Incidental potable water reuse in a Catalonian basin: living downstream

R. Mujeriego, M. Gullón and S. Lobato

ABSTRACT

A preliminary assessment of incidental potable water reuse (IPR) in the Llobregat River basin has been conducted by estimating the dilution factor of treated effluent discharges upstream of six river flow measurement sections. IPR in the Llobregat River basin is an everyday occurrence, because of the systematic discharge of treated effluents upstream of river sections used as drinking water sources. Average river flows at the Sant Joan Despí measurement section increased from 400,000 m^3/d (2007) to 864,000 m^3/d (2008) and to 931,000 m^3/d (2013), while treated effluent discharges upstream of that section ranged from 109,000 m^3/d to 114,000 m^3/d in those years. The highest degree of IPR occurs downstream of the Abrera and Sant Joan Despí flow measurement sections, from where about half of the drinking water supplied to the Barcelona Metropolitan Area is abstracted. Based on average annual flows, the likelihood that drinking water produced from that river stretch contained treated effluent varied from 25% (2007) to 13% (2008) and to 12% (2013). Water agencies and drinking water production utilities have strived for decades to ensure that drinking water production satisfies applicable quality requirements and provides the required public health protection.

Key words | incidental water reuse, indirect potable water reuse, living downstream, unplanned reuse

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INTRODUCTION

Incidental water reuse has been taking place in our rivers and streams since historical times. Wastewater with different degrees of treatment, ranging from basic treatment up to advanced biological and physico-chemical treatments, are commonly disposed into rivers from where, after mixing and dilution, they are abstracted downstream to serve as a water source for drinking water production. During recent decades, this process has intensified due to population growth in urban areas close to river beds, particularly in basins with semi-arid climatic conditions. In spite of the widespread and traditional occurrence of this phenomenon, urban dwellers are generally unaware of this natural process and tend to perceive river water sources as of pristine quality, rarely associating water abstraction points for urban drinking water production with river stretches of inadequate aesthetic, biological and chemical quality.

Indirect potable water reuse projects, like the one in Orange County Water District (Dahl 2014) have made evident the critical importance of public perception and acceptance on the ultimate success of those initiatives. To achieve public acceptance of reclaimed water, particularly for potable reuse, it has become necessary to present to users the basic concepts involved in providing drinking water as well as the safe practices used for wastewater collection, treatment and disposal. To secure public acceptance of indirect and direct potable water reuse, it has become essential to ensure that the public has a clear and accurate perception of the treatment processes that our conventional drinking water sources undergo, before

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drinking water runs out of our taps. The expression 'living downstream' (Macpherson & Snyder 2013) has been used to convey to the public the notion that the water most of us drink has been incidentally used by others living in upstream locations. Once those concepts are understood and perceived as a common reference condition, the purification capacity of the proposed water reclamation schemes does fit into place, and the public may be able to assess their ability to produce water of equal or better quality than that derived from conventional sources (Cotruvo 2014).

Recent drought episodes, like the one currently affecting California and the one occurring in Texas until some months ago, have considerably raised the interest in conveying to the public a clearly articulated and properly described reality of the water cycle. Emphasis has been made on the need to use proper and consistent terminology, so as to prevent confusion and rejection (Macpherson 2015). The water recovery system used at the International Space Station has been used as an ultimate example of water reuse, where astronauts' perspiration and urine are endlessly collected, purified and reused, illustrating the ability of current technological solutions to provide potable water under the most challenging conditions. Education and outreach programmes like those applied in Windhoek, Namibia, since direct potable reuse was started in 1968 (www.wingoc.com.na/index.html), at the Groundwater Replenishment System in Orange County, California (www.gwrsystem.com/) and at the West Basin Municipal Water District, California (www.westbasin.org/) clearly indicate that personal attention, transparency and particularly trust building by local agencies and water plant operators are key factors in achieving acceptance of reclaimed water for direct or indirect potable water reuse. Such acceptance is particularly effective among local populations, those able to 'see it and touch it', while the convincing ability of those same examples significantly diminishes as the geographical location gets farther away, thus highlighting the significance of local demonstration projects for achieving effective public acceptance. This is precisely the intention of this paper: to bring public attention to how incidental potable water reuse (IPR) is currently taking place in the water supply sources of the Llobregat River basin in Catalonia, Spain, so drinking water consumers can better understand the implications and potential benefits of future proposals for engineered initiatives incorporating indirect or direct potable water reuse.

An evaluation of the spatial and temporal variation of *de facto* wastewater reuse affecting drinking water systems across the USA has been recently published (Rice & Westerhoff 2015). The study covers 2,056 surface water intakes associated with 1,210 drinking water facilities, each serving more than 10,000 people, covering approximately 82% of the nation's population. Authors observed a high frequency of *de facto* reuse, with 50% of the drinking water facilities being potentially impacted by upstream treated effluent discharges. The magnitude of *de facto* reuse was relatively low (50% of water abstractions containing less than 1% treated municipal effluent) under average stream flow conditions, but increased greatly under low stream flow conditions.

