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Research Paper

Adapting the IWA water balance to intermittent water supply and flat-rate tariffs without customer metering

Miran Mastaller and Philipp Klingel

ABSTRACT

The International Water Association water balance is an approach applied worldwide for determining and analysing water losses in water distribution systems (WDS) up to the point of customer metering. Thus, water losses occurring 'before' a customer meter are at the expenses of the water utility while water lost or wasted 'after' the meter is paid for by the customer. This applies to systems where customer metering is in place and/or consumption is charged according to the consumed volumes. However, many WDS in the world lack customer meters, are operated intermittently and a considerable amount of water is lost or wasted within the private property, e.g. by overflows of private tanks. The flat-rate tariff applied might not cover this amount or part of the amount. Thus, actual consumption and wastage should be separately quantified or estimated with respect to the utility's water reduction measures and the calculation of revenue water. This paper presents a water balance approach adapted to WDS which are operated intermittently, lack customer metering and charge flat-rate tariffs as well as a methodology for establishing the balance. The application is demonstrated for a district metered area of the city of Tiruvannamalai, India.

Key words | intermittent water distribution, water balance, water losses

Miran Mastaller (corresponding author)
Philipp Klingel
Karlsruhe Institute of Technology (KIT),
Institute for Water and River Basin Management,
Kaiserstraße 12,
76131 Karlsruhe,
Germany
E-mail: *miran.mastaller@kit.edu*

INTRODUCTION

The water balance introduced by Lambert & Hirner (2000) of the Water Loss Task Force of the International Water Association (IWA) is a worldwide recognised and applied approach to assess water losses in a water distribution system (WDS) or district metered area (DMA), see for example, US EPA (2010). To establish the water balance, all of the water volumes added to or subtracted from the distribution system up to the point of customer metering are determined and entered into the balance. Figure 1 shows the IWA water balance and the standard terminology of its components. For establishing a water balance, system input volume and authorised consumption should be measured as accurately as possible. Calculating the difference between system input volume and authorised consumption gives water losses. Authorised consumption can be billed or unbilled and metered or unmetered. Furthermore, a distinction is made between apparent and real losses. Apparent losses comprise delivered water volumes billed not correctly or not at all (unauthorised consumption, metering inaccuracies and data handling errors). Real losses include leakages on tanks, mains and service connections up to the point of customer metering. The components of unbilled consumption and water losses add up to non-revenue water while revenue water is equal to billed authorised consumption (Lambert & Hirner 2000).

Hence, the IWA water balance covers those parts of a WDS the water utility is responsible for, i.e. up to the point of customer metering. Water losses occurring 'before' a customer meter are considered to be at the expense of the water utility while water lost or wasted 'after' the customer meter is assumed to be paid for by the customer. This assumption is

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<table>
<tr><th colspan="5">Standard IWA water balance according to Lambert & Hirner (2000)</th><th>Seago & Mckenzie (2007)</th><th>Kanakoudis & Tsitsifli (2010)</th></tr>
<tr><td rowspan="10">System Input Volume (SIV)</td><td rowspan="4">Authorised Consumption</td><td rowspan="2">Billed Authorised Consumption</td><td>Billed Metered Consumption</td><td rowspan="2">Revenue Water</td><td>Free Basic Water
Recovered Revenue Water</td><td>Minimum Charge Difference
Recovered Revenue Water</td></tr>
<tr><td>Billed Unmetered Consumption</td><td>Non-Recovered Revenue Water</td><td>Non-Recovered Revenue Water</td></tr>
<tr><td rowspan="2">Unbilled Authorised Consumption</td><td>Unbilled Metered Consumption</td><td rowspan="8">Non-Revenue Water</td><td rowspan="8">Non-Revenue Water</td><td rowspan="8">Non-Revenue Water</td></tr>
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<tr><td rowspan="6">Water Losses</td><td rowspan="3">Apparent Losses</td><td>Unauthorised Consumption</td></tr>
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<tr><td>Leakage and Overflows at Storage Tanks</td></tr>
<tr><td>Leakage on Service Connections up to point of Customer Metering</td></tr>
</table>

