doi:10.5194/piahs-366-86-2015

What part of natural flow can be considered a 'water resource'?

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Abstract In this paper, we discuss an unfortunate semantic shortcut – the use of the expression 'water resources' as a synonym for 'river/groundwater flow' – which causes great confusion in all Water Security-related discussions. We show that only a part of the flow can be considered a resource, and that the efficiency of the flow-to-resource conversion is a complex function of: (i) the hydrologic regime, (ii) environmental constraints (in-stream reserved flows), (iii) the type of water demand, and (iv) the existence of artificial reservoirs. Last, we illustrate how the flow-to-resource conversion can be affected by future climatic changes. Hydrologic data and climate change simulations for three French rivers (the rivers Vilaine, Durance and Garonne) are used to illustrate this discussion.

INTRODUCTION

An overly naïve question?

Humans are used to looking at water flows in a very utilitarian manner, and the press (either generalist or scientific) often uses the expression 'water resources' as a synonym for 'river/ groundwater flow'. Despite its hydrological etymology, the word 'resource' belongs to economics. The combination of the words 'water' and 'resources' into a single expression is quite recent (see e.g. McGee 1909; Margat *et al.* 1979).

Nowadays, national and international databases (i.e. AQUASTAT-FAO, EUROSTAT, World Bank databases) call 'internal water resources' the totality of the 'blue' water flow originating on the territory of a country, and 'external water resources' the amount of water flowing to this country. These definitions imply that the entire[1] water flow is a resource, and it is precisely this underlying hypothesis that we would like to discuss in this paper. Although the distinction between *natural flow* and *water resource* is apparently extremely simple, we consider that this unfortunate misnomer has caused much confusion in all discussions concerning water security issues. This is why we wish to focus our discussion on the efficiency of the flow-to-resource conversion.

Three catchments to illustrate the discussion

Hydrological data from three French rivers (the rivers Vilaine, Durance and Garonne) were chosen to illustrate this discussion. Daily flow data were available over the 1960–2012 time period. Figure 1 illustrates the average distribution of the monthly flows for the three rivers, and Table 1 gives the main flow characteristics. Because of its mixed pluvio-nival feeding, the River Garonne is the most regular. The Vilaine and Durance have more pronounced low-flow periods (during winter for the Durance, which has a nival regime, and during summer for the pluvial Vilaine, whose climate is oceanic). Overall, these three rivers represent different climates and areas in France (Fig. 2).

A water allocation model working under simple hypotheses to compute the efficiency of the flow-to-resource conversion and simulate the impact of reservoir construction

The efficiency of the flow-to-resource conversion was assessed based on a daily water allocation model, performing a balance of water supply and demand, based on the following rules:

[1] One even finds surprising wordings sometimes such as 'unexploitable water resources' (which is meaningless since only exploitable flows are available for use, and as such, constitute an actual resource).

Table 1 Characteristics of the three French rivers chosen to illustrate the flow-to-resource conversion issue (average for 1960–2012).

Hydrological code	River	Catchment area (km^2)	Annual average flow (mm/year)	(m^3/s)
J7700610	Vilaine	4 160	193	25
O1900010	Garonne	10 000	553	175
X0500010	Durance	3 580	705	80