OBJECTIVES

The main objective of this paper is to conduct a preliminary assessment of the degree of IPR that is taking place in the Llobregat River basin, one of the main sources for surface water supply in Catalonia, northeast Spain. The assessment has been based on the information available for surface water flows and treated effluent discharges during one dry year (2007), a partially dry year (2008) and a normal wet year (2013) in the region. The results and conclusions of this preliminary assessment should help in raising awareness among water users in the region about the origin of the water they are currently drinking, and most importantly, in providing them with a solid reference for evaluating innovative water resources management strategies that could be proposed, involving indirect or even direct potable water reuse.

MATERIALS AND METHODS

The initial information needed for this assessment was collected and evaluated in a master's thesis presented by one of the authors (Lobato 2014). A more detailed assessment has been conducted based on subsequent data provided by the Catalan Water Agency (CWA).

The Llobregat River is one of the main water courses in Catalonia. It has a length of 160 km, a basin surface area of 5,000 km^2, and its downstream stretches serve as water supply source for more than 45% of approximately four million people living in the Barcelona Metropolitan Area (BMA). Most of the Llobregat basin has semi-arid climatic conditions, resulting in widely variable stream flows at its final stretches that can range from an annual average of 400,000 m^3/d in a dry year (2007) to 931,000 m^3/d in a wet year (2013). It has two main subsidiaries, the Cardener River (107 km) and the Anoia River (68 km). The very limited water resources of the Llobregat River, as compared to similar urban water supply sources in central and northern Europe, are also embedded, particularly in its final stretches, into an extremely complex, dense, diverse and numerous set of activities (including urban, commercial, industrial and mining) that renders a detailed stream flow evaluation a most difficult task, mainly due to the lack of accurate information on changes of water flows and quality levels associated with each activity.

The CWA supervises the 32 wastewater treatment plants (WWTPs) that discharged about 110,000 m^3/d (2007, 2008 and 2013) of treated effluent into the Llobregat River and its tributaries, before the last abstraction point for urban water supply at Sant Joan Despí (CWA 2012). Most of those facilities include a secondary biological treatment process, satisfying the maximum discharge limits set forth by European Directive 91/271 (EUR-lex 1991) of biochemical oxygen demand (BOD_5) = 25 mg/L, suspended solids (SS) = 35 mg/L and chemical oxygen demand (COD) = 125 mg/L. Table 1 indicates the five flow measuring sections operated by the CWA along the Llobregat River, the first one at its headwaters, near the town of Castellar de n'Hug, and the last one at the town of Sant Joan Despí, immediately upstream (15 m) of one of the major water abstractions for supplying the BMA, and 10 km before the river discharges into the Mediterranean Sea. Table 1 also includes the characteristics of two virtual measurement sections (5v and 6v), as defined in subsequent sections. Annual average flows measured in these five sections were used for one dry year (2007), a partially dry year (2008) and a normal wet year (2013), as provided by the CWA. Monthly flows for 2008 were also used to make a more precise seasonal assessment, particularly considering that the intense dry conditions that prevailed during 2007 continued until early May 2008, at which point wet weather conditions resumed and have continued, up to the first quarter of 2016.

Table 1 | Water flow measurement sections in the Llobregat River and distances between two consecutive sections

Measurement section	Geographical name	Distance between sections, km
1	Castellar de n'Hug	3
2	Guardiola de Berguedà	11
3	Balsareny	40
4	Castellbell i el Vilar	30
5v	Abrera (virtual)	21
6v	Sant Joan Despí (virtual)	21
5	Sant Joan Despí	46 (*)

(*) Distance from sections 4 to 5.

The Llobregat River hydrology reaches its highest degree of complexity at the 46-km river stretch upstream of Sant Joan Despí. After flowing through the Castellbell i el Vilar flow measurement section (no. 4), and along 6 km of riverbed, the river receives treated effluent discharges from two WWTPs. Then, 15 km downstream, it undergoes a significant water abstraction from the Abrera drinking water treatment plant (DWTP) (55 hm^3/y in 2008). During the next 6 km, the river receives treated effluent discharges from five WWTPs plus the Anoia River tributary that contributes treated effluents from another five WWTPs. During the subsequent 15-km stretch, no significant discharges of treated effluent take place, but the river has an important water abstraction for agricultural irrigation at the end of it. Finally, 5 km downstream, the river gets to the Sant Joan Despí flow measurement section, immediately after which (15 m) it undergoes a final water abstraction for the Sant Joan Despí DWTP (88 hm^3/y, in 2008, plus 34 hm^3/y from nearby groundwater wells).

These complex conditions have made it necessary to consider two virtual water flow measurement sections (5v and 6v), the first located just immediately before the Abrera DWTP (21 km downstream from section 4) and the second below the Anoia River intersection, about 21 km downstream of the previous virtual section, just before the location of a major agricultural irrigation channel, and about 5 km upstream of the Sant Joan Despí DWTP.

