impact on the hydrological cycle could be considered. In practice, the type of influences present in the basin seem to impact the choice of method. In studies that take into account land use and land cover changes in their naturalization process, only Extension and Reconstitution methods are used. The Extension method is calibrated on the basin conditions before the evolution of the cover. The Reconstitution method makes it possible to take the land cover directly into account during the calibration and then modify it. As land use changes indirectly modify the flow, it is easier to take these interactions into account with a hydrological model. For the Regionalization methods, this would require a neighbouring basin with a land cover similar to the influenced basin in its natural state. These methods could be applied on small experimental Paired Catchments (Brown et al., 2005) but do not seem to be applicable to large catchments.

Regionalization methods are applied on catchments which are strongly influenced by dams and other influences. This can be explained by the fact that it is now difficult to access databases with completely uninfluenced catchments. Weingartner and Aschwanden (1994) explain that Regionalization methods are easier to apply in cases where the hydrological conditions encountered are very complex, as in multi-influenced basins. The complexity of the influences and their impact on the catchment could be a limit of the Reconstitution method. For example, in the case where irrigation return flow is taken into account, the difficulty in quantifying them (Dewandel et al., 2008) may lead to eliminating the choice of Reconstitution method.

5.3 Operational implementation of naturalization methods: the case study on the Rhône basin (France)

From theory to practice, it is always useful to see the way practitioners implement methods proposed in the scientific literature. We describe a case study from France. In France, one of the objectives of the Law on Water and Aquatic Environments (LEMA in French) of 30 December 2006 is to restore the balance between water supply and demand. Consequently, studies of “withdrawable” water volumes (i.e. water available for withdraw/human-use) were carried out at the catchment scale in order to determine the quantitative state of water resources and then to propose a preservation strategy of the existing balance or reduce the deficit. These studies include several phases, including an important phase on the identification and quantification of anthropogenic influences and a phase on the estimation of the water resource using naturalization methods. The reports produced at the end of these studies are a useful source of information on the application of naturalization methods in operational contexts. Because low-flow periods are of particular concern, naturalized flows are preferentially obtained at a daily scale to calculate drought indicators.

Among the many reports available, we made a selection over 20 basins in the the Rhône-Mediterranean Water Agency district (Appendix 1, figure 9). These reports were generally produced by consulting firms and were chosen here in order to have the widest possible panorama (Appendix 1, Table 7). Naturalization methods were applied on sub-basins from a few dozen to several hundreds of square kilometres.

With regard to the choice of methods, the most widely used methods are the Water Balance and the Reconstitution methods. The choice of the methods is not clearly justified but can be explained by several factors. First, all influences in the basin are taken into account. This excludes the Extension method where it is almost impossible to have a period when there is no withdrawal, and the Regionalization method where it is also complicated to have neighbouring basins with no withdrawals. However, a variant of the Neighbourhood method used in an operational context consists in calibrating the hydrological model on the naturalized flow of the upstream influenced sub-basins, and then to use the set of parameters obtained on the influenced downstream basin (CEREG Ingénierie, 2011). Moreover, in these studies considerable preliminary work is undertaken to identify and quantify the anthropogenic influences present in the basins. This facilitates the application of the Water Balance and Reconstitution methods.

The synthesis of these reports also highlights the implementation of hybrid naturalization methods to address data gaps. Given that hydrological indicators are calculated on the naturalized flow series, the times series must be long enough. These hybrid versions are presented as a solution in cases where the observational data on influence and streamflow are too short. One version is to first naturalize the streamflow with the Water Balance method and then to apply the Extension method in calibrating the hydrological model on these naturalized flows. Inversely, the influenced flow time series can be extended with a hydrological model and then be naturalized with the Water Balance method. It should be noted that each addition of steps in the naturalization process is a potential source of uncertainty.

In the terms of reference of these studies, authors were requested to clarify the limits and uncertainties related to the naturalization process. The level of reflection is very heterogeneous depending on the studies. It appears that most of the authors were able to identify sources of uncertainty. The main sources of uncertainties cited were the streamflow data, the data on the influence and the climatic data used as model input and model calibration. No study has clearly quantified the global uncertainty of the naturalized streamflow obtained. In the Les Gardons catchment, it was highlighted that a 7% error on the naturalized flow had an impact on the study conclusions.