Figure 1 | Standard IWA water balance according to Lambert & Hirner (2000) and modifications of Seago & Mckenzie (2007) and Kanakoudis & Tsitsifli (2010).

valid for systems where customer metering is in place and/or water consumption is charged according to the consumed volumes. However, many WDS in the world, especially in developing countries, lack customer meters, are operated intermittently and apply a flat-rate tariff not reflecting the actual water consumption (Farley & Trow 2003; Kingdom *et al.* 2006; Fanner 2009; Klingel 2011). Furthermore, in intermittent supplies a considerable amount of water is lost or wasted within the customers' premises, e.g. by overflows of private tanks during supply or tank emptying prior to the supply period in order to get fresh water (Bradley *et al.* 2000; Totsuka *et al.* 2004; Butler & Memon 2006; Klingel 2011). Following the IWA water balance definition, all the water supplied to the customers is considered to be paid for by the customers. However, these assumptions do not hold in intermittent systems (Kumpel 2014). The flat-rate tariff actually might not cover the total amount of the supplied volume or part of it. Thus, actual consumption and wastage should be separately quantified or estimated with respect to the utility's water reduction measures and the calculation of revenue water.

Considering the constraints described above leads to the necessity of adapting the IWA water balance and the methods to determine the balance components. For the case of South Africa, Seago & Mckenzie (2007) and later McKenzie *et al.* (2012) subdivided the revenue water component of the IWA water balance. Subsidised water volumes are defined as free basic water, billed and actually paid volumes are called recovered revenue water and non-recovered revenue water is billed but not paid (Figure 1). Kanakoudis & Tsitsifli (2010) further modified that approach for the case of Greece by introducing the minimum charge difference. Customers pay a minimum charge equal to a certain minimum volume. The component comprises the proportion of the paid minimum volume actually not consumed (Figure 1). However, while the two modifications provide approaches for a detailed analysis of the revenue water component, intermittent supply as well as losses and wastage within the private property are still not considered.

This paper presents an adapted water balance for systems which are intermittently operated, apply a flat-rate tariff without customer metering and thus lack the preconditions to establish the standard IWA water balance. The developed approach enables a target-oriented assessment of water losses for WDS described above, as it features some components which are the most relevant, e.g. the wastage within the customers' premises. The method to determine the balance components is adapted and comprises metering of the supply to and the consumption within a sample of households as well as the statistical analysis of the sampled values.

First the adapted water balance is introduced before the methodology for determining the balance components is presented in the following section. Next, the application of the approach is demonstrated for a DMA of the city of Tiruvannamalai, Tamil Nadu, India. Finally a conclusion is given in the last section.

ADAPTED WATER BALANCE

The boundary conditions described in the introduction are considered within the adapted water balance, which is shown in Figure 2 and explained in detail in the following. The component authorised consumption from the IWA water balance is replaced by the component Authorised Supply Q_S, which comprises the two components Flat-Rate Billed Authorised Supply Q_{BS} and Unbilled Authorised Supply Q_{US}. The first represents the water volume actually supplied to the customers which are billed by the flat-rate tariff. The latter includes the volumes taken by unbilled customers, the utility and other authorised parties in accordance with the IWA definition of unbilled authorised consumption, see for example Lambert & Hirner (2000). Using the term 'supply' instead of 'consumption' is required as not all of the water supplied to the customers' premises is actually consumed but partly lost or wasted, which might not be covered by the flat-rate tariff.

Wastage within the private properties is authorised and billed due to the flat-rate tariff. However, these volumes should be quantified or at least estimated for determining the water loss reduction potential and checking the flat-rate tariff arrangement. Therefore, the Flat-Rate Billed Authorised Supply Q_{BS} is split into the two components Consumption Q_{BSC} and Wastage Q_{BSW}. The components System Input Volume Q_{SIV}, Water Losses Q_L and Real Losses Q_{RL} remain the same as in the IWA water balance as, for example, the type of losses stay the same in intermittently operated WDS. Apparent Losses Q_{AL} comprise only the sub-component Unauthorised Consumption Q_{ALC}. The other two sub-components metering inaccuracies and systematic data handling errors from the IWA water balance are not depicted separately in the adapted water balance, as water meters are not installed and thus, billing is not based on meter readings. Nevertheless, known meter inaccuracies and systematic data handling errors of the monitoring system should already be considered when quantifying the volumes of System Input Volume Q_{SIV} as well as Flat-Rate Billed Authorised Supply Q_{BS} (outlined in the following sections).