Those two virtual sections have made it possible to take into account that the Abrera DWTP receives stream water with two treated effluent discharges in the stretch above it, while the Sant Joan Despí DWTP receives stream water with treated effluent discharged from five WWTPs in the Llobregat River plus the effluents from another five WWTPs in the Anoia basin. As a result, the Sant Joan Despí DWTP has to treat source water with a significantly higher content of treated effluent than that used by the Abrera DWTP.

Figure 1 shows a diagram of the Llobregat River basin, the river stretches delimited by the river flow measurement sections considered (five real plus two virtual), and the Abrera and Sant Joan Despí main water abstraction points for drinking water production at the BMA. A very elaborated system of diversion channels has been developed over the years in the lower part of the Llobregat River basin to prevent further treated effluents, runoff streams and other surface water contaminated streams reaching the river bed upstream of the Sant Joan Despí water abstraction point; they are discharged either along the last 10 km river stretch or at a large WWTP located near the coast.

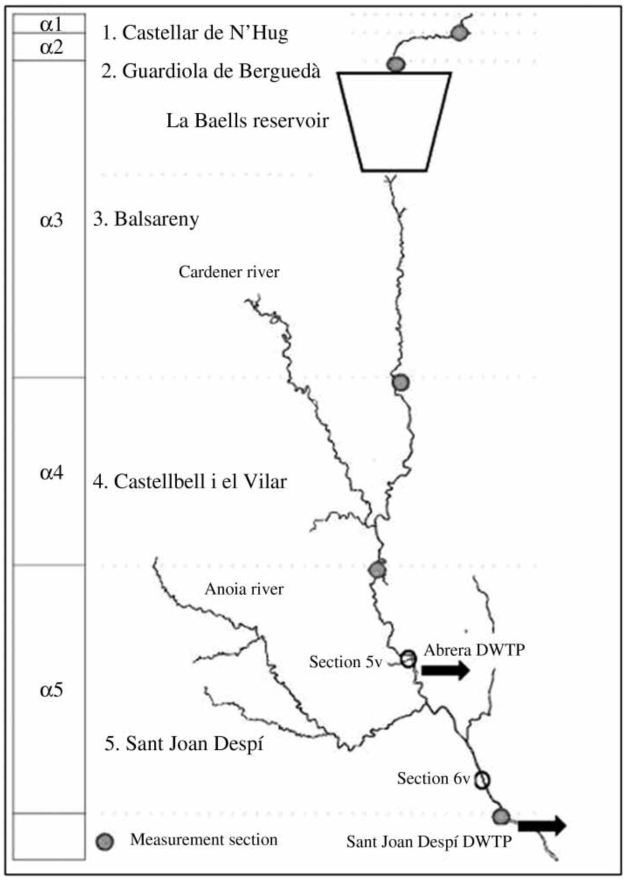

Figure 1 | Diagram of the Llobregat River, with its flow measurement sections, its main tributaries and the Abrera y Sant Joan Despí drinking water abstraction points.

The basic numerical indicator used in this preliminary assessment of IPR has been the 'dilution factor', representing the fraction of treated effluent present in the stream water flowing through a given flow measurement section. The 'dilution factor' reached a flow measurement section is calculated by dividing the treated effluent discharged in the river stretch immediately upstream of that flow measuring section by the total stream water flow recorded at that flow measuring section. Figure 2 summarizes the numerical expression used to estimate the 'dilution factor' and the basic probability model used to estimate the occurrence of incidental water reuse taking place when water is abstracted downstream of a given flow measurement section.

The extraordinary hydraulic complexity of the Llobregat River basin makes it necessary to recognize a series of approximations when evaluating the likelihood of the IPR that is taking place, using the simplified numerical model proposed in Figure 1 and the treated effluent and stream water flows available. Those approximations have to be highlighted, so readers can assess the actual limitations that such an evaluation inevitably faces, as well as the influence that they may have on the precision of the conclusions reached. Among the more significant approximations, the following have to be mentioned. (1) The proposed model assumes a linear river flow progression from its headwaters to its discharge point at the coast, when in fact actual stream flows are closer to a 'tree-like' model, due to the existence of two important tributaries that contribute significant flows (containing surface water and treated effluent) to the main river; those two main tributaries have been considered as localized effluent discharges, equivalent to the upstream treated effluent discharges they receive. (2) The proposed model has been mainly based on average annual flows, which may conceal a higher seasonal variability of the dilution factor actually reached; to estimate the degree of those short-term variations, a more detailed evaluation has been conducted using monthly flows for the year 2008, as it did include dry and wet conditions, considering that early May 2008

Dilution factor (α_i) at a given flow measurement section

$$\alpha_i = Q_{effluent} / Q_{stream\ flow}$$

i = flow measurement section number, from 1 to 6
$Q_{effluent}$ = treated effluent discharged in the upstream stretch, m^3/d
$Q_{stream\ flow}$ = stream flow recorded at the measuring section, m^3/d
$x \neq 0$ and $x=0$ represent presence and absence, respectively, of treated effluent