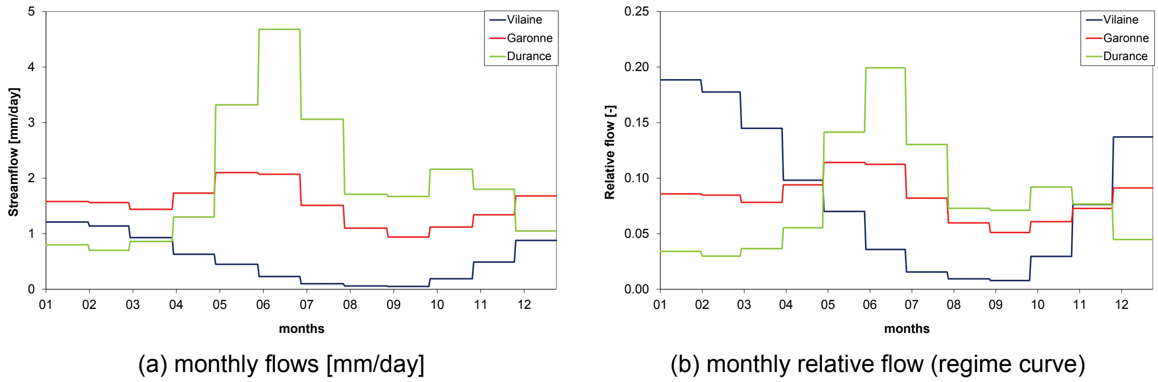

Fig. 1 Seasonal flow characteristics of the three French rivers examined in this paper.

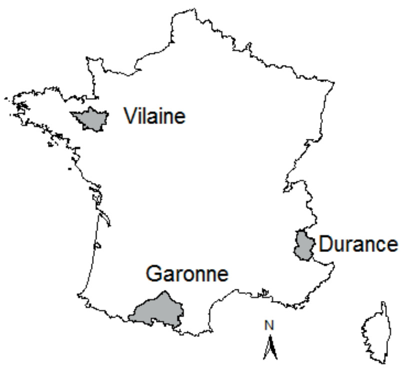

Fig. 2 Location of the three catchments.

- The environmental demand (in-stream flow) is served first;
- Once the in-stream demand is fulfilled, the economic demand is served partially or totally, depending on flow availability;
- When a reservoir exists, it is filled after the environmental and economic demands have been fulfilled. In low-flow periods, the reservoir first serves the environmental demand and then the economic demand.

This simple model requires specification of the daily in-stream reserved flow, the reservoir size (when present) and the daily economic demand. Two scenarios of economic demand were tested: a constant "urban" demand and a seasonal "agricultural" demand. Unless otherwise specified, the in-stream reserved flow was set at 10% of the long-term average flow. The economic demand corresponded to the long-term average flow (either spread equally over the year for the urban demand, or distributed seasonally for the agricultural demand scenario).

Climate change projections

CMIP5 (WRCP) projections were used to assess the impact of climate change on water resources in this paper. The Representative Concentration Pathway 8.5 (the worst case scenario) from the

CNRM/CERFACS Global Circulation Model (CNRM-CM5) was chosen. A downscaling method, the Advanced Delta Change (van Pelt *et al.* 2012), was applied to obtain precipitation and temperature projections at the same spatial resolution as observed data. By this means, 52 years of climate data whose statistics are representative of the 2071–2100 period, were available.

Scope of the paper

This paper will successively examine the main factors affecting the efficiency of the flow-to-resource conversion: natural hydrological variability ('regime'), reserved in-stream flows, type of use, existence and size of reservoirs, and climate change. For each, examples from the three case studies will be used as an illustration.

FACTORS AFFECTING THE EFFICIENCY OF THE FLOW-TO-RESOURCE CONVERSION

1 The efficiency of the flow-to-resource conversion depends on the local hydrologic regime

A water flow can only be accounted for as a resource if it can be used by humans, i.e. if it occurs at the *right time*[2]. Thus, the short-term regularity of the flow and its longer-term seasonality will affect the capacity of humans to use water. Table 2 presents the average resource conversion efficiency figures obtained for the three catchments for a simple 'urban' demand, constant all year round. This efficiency varies between 48% and 60%, and it is clearly related to the river flow regime (see Fig. 1): the River Garonne, which has the most stable flow, reaches a mean flow-to-resource conversion of 68% over the 1960–2012 period (note that due to the reserved in-stream flow, the theoretical maximum is 90%). The rivers Durance and Vilaine have significantly lower rates, because of the greater variability of their respective flow regimes.

Table 2 Flow-to-resource conversion efficiency simulated for the three French rivers under the following hypotheses: no reservoir storage, in-stream reserved flow equal to 10% of the module, constant (urban) demand equal to the flow module year round.