The determination of Revenue Water Q_{RW} and Non-Revenue Water Q_{NRW} is not straightforward and cannot be calculated following the top down approach of the IWA water balance outlined in the introduction. This is due to the flat-rate tariff, which does not necessarily reflect the volume actually supplied to the customers. Therefore, both components have to be calculated separately, where three scenarios are possible. In scenario 1, customers actually are supplied with exactly the water volume that is billed. In this case Revenue Water Q_{RW} equals Flat-Rate Billed Authorised Supply Q_{BS} ($Q_{RW} = Q_{BS}$). In scenario 2, customers pay for more water than they are supplied with, thus, Revenue Water Q_{RW} is greater than Flat-Rate Billed Authorised Supply Q_{BS} ($Q_{RW} > Q_{BS}$). The amount of water consumers are not supplied with but pay for is defined as Excess Revenue Water Q_{ERW} ($Q_{ERW} = Q_{RW} - Q_{BS}$). In the third scenario, consumers pay for less water than they are supplied with. Hence, Revenue Water Q_{RW} is smaller than Flat-Rate Billed Authorised Supply

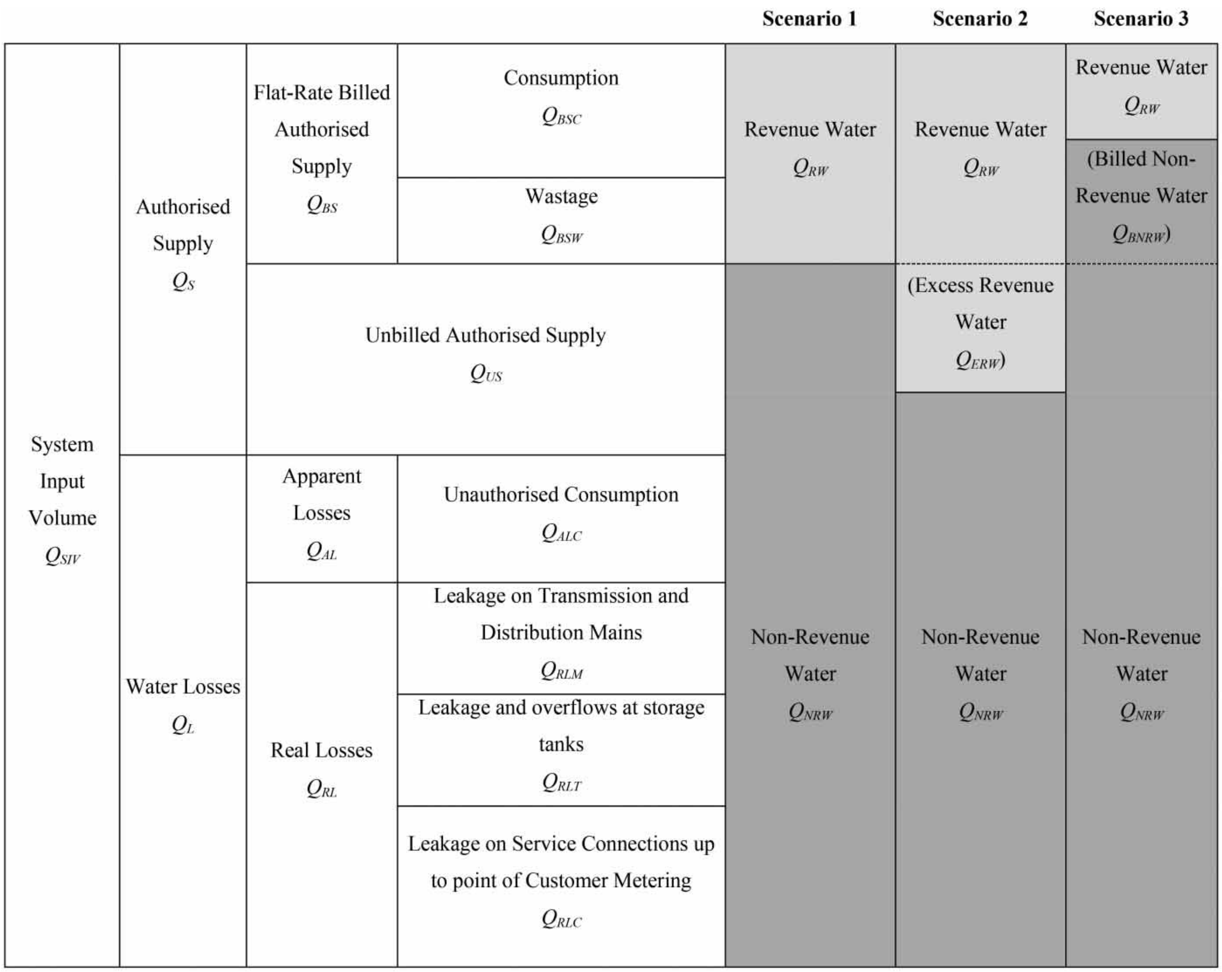

Figure 2 | Adapted water balance for an intermittently operated WDS without customer metering and charging flat-rate tariffs (unit: volume per balancing period).

Q_{BS} ($Q_{RW} < Q_{BS}$). The supplied water volumes assumed to be billed but actually not paid for by the consumers is called Billed Non-Revenue Water Q_{BNRW} ($Q_{BNRW} = Q_{BS} - Q_{RW}$).

Besides quantifying the components which are of particular interest regarding the technical aspects of the WDS, this approach allows for analysing whether the customers are billed exactly the supplied water, more than actually supplied or less. Regarding water loss reduction the focus should be put on Water Losses Q_L and Wastage Q_{BSW} instead of Non-Revenue Water Q_{NRW}. Especially in the case of scenario 2, in which Revenue Water Q_{RW} can be 'artificially' increased by charging for more water than actually supplied ($Q_{ERW} > 0$). Furthermore, it has to be noted that often the revenue generated by the flat-rate tariff does not cover the cost for production and delivery of the Flat-Rate Volume Q_{FR} (Katko 1990; Le Blanc 2007).