Probability that downstream water users from measurement section "i" are using water containing ($x \neq 0$) treated effluent: $P(x \neq 0)_i = \alpha_i$

Probability that downstream water users from measurement section "i" are using water free ($x=0$) from treated effluent: $P(x=0)_i = 1 - \alpha_i$

Figure 2 | Numerical indicator and probability model used for a preliminary assessment of IPR in the Llobregat basin.

marked the end of a continued two-year drought episode and the return to normal wet conditions. Although those two simplifications may introduce deviations in estimating simple or consecutive episodes of incidental water reuse in upper river stretches, its consequences are likely to be much less pronounced when estimating the occurrence of IPR in lower stretches, where the higher and localized water abstractions take place.

Additional approximations that have to be recognized when using this simplified numerical model are as follows. (3) Only urban treated effluent discharges were considered, raising the need for other wastewater discharges (both urban and agricultural runoff) to be included in future refinements of this assessment. (4) River water extractions for drinking water supplies were considered equal to drinking water flows actually supplied, even if this assumption may not be totally realistic in practice, as local groundwater sources are commonly used to supplement river water abstractions for water supply. (5) Annual averages of river water flows recorded at the five flow measurement sections, plus those estimated at the two virtual measurement sections, were used as reference values for estimating dilution factors, in addition to the monthly flows recorded in 2008. (6) Water abstractions within a river stretch are supposed to be of uniform quality; the actual occurrence of this condition may vary throughout the river bed, mainly depending on the spatial distribution of discharges along the stretch considered and on whether the narrow upper river sections (intense mixing) or the downstream sections are considered, where shallow water depths and larger river beds may promote some degree of preferential currents.

Partial gaps and incomplete river flow series for 2013 made it necessary to use the corresponding values for 2010 in two measurement sections. Furthermore, the complete series for treated effluent discharges during 2012 has been used to estimate dilution factors with river flow measurement obtained during 2013 (incorporating two values from 2010). Although this latter approximation may compromise estimates of IPR during the year 2013, it can be considered as a valid estimation of the incidental water reuse process taking place during the series of continued and regular wet years that began in May 2008, considering the stable population and drinking water consumption in the Llobregat basin. On the other side, the complete water flow series for 2007 and 2008 provides a realistic estimation of the IPR taking place during typical drought conditions and partially dry conditions, respectively.

The probability of IPR taking place downstream of one flow measurement section, based on the dilution factor reached in the upstream river stretch, can be used sequentially to estimate the conditional probability that a given volume of water has been incidentally used a number of times (designated by the variable 'x', ranging from 1 to 6) by users downstream of a given flow measurement section. That degree of incidental reuse would start at one ($x = 1$) after the first flow measurement section and increase accordingly after each subsequent section.

Assuming complete mixing is reached by the time stream water overflows the first measurement section, where a dilution factor 'α_1' has been reached, the discrete probability that downstream water users are consuming water that contains treated effluent discharged upstream can be estimated by the expression $P(x \neq 0)_1 = \alpha_1$; consequently, the probability that water abstracted from a point downstream of such a measurement section, before it reaches the subsequent measurement section, is free from treated effluent is $P(x = 0)_1 = 1 - \alpha_1$. The same logic can be applied to calculate the probability that water abstracted after the second flow measurement section has been previously used. Now, there are three possible outcomes: (1) water is free from treated effluent, (2) water contains treated effluent disposed either before the first or the second measurement section, and (3) water contains treated effluent that has been used twice, while flowing through the two previous stretches.

Table 2 summarizes the probability of the two extreme possible outcomes affecting water abstracted downstream of each flow measurement section. The values for the first section are: (1) treated effluent is present $P\ (x \neq 0)_1 = \alpha_1$ and (2) treated effluent is absent $P\ (x = 0)_1 = 1 - \alpha_1$. Similarly, the values for water abstracted downstream of the second section are calculated by estimating first the probability of the absence of treated effluent ($P\ (x = 0)_2 = (1 - \alpha_1)\ (1 - \alpha_2)$) and then the probability of the presence of treated effluent ($P\ (x \neq 0)_2 = 1 - P\ (x = 0)_2$), regardless of how many times it has been used (one or two at that point). The probability expressions for other conditional outcomes (from 1 to 6) of the number of reuse episodes, applicable to water abstractions downstream of a measurement section, can be calculated by adding the conditional probability of the outcome combination considered.