5.4 Level of confidence associated with naturalized streamflow

The previous section on the operational application of naturalization methods in France showed that there is a request on how to assign a level of confidence to naturalized flow. Because naturalized streamflow is used as a reference for many applications (as discussed in section 1.2), it is important to quantify the associated uncertainties in order to make robust decisions (Refsgaard et al., 2007). The error associated with naturalized flows is not directly quantifiable because there is no observation of natural flows over the influenced period. The estimation of the confidence in the methods can therefore only be done indirectly. Among the articles analysed, there does not currently seem to be a methodology to evaluate the naturalization process. In this part, we discuss how to indirectly estimate the confidence in results.

5.4.1 Uncertainties in data

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

- Streamflow time series. We distinguish the streamflow time series corresponding to an observed natural flow and the time series corresponding to an influenced observed flow. The main uncertainties come from the measurement system in place, the operational conditions and the post-processing step to estimate the flow (e.g. the stage-discharge relationship). Usually a post-processing step corrects the occasional errors. In case of a direct impact, the influenced series can be distinguished from the natural series by the presence of sudden changes in the time series. This implies a more thorough post-treatment to distinguish changes due to measurement errors from those due to anthropogenic influences. Ideally, the measurement system should not change in time. Naik and Jay (2005) pointed out that flow errors can be much more important at the beginning of the period of record. When choosing a method from the hydrological modelling family, questions should be raised on the confidence placed in the natural flow in the past and the observed flow in the present. When the observed data appear uncertain in both cases, it may be beneficial to use the Neighbouring basin method.

- <u>Climatic time series</u>. The main climatic variables used in the studies are precipitation and evapotranspiration. Precipitation estimation at the catchment scale is carried out using interpolation methods of local rainfall measurements. The measurement system put in place must therefore be adapted to the spatial and temporal variability of rainfall events in the basin (Lebecherel, 2015). Since actual evapotranspiration is not measurable at the catchment scale, point evapotranspiration is used most of the time in the studies. However, this potential evapotranspiration corresponds to a model output (Oudin et al., 2005), and therefore includes uncertainties. Precipitation can also be estimated by radar data. In contrast to the raingauge, it is an indirect measurement which is also uncertain.
- <u>Volume time series of human influences</u>. Since the influence measurements are not always available, different techniques and assumptions are used to estimate influence time series. For example, in the naturalization studies examining agricultural withdrawals, the volume time series are estimated based on data reported by farmers (Irwin et al., 1975) or models based on cropping patterns, irrigation water needs and irrigation efficiency (Davtalab et al., 2017; Wallace and Pavvloski, 1988). Uncertainties associated with these processes seem not to be quantified, but it can be assumed that these uncertainties could be greater than for the other input data. It is also difficult in naturalization studies to get sufficient data to characterize all the influences at play on the catchment. Often

one has data on the major influences (typically dams, abstractions in rivers), but it is harder to quantify the impact of other influences on flows (land use change, groundwater abstractions). This may leave a level of uncertainty difficult to remove in naturalized flow estimates.

A first perspective would be to assess the impact of the quality of these data on the naturalized flow obtained in a sensitivity study (Devak and Dhanya, 2017). Model parameters are sensitive to the errors contained in input data. Several studies have already shown the sensitivity of the models to climate variables (Andréassian et al., 2004; Oudin et al., 2006). For example, Andréassian et al. (2004) showed that having a better estimate of potential evapotranspiration does not give better results. In the case of withdrawable water volume studies in France, there are often strong uncertainties on the influence data, especially on irrigation data. It would therefore have been interesting to see the sensitivity of the calculated hydrological indicators to influence data.

5.4.2 Uncertainties in model structure

Model structures can be a source of uncertainties if they are not in line with reality (Pechlivanidis et al., 2011). The model is a simplification of reality and it may be that not all processes are represented. In the Reconstitution method, where the model takes anthropogenic influences into account in the model, it is important to ensure that the structure of the model is adapted to represent the potential impacts of the human activities on the different components of the hydrological cycle. The structure of the Water Balance method can be attractive because of its simplicity, but, during low-flow periods, errors can lead to obtaining abnormally low or even negative flow rates (Agosta, 2007; Littlewood and Marsh, 1996). With the Reconstitution method, the simulated streamflow can be extremely low, which raises questions about its interpretability, especially in intermittent rivers (De Girolamo et al., 2015).