DETERMINING THE WATER BALANCE COMPONENTS

System Input Volume Q_{SIV}

System Input Volume Q_{SIV} is defined as in the IWA water balance. The component should be measured precisely and comprehensively as well as be corrected for known meter inaccuracies.

Flat-Rate Billed Authorised Supply Q_{BS}

A full coverage of the initially unmetered WDS or DMA usually is not possible due to financial, social and/or political reasons. Hence, a representative and random sample of households is equipped with meters at the service connection to estimate Flat-Rate Billed Authorised Supply Q_{BS} by application of statistical sampling methods. The size of the sample cannot be accurately calculated due to the explorative nature of the method. However, 5% of the total number of households is assumed to ensure an adequate representativeness (Heller, personal communication).

The total volume of Q_{BS} is then estimated based on the mean of the sampled volumes supplied to the metered customers by application of statistical sampling methods. Two different sampling methods can be used and evaluated regarding the degree of uncertainty of the estimation. For simple sampling, the mean $\hat{\bar{Y}}_S$ is calculated by dividing the sum of the sampled values $y_1, \dots y_n$ by the size of the sample n, as shown in Equation (1). The post-stratified sampling method can be applied using auxiliary information about the households, e.g. occupancy or type of water supply, to separate the population into non-overlapping subpopulations (strata). By adequate stratum selection the precision of the estimates can be increased. The mean of the post-stratified sample $\hat{\bar{Y}}_{PS}$ is composed of the sum of the individual strata means $\bar{y}_h$. As shown in Equation (2), the means are weighted by the relative size of each stratum N_h/N which automatically corrects the estimator for any bad balanced sample (Holt & Smith 1979).