River	Flow-to-resource conversion efficiency (ratio of usable flow to total flow)	Average number of days per year for which water request cannot be fulfilled
Vilaine	48%	70
Garonne	68%	68
Durance	60%	70

2 The efficiency of the flow-to-resource conversion depends on the volume of in-stream reserved flows

Environmental law requires maintaining or reserving minimum in-stream flows to protect river ecosystems. These environmental constraints (which are naturally beneficial to the ecosystems they are deemed to protect) reduce the water available for other uses. In this article, we have considered a reserved in-stream flow equal to 10% of the module that would have priority over other uses. Table 3 presents the figures of the flow-to-resource conversion efficiency for other reserved flow hypotheses. In the absence of a reservoir, doubling the reserved flow (from 10% to 20% of the module) only reduces the water resource by 5–7%.

Table 3 Flow-to-resource conversion efficiency simulated for the three French rivers under different hypotheses of in-stream reserved flow. Other hypotheses: no reservoir storage, constant (urban) demand equal to the flow module year round.

River	Flow-to-resource conversion efficiency (ratio of usable flow to total flow), according to a reserved flow equal to the flow module times				
	0.00	0.05	0.10	0.15	0.20
Vilaine	54%	51%	48%	45%	43%
Garonne	75%	72%	68%	65%	61%
Durance	67%	64%	60%	57%	53%

[2] Note, since groundwater flows are much more regular than surface water flows, this notion of *right time* mainly applies to river flow.

3 The efficiency of the flow-to-resource conversion depends on the planned use

We have already mentioned the notion of *right time* above, but this obviously depends not only on the river regime but also on the planned use. For irrigation, the *right time* will be the summer; for hydroelectricity, the *right time* will be the peak hours of electricity consumption. In Table 4, we compare the resource conversion efficiency for two basic water-use scenarios:

- urban scenario: the demand is constant throughout the year;
- agricultural scenario: the demand is seasonal, concentrated on the May–October period, with a peak in June, July and August.

To make things comparable, we have kept the annual volume of the demand the same (equal to the flow module).

Table 4 Flow-to-resource conversion efficiency simulated for the three French rivers under two hypotheses of water demand. Other hypotheses: no reservoir storage, in-stream reserved flow equal to 10% of the module.

River	Flow-to-resource conversion efficiency (ratio of usable flow to total flow), according to the type of water use	
	Constant (urban) water demand	Seasonal (agricultural) water demand
Vilaine	48%	11%
Garonne	68%	39%
Durance	60%	56%

The resource conversion efficiency differs enormously between the three rivers for the seasonal water demand scenario. This is not surprising if we consider the difference between the three rivers in terms of flow regime (see Fig. 1): the River Durance, with its nival regime, which peaks in summer, matches the seasonality of the agricultural demand, while the River Vilaine, with its summer low flows, cannot provide much irrigation water. The River Garonne, with its less variable flows, is intermediary. For the steady water demand scenario, the differences in resource conversion efficiency are smaller. This time, the River Garonne obtains the best efficiency, which is not surprising given its regularity.

4 The efficiency of the flow-to-resource conversion can be increased by the construction of storage reservoirs

Humans can modify the natural variability of river flows by building reservoirs to store water (provided that suitable sites exist). Reservoirs allow turning of a larger part of river flow into a usable water resource[3]. To illustrate the impact of reservoirs, Fig. 3 presents the result of a reservoir simulation, which shows how the reservoir can attenuate the irregularity of river flow during most months. To make things comparable, we have represented the reservoir size in mm equivalent flow.

Figure 4 shows that a reservoir makes it possible to use a larger part of the average flow and to approach 90% efficiency (which is the limit imposed by the condition of a 10% in-stream reserved flow). However, the more irregular the river, the larger the required reservoir will be. The seasonality of water demand also plays a role: for the River Vilaine, which has low flows in summer when the irrigation demand is high, a very large reservoir (with a capacity of 50% of the mean annual flow) is required to warrant 50% flow-to-resource conversion for an agricultural demand, a figure which could be reached without any reservoir for an urban demand.