5.4.3 Validation of the method's hypothesis

Each naturalization method is based on different assumptions (see section 4). One key issue in all methods is the uncertainty linked to the transfer of information in space and time. This aspect is however not so easy to quantify in the case of naturalization since no natural flow observation is available on the influenced period and standard split sample or proxy-basin approaches (Klemes, 1986) cannot be directly applied.

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

In the case of the hydrological modelling family, methods are based on the transferability of the parameter set. In fact, there is no single set of parameters that can perfectly reproduce the uninfluenced flow (Beven, 2000). The problem in naturalization is to know which method makes it possible to transfer the parameter sets with the least possible uncertainty. With a temporal transposition, robustness can be assessed using the split-sample test (Coron et al., 2012; Klemes, 1986). This method consists of evaluating the performance obtained over a subperiod different from the calibration period. In the case of a spatial-proximity-transposition, robustness can be assessed using the hydrometrical desert method (Lebecherel et al., 2016). For the Reconstitution method, the uncertainty obtained at calibration on the simulated influenced streamflow can be transferred to the simulated naturalized streamflow.

6 Conclusion

Human activities can directly impact the observed flow or several components of the hydrological cycle. These human influences can have an impact at the catchment, regional or global levels. Consequently, most of the observed flows are influenced. To have a reference to the natural regime of influenced rivers, an increasing number of studies apply different naturalization methods. However, no state of the art on the topic has yet been made. The inventory of the terms to designate a naturalized streamflow shows that there are several definitions considering different human influences. We believe that it would currently be too restrictive to propose a single definition of the naturalized flow. We advise that studies propose a clear definition of the influences and impacts considered by the naturalization process.

The main naturalization methods were presented and a classification into three families based on the information they used. Although data availability appears to be the main constraint in the choice of methods to be applied, other criteria play an important role. When intermediate phenomena such as runoff impact the water flow from upstream to downstream, a method from the hydrological modelling family will be more appropriate. The influences and their impacts considered in the naturalization process also lead to questioning the choice of methods and tools used.

The example of the application of operational methods shows that the most commonly applied methods for estimating water resources are the Water Balance and Reconstitution methods. This choice is explained by the fact that the authors' goal is to take into account all the influences of the basins and by the difficulty of having access at a completely natural reference over an earlier period or a neighbouring basin. The development of hybrid methods is a consequence of the difficulty of having both an estimate of the natural flow without any influence and a sufficiently long series to calculate robust hydrological indicators.

In these studies of withdrawable water volumes, the uncertainties associated with the naturalization procedure were investigated. It appeared that the authors could identify most sources of uncertainty, but did not quantify the total uncertainty of the naturalized flow obtained. The difficulty in estimating the error associated with naturalized flows is that this can only be done indirectly because the naturalized flow is obtained over a period when there is no direct observation of the natural flow. A first perspective to estimate the confidence of the naturalized flow would be to assess their sensitivity to the input data, knowing that very often these inputs do not correspond to observations. A second perspective would be to indirectly assess the assumptions raised by the methods. Methodologies have been established in the literature to assess the ability of models to transfer a set of parameters spatially or temporally.

7 Acknowledgements

The authors thank the Office français de la biodiversité (OFB) for the financial support of the first author. The Land and Water team of CSIRO is thanked for supporting a research residency of the first author at Canberra, and The Bureau of Meteorology is acknowledged for making data available for this study. Rob Pipunic and Christopher Pickett-Heaps from Bureau of Meteorology are thanked for their comments prior to submission.

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1645 ## 10 Appendix 1: Operational implementation of naturalization methods

1646 [Figure 9 here]

[Table 7 here]

Table 1. Definitions of "natural streamflow" and "natural regime" found in the literature.

Table 2. Synthesis of studies applying Water Balance methods.

Table 3. Synthesis of studies applying Reconstitution methods.

Table 4. Synthesis of studies applying Extension methods.

Table 5. Synthesis of models used in studies applying Routing modelling methods.

Table 6. Synthesis of input data and tools used by each of the naturalization methods.

Table 7. Synthesis of withdrawable water volume studies. WB corresponds to the Water Balance method, R to the Reconstitution method, E to the Extension method and N to the Neighbourhood method.

Figure 1. Schematic representation of the impacts of human activities and the water cycle components they may directly impact (derived from Botai et al., 2015).

Figure 2. 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).

Figure 3. Diagram of the three periods distinguished in naturalization.

Figure 4. 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.