$$\hat{\bar{Y}}_s = \frac{1}{n}\sum_{k=1}^{n} y_k \tag{1}$$

$$\hat{\bar{Y}}_{PS} = \sum_{h=1}^{H} \frac{N_h}{N}\bar{y}_h \tag{2}$$

The total Flat-Rate Billed Authorised Supply Q_{BS} is then estimated by multiplying the total population N, e.g. total number of households in the WDS or DMA, with the mean value $\hat{\bar{Y}}$ obtained either by simple sampling or post-stratified sampling, see Equation (3):

$$Q_{BS} = N * \hat{\bar{Y}} \tag{3}$$

Afterwards, the estimated values should be evaluated using variance, standard deviation and confidence intervals. Mastaller & Klingel (2015) describe the method in more detail.

It has to be noted that the metered values are afflicted with inaccuracies. Especially, the meters installed at the service connection are affected by the intermittent supply, e.g. by air intruded into the pipelines, see, for example, Van Zyl (2011). Therefore, possible customer metering inaccuracies have to be considered when estimating the Flat-Rate Billed Authorised Supply Q_{BS}, as this component comprises the water volume actually supplied to the customers. The obtained meter values should be corrected accordingly in advance of the statistical extrapolation using, for example, the approaches of Walter (2015) and Staiger (2016) regarding meter over-registration due to air flow.

Consumption Q_{BSC} and Wastage Q_{BSW}

As outlined above, a flat-rate water tariff without billing the actual Consumption Q_{BSC} could lead to increased Wastage Q_{BSW} within the customers' premises as there is no incentive to prevent wastage. In order to quantify how much of the supplied volume is actually consumed within the premises, a second meter could be installed. A typical household installation consists of one or more private storage tanks to cope with intermittent water supply (Galaitsi *et al.* 2016). In case the system pressure is sufficient, a roof tank is directly filled via the service connection of the household. If the system pressure is too low to directly fill the roof tank, a ground tank is installed which is supplied via the service connection. From this ground tank, the roof tank is filled by running a pump. Usually most of the Consumption Q_{BSC} of the household is covered by the roof tank, which provides an adequate water pressure at the taps within the household's premises (Roof Tank Consumption Q_{RTC}). Thus, the second meter is installed at the outlet of the roof tank to measure the Roof Tank Consumption $Q_{RTC,S}$ at the sample households.

However, part of the supplied water might be consumed directly from the ground tank or anywhere else upstream of the roof tank (Ground Tank Consumption Q_{GTC}). Ground Tank Consumption $Q_{GTC,S}$ of the sample can be estimated by a detailed survey of the daily consumption pattern of the customers, e.g. asking the customers to note the approximate volume of ground tank consumption in a protocol over a certain survey period.

The actual Consumption $Q_{BSC,S}$ is calculated by adding the Ground Tank Consumption $Q_{GTC,S}$ and the Roof Tank Consumption $Q_{RTC,S}$, as shown in Equation (4):

$$Q_{BSC,S} = Q_{GTC,S} + Q_{RTC,S} \tag{4}$$

Then the Wastage $Q_{BSW,S}$ equals Flat-Rate Billed Authorised Supply $Q_{BS,S}$ minus Consumption $Q_{BSC,S}$ of the sample households, see Equation (5):

$$Q_{BSW,S} = Q_{BS,S} - Q_{BSC,S} \tag{5}$$

Using the sample values, the total volume of the components Wastage Q_{BSW} and Consumption Q_{BSC} can be estimated applying the statistical approach introduced in the previous section.

It has to be noted that some households might store the water in a ground tank and directly pump the stored water to the taps inside the house and not to a roof tank. In this case the second meter should be installed directly downstream from the ground tank. Then this measured consumption has to be taken into account instead of the Roof Tank Consumption $Q_{RTC,S}$ in Equation (4). The further steps to calculate the components Wastage Q_{BSW} and Consumption Q_{BSC} remain the same.