Table 3 shows the annual average flows of the Llobregat River at the six flow measurement sections. Water flows increase significantly as the river flows downstream, where it receives natural water flows and larger treated effluent flows, particularly coming from its main tributaries. Stream flows during 2007 and partially in 2008 clearly reflect the drought conditions prevailing during those years as compared to the common wet conditions recorded in 2013. Stream flows undergo a significant reduction at the last two measurement sections, mainly because of the significant water abstraction that takes place at the Abrera DWTP to provide drinking water to the BMA, just immediately after the virtual flow measurement section 5v. A portion of the urban water supplies from Abrera DWTP are subsequently discharged to the Llobregat River as treated effluent, where they mix with the Anoia River flows (including its own treated effluent discharges) just immediately before the virtual flow measurement section 6v. Downstream of section 6v, river flows are used for irrigation water supplies, water abstracted at the San Joan Despí DWTP and stream water flows. Most of the treated effluent generated from the Abrera drinking water supplies are discharged through a coastal submarine outfall from a large WWTP near the coast. To make a realistic estimation of the IPR taking place downstream of the Abrera virtual measurement section (no. 5v), stream flows at the preceding flow measurement section (no. 4) have been added to those of the two WWTP discharging into that stretch. Similarly, river flows at the Sant Joan Despí virtual flow measurement section (no. 6v), have been estimated by adding those of virtual section 5v to those of the five WWTPs discharging

Table 2 | Probability model for estimating whether water abstracted downstream of a river flow measurement section is either free from or contains treated effluent discharged upstream of that section

Meas. section	Dilution factor	Probability of absence of treated effluent	Probability of presence of treated effluent
1	α_1	$P\ (x = 0)_1 = 1 - \alpha_1$	$P\ (x \neq 0)_1 = \alpha_1$
2	α_2	$P\ (x = 0)_2 = (1 - \alpha_1)\ (1 - \alpha_2)$	$P\ (x \neq 0)_2 = 1 - P(x = 0)_2$
3	α_3	$P\ (x = 0)_3 = (1 - \alpha_1)\ (1 - \alpha_2)\ (1 - \alpha_3)$	$P\ (x \neq 0)_3 = 1 - P(x = 0)_3$
4	α_4	$P\ (x = 0)_4 = (1 - \alpha_1)\ (1 - \alpha_2)\ (1 - \alpha_3)\ (1 - \alpha_4)$	$P\ (x \neq 0)_4 = 1 - P(x = 0)_4$
5v	α_5	$P\ (x = 0)_5 = (1 - \alpha_1)\ (1 - \alpha_2)\ (1 - \alpha_3)\ (1 - \alpha_4)\ (1 - \alpha_5)$	$P\ (x \neq 0)_5 = 1 - P(x = 0)_5$
6v	α_6	$P\ (x = 0)_6 = (1 - \alpha_1)\ (1 - \alpha_2)\ (1 - \alpha_3)\ (1 - \alpha_4)\ (1 - \alpha_5)\ (1 - \alpha_6)$	$P\ (x \neq 0)_6 = 1 - P(x = 0)_6$

Table 3 | Annual average flows recorded at measurement sections in the Llobregat River during 2007, 2008 and 2013

	Average flow, m³/d		
Section number	Year 2007	Year 2008	Year 2013
1	48,000	86,700	103,000 (*)
2	154,000	372,000	492,000
3	405,000	582,000	729,000 (*)
4	456,000	808,000	968,000
5v	461,000	937,000	972,000
6v	400,000	864,000	931,000

(*) River flows estimated from the 2010 series.

Table 6 | Dilution factor at the Llobregat River flow measurement sections, based on annual average stream flows of 2013 and 2010 and effluent discharges of 2012

Section number	River flow, m³/d	Effluent discharges in upstream stretch, m³/d	Dilution factor, α_i, in %
1	103,000	70 (*)	0.07
2	492,000	1,990	0.40
3	729,000	9,730 (*)	1.33
4	968,000	39,720	4.10
5v	972,000	4,350	0.45
6v	931,000	58,500	6.29

(*) Stream flows from the 2010 year series.

directly into the Llobregat River stretch and those of the Anoia River itself; to complete that estimation, stream water flows abstracted at the Abrera DWTP were subtracted from the previous calculation.

Tables 4–6 summarize the Llobregat River flows at the measurement sections considered, the treated effluent flows discharged in the stretch upstream of each of those sections and the corresponding dilution factors for the years 2007, 2008 and 2013. The dilution factor increases as the river flows downstream, reaching its highest values at the final measurement section: 13% (2007), 5.7% (2008) and 6.3% (2013), in accordance with the severity of the drought conditions experienced during those years in the river basin.