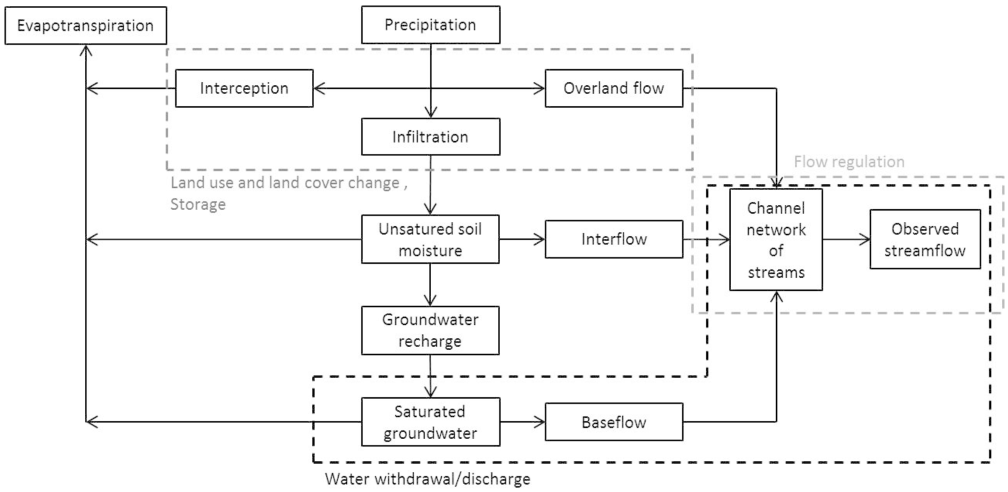
Figure 5. Diagram of the choice of naturalization according to the available data.

Figure 6. Naturalization methods applied in the studies reviewed.

Figure 7. Illustration of the two application steps of the Reconstitution method.

Figure 8. Illustration of the two application steps of the Extension method.

Figure 9. Map of the withdrawable water volumes in the catchments studied (Rhône-Mediterranean district).



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)

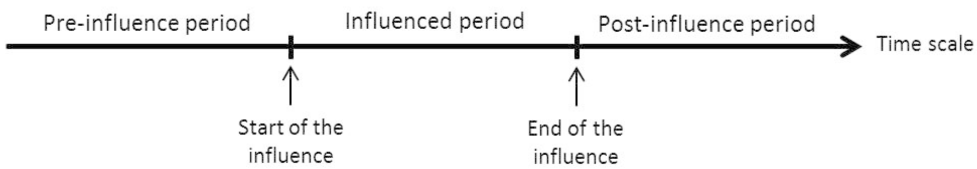
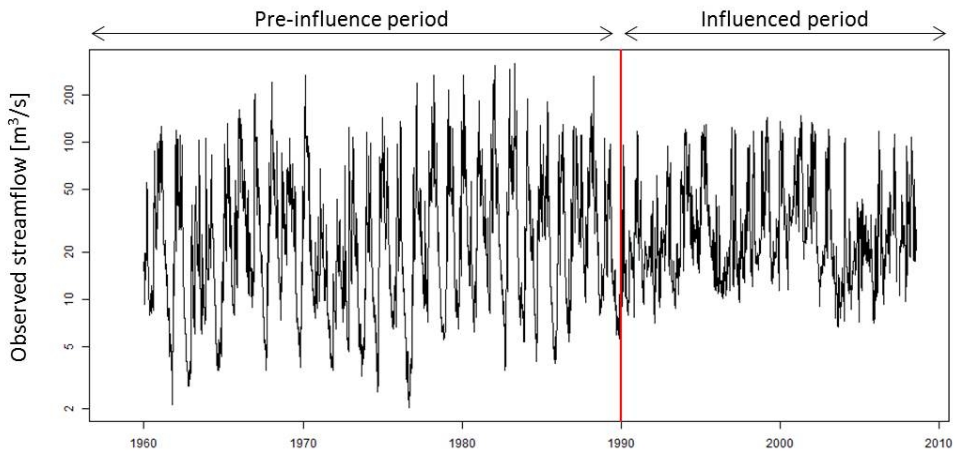


Diagram of the three periods distinguished in naturalization.