Unbilled Authorised Supply Q_{US}

The component Unbilled Authorised Supply Q_{US} is defined as by the IWA. It can be determined applying state of the art methods, described, for example, by the American Water Works Association (2009) as well as by Farley & Trow (2003), Lambert & Taylor (2010) and Baader *et al.* (2011).

Apparent Losses Q_{AL}

As outlined before, Q_{AL} comprises only the volume of Unauthorised Consumption Q_{ALC} which can be determined using state of the art methods, for example house-to-house surveys or estimations. Known meter inaccuracies and systematic data handling errors are already considered in the determination of System Input Volume Q_{SIV} and Flat-Rate Billed Authorised Supply Q_{BS}.

Real Losses Q_{RL}

Adding Flat-Rate Billed Authorised Supply Q_{BS} and Unbilled Authorised Supply Q_{US} gives Authorised Supply Q_S. Water Losses Q_L are determined by subtracting Authorised Supply Q_S from System Input Q_{SIV}. The difference between Water Losses Q_L and Apparent Losses Q_{AL} or System Input Q_{SIV}, Authorised Supply Q_S and Apparent Losses Q_{AL} respectively gives Real Losses Q_{RL} (Equation (6)):

$$Q_{RL} = Q_{SIV} - Q_S - Q_{AL} = Q_L - Q_{AL} \tag{6}$$

Revenue Water Q_{RW} and Non-Revenue Water Q_{NRW}

To determine Revenue Water Q_{RW}, the flat-rate tariff has to be analysed whether it is based on a certain Flat-Rate Volume Q_{FR} or not. If this is the case, Revenue Water Q_{RW} is calculated by multiplying that fixed Flat-Rate Volume Q_{FR} (volume/customer), the number of customers N_C (customer) billed with the flat-rate tariff and the duration of the balancing period t, see Equation (7). If the flat-rate calculation is not based on a certain volume Q_{FR}, Q_{RW} can be determined using a Volumetric Water Price C_{Vol} (cost/volume) applied in a comparable city and the Flat-Rate Tariff C_{FR} (cost/customer) charged in the project area within the balancing period. Then Q_{RW} equals C_{FR} divided by C_{Vol} and multiplied by the number of customers N_C (customer) and the duration of the balancing period t, as shown in Equation (8):

$$Q_{RW} = Q_{FR} \times N_C \times t \tag{7}$$

$$Q_{RW} = \frac{C_{FR}}{C_{Vol}} \times N_C \times t \tag{8}$$

Revenue Water Q_{RW} can be equal, higher or smaller than Flat-Rate Billed Authorised Supply Q_{BS} as shown in Figure 2. Non-Revenue Water Q_{NRW} is determined for the three scenarios by adding the Water Losses Q_L, Unbilled Authorised Supply Q_{US} as well as the difference between Flat-Rate Billed Authorised Supply Q_{BS} and Revenue Water Q_{RW}, see Equation (9). In scenario 2, Excess Revenue Water Q_{ERW} is calculated by subtracting Flat-Rate Billed

Authorised Supply Q_{BS} from Revenue Water Q_{RW} (Equation (10)). Flat-Rate Billed Authorised Supply Q_{BS} minus Revenue Water Q_{RW} gives Billed Non-Revenue Water Q_{BNRW} in scenario 3 (Equation (11)):

$$Q_{NRW} = Q_L + Q_{US} + (Q_{BS} - Q_{RW}) = Q_{SIV} - Q_{RW} \tag{9}$$

$$Q_{ERW} = Q_{RW} - Q_{BS};\ \textit{Scenario}\ 2\ (Q_{RW} > Q_{BS}) \tag{10}$$

$$Q_{BNRW} = Q_{BS} - Q_{RW};\ \textit{Scenario}\ 3\ (Q_{RW} < Q_{BS}) \tag{11}$$

CASE STUDY TIRUVANNAMALAI

A DMA, supply zone 5, of the WDS of the Indian City of Tiruvannamalai was chosen as a case study which is part of the research and development project Water Losses in Urban Environment (WaLUE 2017). The DMA covers approximately 710 service connections with a total population of 3,078 people and shows the typical boundary conditions for which the outlined approach has been developed (Figure 3). The DMA is supplied by the Thamarai Nagar elevated storage tank (Thamarai Nagar ESR) and partly by the Anna Nagar overflow tank (Anna Nagar OT).