5 The efficiency of the flow-to-resource conversion can be reduced by climate change

Future climate change may change precipitation amounts and river flows. Projections are still quite uncertain. However, temperature trends seem more trustworthy, and they imply that in

[3] However, one should note that, because of the unavoidable evaporative losses caused by reservoir lakes, increasing the ratio of water resource to total water flow also has a 'water' cost.

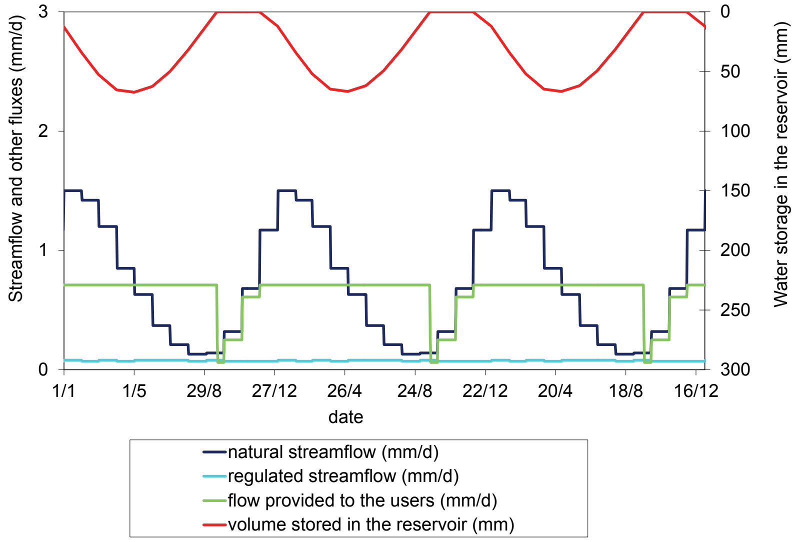

Fig. 3 Typical cycle of storage simulated in a water resource reservoir.