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)

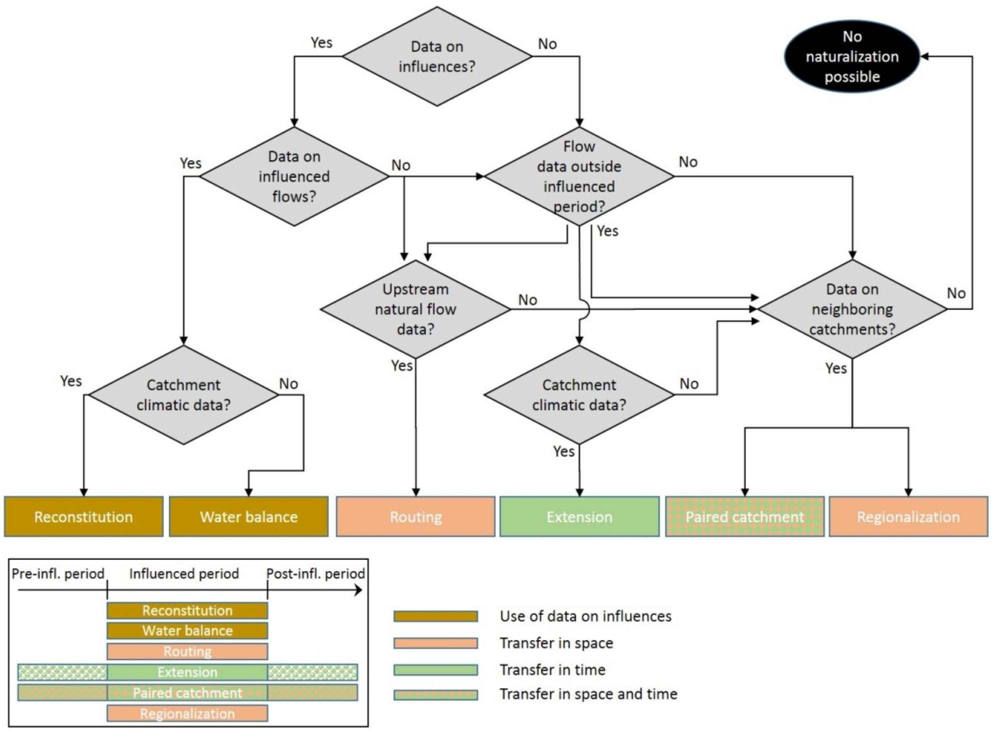
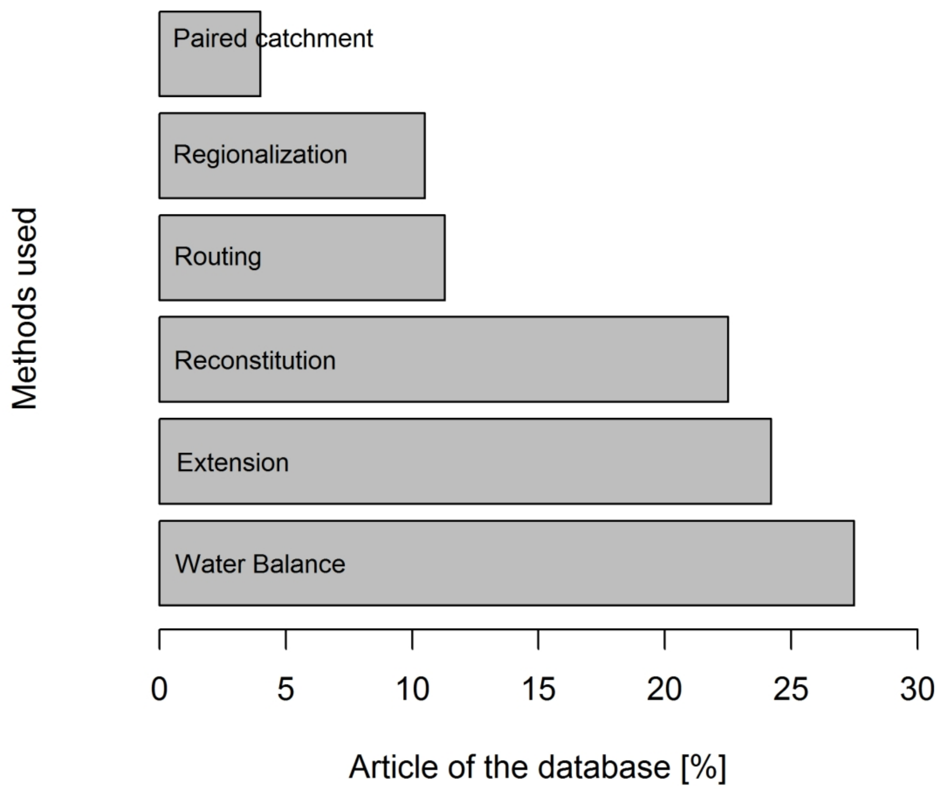


Diagram of the choice of naturalization according to the available data.