In order to determine the System Input Volume Q_{SIV} a monitoring system consisting of ultrasonic flow measurement devices (SebaKMT UDM 200-M) for measuring the system input into the DMA was installed. Due to technical restrictions the duration of continuous measurement and therefore of the balancing period was 23 days. The results of the adapted water balance for the case study are shown in Figure 4, with the System Input Volume Q_{SIV} during the balancing period being measured to approximately 15,400 m^3 (100%).

For estimating the actual Flat-Rate Billed Authorised Supply Q_{BS}, customer meters (Zenner single-jet dry-running meters) were installed at a sample of 42 service connections. The locations of the households with metered service connections are marked in grey in Figure 3. With 42 of 710 service connections being metered, coverage of approximately 5.9% was achieved which is more than the recommended 5%. The selection was based on a preliminary

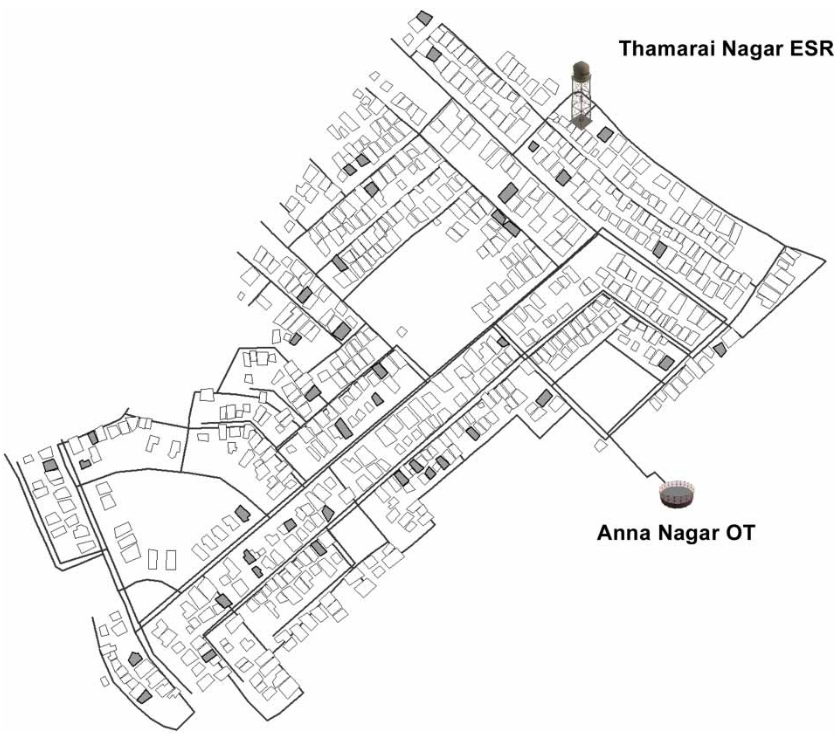

Figure 3 | WDS of the DMA with locations of the sampled service connections (in grey).

<table>
<tr><th colspan="5" style="text-align:right">Scenario 3</th></tr>
<tr>
<td rowspan="5">System Input Volume
Q_{SIV} = 15,400 m³
(100%)</td>
<td rowspan="3">Authorised Supply
Q_S = 11,613 m³
(75%)</td>
<td rowspan="2">Flat-rate Billed Authorised Supply
Q_{BS} = 11,613 m³
(75%)</td>
<td>Consumption
Q_{BSC} = 7,504 m³
(49%)</td>
<td>Revenue Water
Q_{RW} = 4,083 m³
(26%)</td>
</tr>
<tr>
<td>Wastage
Q_{BSW} = 4,109 m³
(26%)</td>
<td>(Billed Non-Revenue Water
Q_{BNRW} = 7,530 m³)</td>
</tr>
<tr>
<td colspan="2">Unbilled Authorised Supply
Q_{US} = 0 m³
(0%)</td>
<td rowspan="3">Non-Revenue Water
Q_{NRW} = 11,317 m³
(74%)</td>
</tr>
<tr>
<td rowspan="2">Water Losses
Q_L = 3,787 m³
(25%)</td>
<td colspan="2">Apparent Losses
Q_{AL} = 0 m³
(0%)</td>
</tr>
<tr>
<td colspan="2">Real Losses
Q_{RL} = 3,787 m³
(25%)</td>
</tr>
</table>