Table 7 summarizes the conditional probability that water abstracted from a given river stretch is either free from or contains treated effluent discharged at any of the upstream stretches. The values in Table 7 have been calculated using the formulas of Table 2 and the dilution values of Tables 4–6. The likelihood that water abstracted from the river contains treated effluent increases significantly as the river flows downstream and particularly at the water abstraction points of the Abrera DWTP and the Sant Joan Despí DWTP. That likelihood ranges from 13% (2007) to

Table 4 | Dilution factor at the Llobregat River flow measurement sections, based on annual average flows, during 2007

Section number	River flow m³/d	Effluent discharges in upstream stretch, m³/d	Dilution factor, α_i, in %
1	48,000	90	0.19
2	154,000	2,030	1.32
3	405,000	8,190	2.02
4	456,000	42,300	9.28
5v	461,000	4,340	0.94
6v	400,000	52,100	13.02

Table 5 | Dilution factor at the Llobregat River flow measurement sections, based on monthly average flows, during 2008

Section number	River flow m³/d	Effluent discharges in upstream stretch, m³/d	Dilution factor, α_i, in %
1	86,700	88	0.10
2	372,000	1,970	0.53
3	582,000	10,200	1.76
4	808,000	37,600	4.65
5v	937,000	4,200	0.45
6v	864,000	48,900	5.65

Table 7 | Probability that water abstracted downstream of a given flow measurement section either contains or is free of treated effluent discharged upstream during 2007, 2008 and 2013

	Year 2007		Year 2008		Year 2013	
Section number	$P(x=0)_i$	$P(x\neq 0)_i$	$P(x=0)_i$	$P(x\neq 0)_i$	$P(x=0)_i$	$P(x\neq 0)_i$
1	1.00	0.00	1.00	0.00	1.00	0.00
2	0.98	0.02	0.99	0.01	1.00	0.00
3	0.97	0.03	0.98	0.02	0.98	0.02
4	0.88	0.12	0.93	0.07	0.94	0.06
5v	0.87	0.13	0.93	0.07	0.94	0.06
6v	0.75	0.25	0.87	0.13	0.88	0.12

6% (2013) at the Abrera DWTP and from 25% (2007) to 12% (2013) at the Sant Joan Despí DWTP, highlighting the considerable challenges that the Sant Joan Despí DWTP has to face to ensure that drinking water produced in its facilities satisfies water quality regulations.

The smaller stream flows recorded during 2007, due to prevailing drought conditions, had a lower capacity to dilute the relatively uniform monthly discharges of treated effluents and consequently resulted in a higher likelihood of IPR when consuming drinking water produced from those river stretches. This observation is in accordance with the intense, sophisticated and highly reliable drinking water treatment processes installed over the years in those two drinking water production facilities to ensure that drinking water provided to BMA residents satisfies the drinking water quality requirements applicable. This observation also explains the intense control measures available in those DWTPs to ensure that any water quality deviation upstream of their water abstraction points is promptly detected and prevention measures quickly applied, ranging from full interruption of river water abstraction to reinforcement of specific treatment processes.

Those same numerical results are graphically presented in Figures 3–5. The three figures clearly show that the probability that water abstracted from the river is free from treated effluent, $P(x=0)_{\mathrm{i}}$, gradually decreases as the river flows downstream. The value of $P(x=0)_i$ at the sixth measurement section, before the water abstraction point for the Sant Joan Despí DWTP, increases from 75% in 2007 (dry year) to 87% in 2008 (partially dry year) and to 88% in 2013 (wet year), resulting in corresponding probabilities of 25% (2007), 13% (2008) and 12% (2013) that the river stretch did contain treated effluent discharged in upstream stretches. While the number of consecutive incidental uses may reach up to two, downstream of the sixth measurement section in 2007, that number remains basically equal to one for all measurement sections during 2008 and 2013.

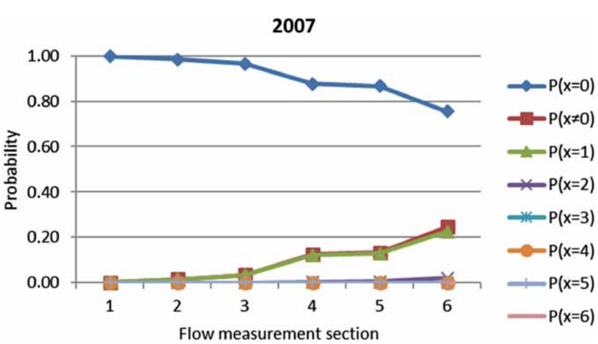

Figure 3 | Probability that IPR may have occurred a given number of times downstream of the flow measurement sections in the Llobregat River during 2007.

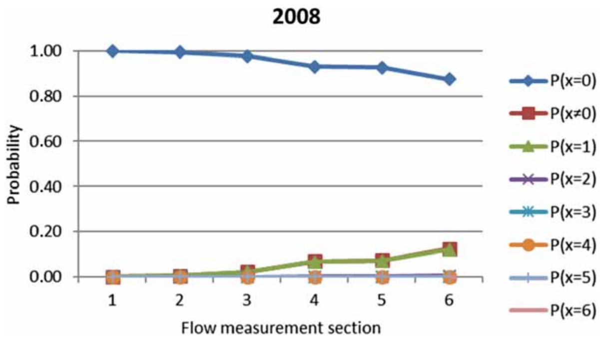

Figure 4 | Probability that IPR may have occurred a given number of times downstream of the flow measurement sections in the Llobregat River during 2008.