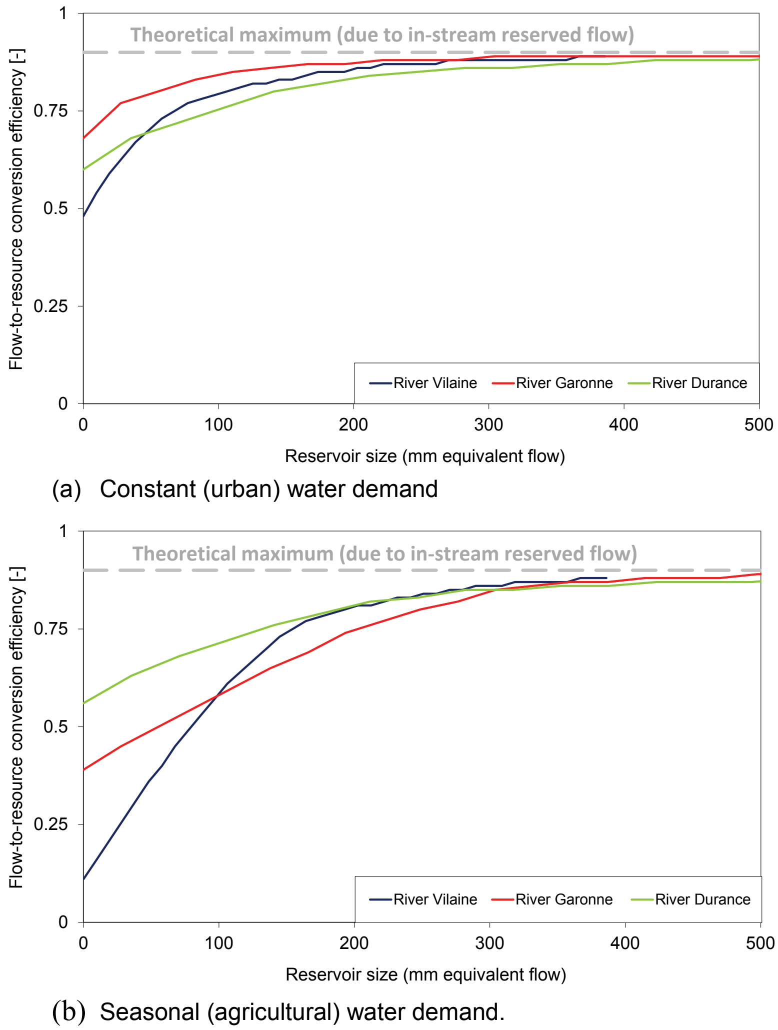

Fig. 4 Impact of a reservoir of increasing size on the flow-to-resource conversion efficiency of three French rivers (reservoir size is expressed as the percentage of the flow module, to allow comparisons between catchments of different sizes and productivity levels). (a) Constant water demand scenario equal to the flow module; (b) seasonal water demand scenario – same total volume as (a). The reservoir simulation takes into account an in-stream reserved flow equal to 10% of the flow module.

mountainous and northern regions, less snowfall and more rainfall will occur. This will undoubtedly have an impact on the seasonality of river flows and perhaps even reduce streamflow.

We used the CMIP5 (WRCP) projections, Representative Concentration Pathway 8.5 (the worst case scenario) from the CNRM/CERFACS Global Circulation Model (CNRM-CM5) to feed the GR4J hydrological model (Perrin *et al.* 2003), to simulate 52 years of streamflow representative of the 2071–2100 period.

Table 5 presents the results of these simulations: in the absence of reservoir storage capacity, the flow-to-resource conversion efficiency may decrease by 5–6% for an urban demand and 3–23% for an agricultural demand. Note that for the urban demand, the River Durance may face a small increase of flow-to-resource conversion efficiency given that, for this strongly seasonal catchment, the future climate projection results in a more regular regime.

Table 5 Resource conversion efficiency simulated for the three French rivers under two water demand hypotheses. Other hypotheses: no reservoir storage, in-stream reserved flow equal to 10% of the module.

River	Flow-to-resource conversion efficiency (ratio of usable flow to total flow), according to the type of water use:			
	Constant (urban) water demand		Seasonal (agricultural) water demand	
	Present climate	Future climate	Present climate	Future climate
Vilaine	48%	43%	11%	8%
Garonne	68%	62%	39%	29%
Durance	60%	63%	56%	33%

CONCLUSION

In this paper, we attempted to shed new light on an old question: the quantification of water resources. We focused specifically on the flow-to-resource conversion efficiency. The main conclusion of this paper is that quantifying *water resources* is more complex than quantifying *river flow*. Indeed, we have shown that the flow-to-resource conversion efficiency:

- is always much less than 100%;
- is reduced by the irregularity of the given river regime;
- is reduced by the amount of in-stream reserved flows;
- is affected (positively or negatively) by the seasonality of the water demand;
- is increased by the construction of reservoirs;
- is potentially (mostly negatively in the three examples here) affected by climate change.

We need to stress here that there is no uniformity in the flow-to-resource conversion because, while the flow and the demand are independent, the resource depends on both flow and demand. The cost of the infrastructure and the costs of exploitation also play a role. Water resources correspond to the water that rivers can supply in the *economic* sense of 'supply and demand'.

Last, we would like to mention that in this article, we have not discussed another factor which impacts on the water resource availability in many countries of the world: the sharing of transboundary rivers by downstream and upstream states (see e.g. Andréassian and Margat 2013). Rivers and aquifers do not respect state boundaries, they flow through them. Unless specific treaties have been signed to detail how transboundary flows are to be shared, each of the neighbouring states usually counts the entire amount of transboundary flow as its own (this is the case in FAO's AQUASTAT database, for example). This means that international statistics overestimate world water flows and thus world water resources. Even if the water flow figures are correct, water resource accounts can be dramatically wrong.

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