252x183mm (150 x 150 DPI)



Naturalization methods applied in the studies reviewed.

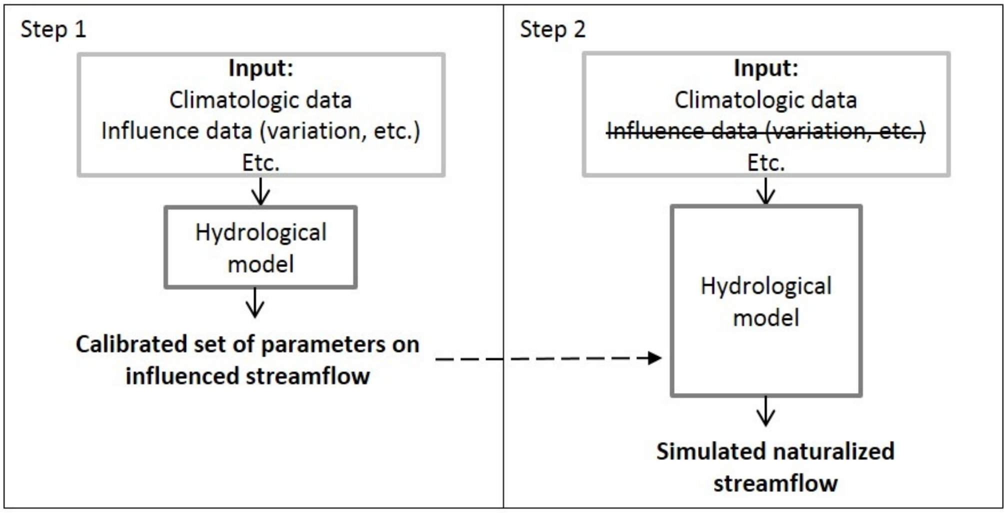


Illustration of the two application steps of the Reconstitution method.

148x76mm (150 x 150 DPI)