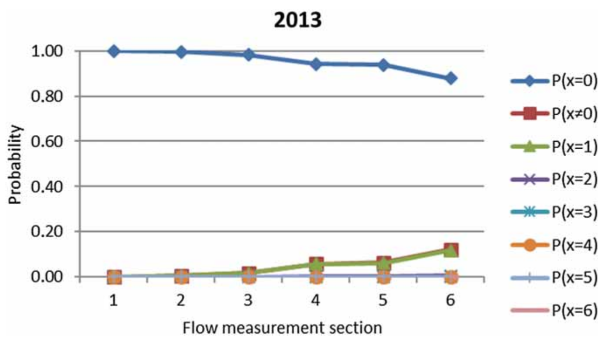

Figure 5 | Probability that IPR may have occurred a given number of times downstream of the flow measurement sections in the Llobregat River during 2013.

To conduct a more precise estimation of the time variation that dilution factors may experience during a year, the monthly average values for stream flows and treated effluent discharges for 2008 were used for a similar assessment. The year 2008 was selected because its four first months were the last of a continued drought episode lasting from 2007. In early May 2008, regular rains returned to the Llobregat basin and have remained as far as the first quarter of 2016. The calculation process has been the same as the one previously adopted for evaluating annual average flows. Figure 6 illustrates the monthly

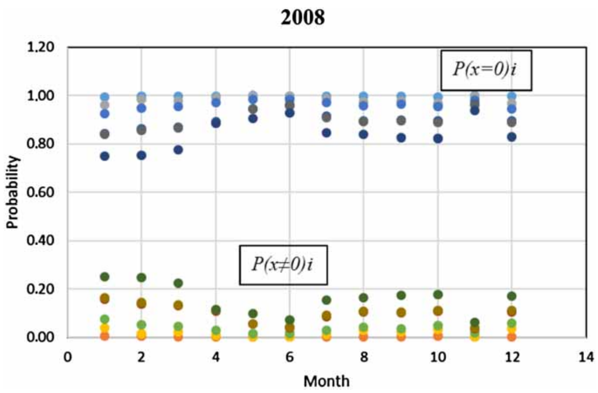

Figure 6 | Probability that IPR may have occurred on a monthly basis, downstream of the flow measurement sections in the Llobregat River during 2008.

values of the probability that river water is either free from or contains treated effluent discharged upstream of the six measurement sections considered. The lowest monthly values of $P\ (x=0)_i$ correspond to section 6v and the ones immediately upstream: sections 5v and 4. The probability of the presence of treated effluent $P\ (x \neq 0)_i$ in section 6v is relatively stable (22–25%) during the first three months, then goes down to around 10% for three months, in accordance with the rain episodes recorded during that period, and finally returns to values in a higher range (15–18%) for the rest of the year. A comparison of those monthly values with the mean annual value (13%) shown in Table 7 for section 6v during 2008 illustrates the significant changes that seasonal rains, spanning over a few months, may introduce in dilution factors and consequently in the degree of IPR in the lower stretches of the Llobregat River. The values for the first three months of 2008 (22–25%) are consistent with the mean annual value estimated for 2007 (25%) in Table 7, as corresponds to the continued dry period recorded for 2007. Similarly, the values for the second semester of 2008 (15–18%) are consistent with the mean annual value estimated for 2013 (12%) in Table 7, as corresponds to the continued wet weather period that followed.

Figure 7 shows a box and whisker diagram of the probability that water at the six measurement sections was either free from or contained treated effluent discharged at any of the upstream Llobregat River stretches. The results illustrate the increasing variation range of those probabilities as the river flows downstream. While the probability that river water was free from treated effluent is very stable and similar between sections 4 and 5v, the mean value notably decreases and its value range expands as the river reaches the sixth measurement section, before the water abstraction for the Sant Joan Despí DWTP.

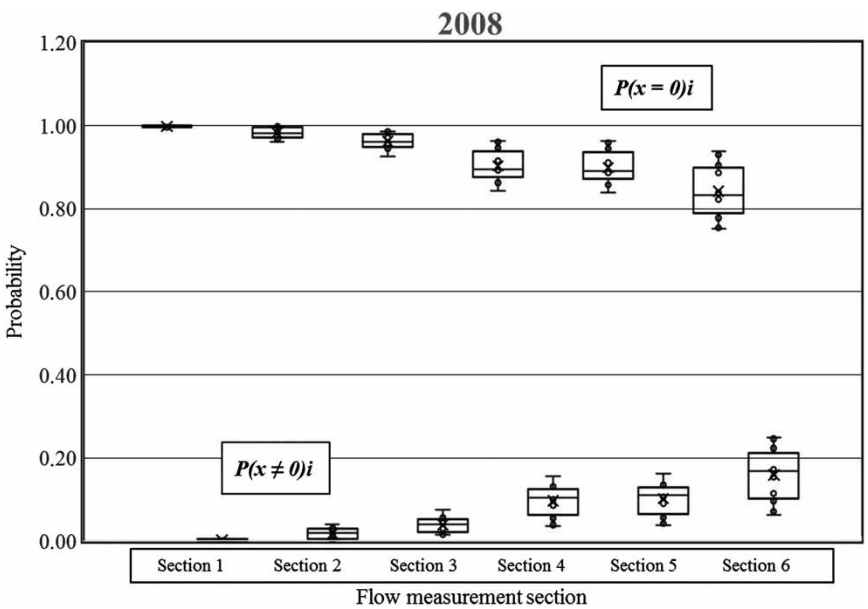

Figure 7 | Box and whisker diagram of the probability that IPR may have occurred downstream of the flow measurement sections in the Llobregat River during 2008.