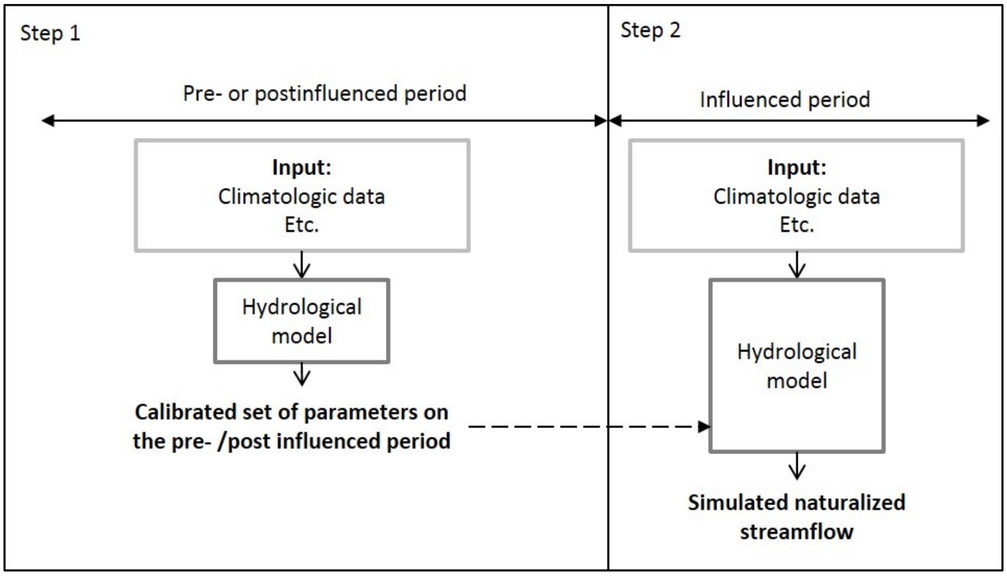
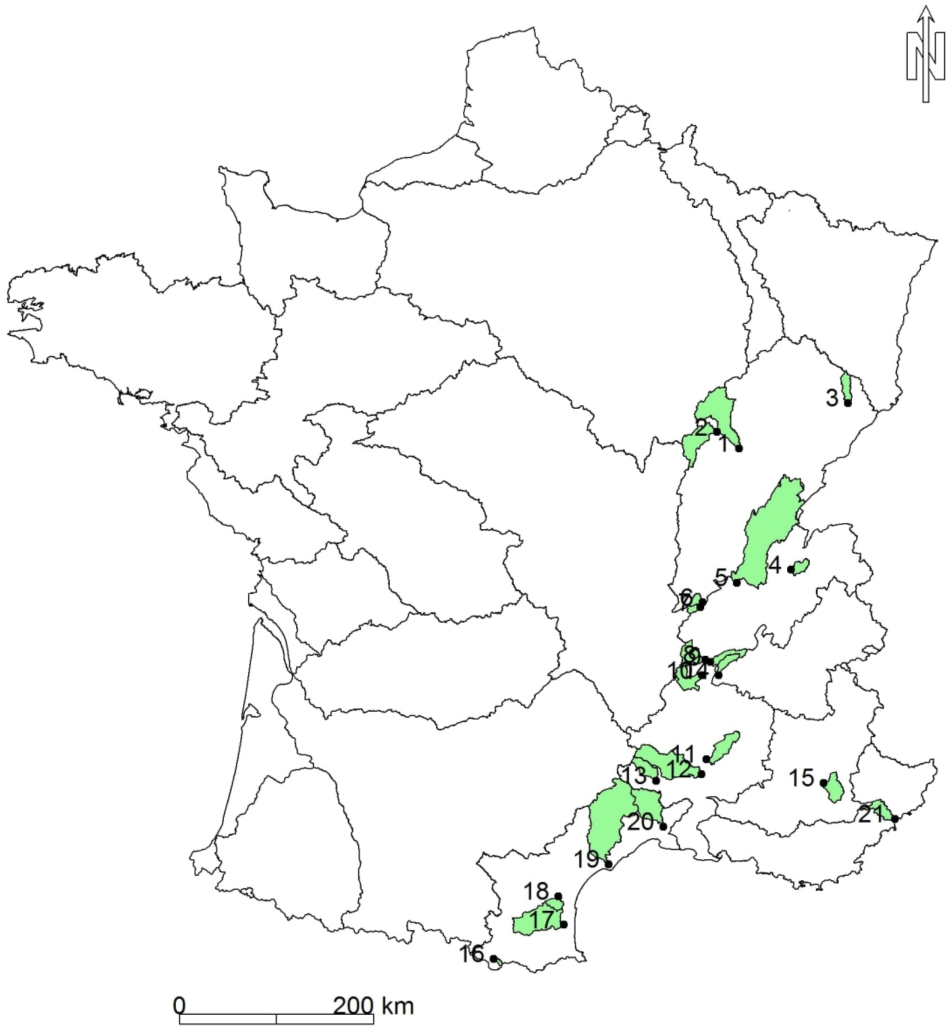


Illustration of the two application steps of the Extension method.

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	Thanes basin to Kingston, United Kingdom	9,950	Reservoirs and abstrasction	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
Maheshwari 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

Authors	Catchment	Country	Influence	Model	Time step	Calibration period	Naturalization period
Siriwardena et al. (2006)	Comet River basin (1 400 km²)	Australia	Land use and land cover change	SIMHYD (Chiew et al., 2008)	Daily	1970-2000	1970-2000
Wen (2009)	Murrumbidgee river (84,000 km²)	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 km²)	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 km²), 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 km²)	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 km²)	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 km²)	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 km²)	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 km²)	China	Agricultural irrigation, industrial development, dam construction	HBV model	Daily	1972/1975-19	1985-2007
Chang et al. (2015)	Jinghe River basin (45,400 km²)	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 km²)	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 km²)	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 km²), New Jersey	United States	Two small dams	Hydraulic (HEC-RAS) + Hydrology (HEC-HMS)
Wu et al. (2015)	Taiwan (680 km²)	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 neigboorhoud catchment				X	X	
Tool used	Hydrological model		X	X	X	X	
	Hydraulic model	X					X
	Mass balance method (catchment area scaling , equipercentile methods, etc.)	X					

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Index	Catchments	Area [km²]	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					Socièté 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	Savoureuse	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)