SUMMARY

Incidental potable water reuse (IPR) in the Llobregat River basin, Catalonia, Spain, is an everyday occurrence, simply because of the systematic discharge of treated effluents made by urban areas upstream of others that use the river as a water source for drinking water production. In this manner, IPR is occurring in urban centres along the river, even if public perception and regulatory requirements rarely make any explicit indication of this condition, and limit their water resources management references to 'surface water' or 'river water'. It has to be highlighted that water agencies and drinking water production utilities have strived for decades to implement the necessary treatment processes and operating strategies to ensure that drinking water produced from those river sources do satisfy applicable quality requirements and provide the highest public health protection possible.

The degree of IPR that takes place in the Llobregat River basin is mainly dependent on river water flows, which in turn are directly determined by water flows released from its upstream reservoirs, according to climatological conditions. The drought episode of 2007 and the first months of 2008 resulted in a significant reduction of Llobregat River flows, reaching 43% of those recorded during a normal wet year like 2013. Water flows estimated at the virtual measurement section upstream of the Sant Joan Despí DWTP increased from 400,000 m^3/d (2007) to 864,000 m^3/d (2008) to 931,000 m^3/d (2013), while cumulative discharges of treated effluents upstream of that section ranged across a much shorter interval: from 109,000 m^3/d in 2007, to 103,000 m^3/d in 2008 and 114,000 m^3/d in 2013.

The degree of IPR increases as the river flows towards its discharge point in the Mediterranean Sea, mainly because direct urban discharges of treated effluent and indirect discharges through its tributaries gradually increase in that flow direction. The highest degree of IPR takes place in water abstractions made downstream of the Abrera virtual section (Abrera DWTP) and the Sant Joan Despí virtual section (Sant Joan Despí DWTP), which together amount to about half of the drinking water supplied to the BMA. The likelihood that drinking water produced from just downstream of the last flow measurement section contains treated effluent varied from 25% (2007) to 13% (2008) and to 12% (2013), based on annual average values. The assessment based on monthly stream flows and treated effluent discharges for 2008 indicates a considerable variability of the degree of IPR, depending on weather conditions: while it reached 22–25% during the first three dry months, it went down to about 10% during the next three rainy months, to return to values of 15–18% for the rest of 2008, resulting in an annual monthly average of 16%.

Those probability values mean that, for a large population and over a long period of time, a significant proportion (from 12% in wet years to 25% in dry years) of the drinking water consumed in part of the BMA is treated effluent discharged from upstream urban areas. Those values are clearly higher than others reported in the literature (Rice & Westerhoff 2015), mainly because of the very limited river flows of the Llobregat River in comparison to the treated effluent discharges taking place along its course. These preliminary estimates could be further evaluated and confirmed in the future by using water quality indicators of the presence of treated effluent in river water flows at different abstraction points.

A recognition that, under the levels of IPR taking place, drinking water production by local water companies has consistently and reliably satisfied the water quality requirements specified by public health authorities should greatly help the public at large, as well as regulatory agencies, and water management agencies in understanding and accepting the ability and reliability of advanced treatment processes to produce reclaimed water, even when directly processing treated effluents, with equal or higher levels of microbiological and physico-chemical quality than those currently produced by drinking water treatment processes using the Llobregat River as a water source. A direct observation by the public of those demonstration facilities, both at current DWTPs and at future advanced demonstration plants, designed to reclaim water for drinking purposes, should greatly help in developing a more favourable attitude and a higher public acceptance of future proposals for indirect or direct potable water reuse in the BMA.

Another favourable consequence of this educational debate could be the economic and environmental convenience that wastewater treatment facilities intensify their treatment performance (benefiting from a more efficient removal of concentrated flows), so as to ensure that water discharged into rivers has a quality closer to that of the water previously abstracted. By doing so, the river would maintain a higher quality level and drinking water treatment facilities would have to provide much simpler, efficient and economic treatment processes, devoted to removing smaller amounts of pollutants. Even more important, the river ecosystem itself would greatly benefit from a much higher water quality from the time treated effluent disposal takes place to the point water abstraction is conducted. Such a change in water resources management policies would basically involve a cost and responsibility transfer from the currently intensive treatment processes applied for drinking water production to more advanced wastewater treatment processes than those currently applied. Implementing such an environmental strategy would inevitably bring about adaptations in water policy and major changes in the way technical and cost responsibilities are assigned for processing drinking water and wastewater.

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