Figure 4 | Adapted water balance for the case study.

household survey regarding household population and type of water supply as well as in consideration of the sample covering the whole DMA. The metered customers have been informed to be still charged as unmeasured and that the metered volumes are solely used for the research project and not for the billing process of the utility. Thereby, no changes in their consumption patterns should be ensured.

With the per capita supply data of the sample, the Flat-Rate Billed Authorised Supply Q_{BS} was estimated for the balancing period using the two statistical methods of simple sampling and post-stratified sampling, see Equations (1)–(3). Comparing the results of the two methods the post-stratification sampling method leads to a lower precision than the simple sampling method. The reason for that are the considerably high variances of the supply values within the strata, which impede the desired stratification effect. As a result, the simple sampling method using per capita supply values showed the highest precision, with an estimated Flat-Rate Billed Authorised Supply Q_{BS} of approximately 13,035 m^3 for the balance period of 23 days. Subtracting inaccuracies of the customer meters due to air flow applying the approach of Walter (2015) and Staiger (2016) results in a corrected Flat-Rate Billed Authorised Supply Q_{BS} of approximately 11,613 m^3 (75%).

For estimating the Consumption Q_{BSC} and Wastage Q_{BSW}, additional customer meters have been installed downstream of the roof tanks at the selected household sample. Two household surveys with the customers taking notes of their approximate ground tank consumption were executed. The surveyed customers have been informed that the data is solely used for research purposes. Consumption Q_{BSC} of 7,504 m^3 (49%) was calculated with Equation (4) using the survey results and the measurement data of the roof tank meters. With Equation (5), Wastage Q_{BSW} was estimated to be 4,109 m^3 (26%).

Unbilled Authorised Supply Q_{US} comprises 0 m^3 as no volumes are taken by unbilled authorised customers, the utility or other authorised parties within the DMA. Hence, Water Losses Q_L equal approx. 3,787 m^3 (25%) within the balancing period considering the above mentioned numbers ($Q_L = Q_{SIV} - Q_{BS} - Q_{US}$). Apparent Losses Q_{AL} are 0 m^3 as no Unauthorised Consumption Q_{ALC} is reported in the balancing period. Thus, Real Losses Q_{RL} equal Water Losses Q_L (Equation (6)).

According to the flat-rate tariff charged in Tiruvannamalai, customers pay 100 Indian rupees (INR) for the supply of 7.5 m^3 per month in addition to a constant water supply tax depending on the property size (Tiruvannamalai Municipality

2013). With $Q_{FR} = 7.5\ m^3$, $N_C = 710$ and $t = 0.76$, Revenue Water Q_{RW} can be calculated for the balancing period to 4,083 m^3 (26%) using Equation (7). Non-Revenue Water Q_{NRW} is 11,317 m^3 (74%) with Equation (9). Thus, the water volume supplied to the customers is considerably higher than the volume billed to and paid by the customers charged with the flat-rate tariff ($Q_{BS} > Q_{RW}$, scenario 3). Accordingly, Equation (11) gives Billed Non-Revenue Water $Q_{BNRW} = 7{,}530\ m^3$. More than one third of Non-Revenue Water Q_{NRW} is due to Wastage Q_{BSW} within the customers' premises.

CONCLUSIONS

This paper presents the adaption of the IWA water balance to intermittently operated WDS applying a flat-rate tariff without metering and billing of the actual consumption. In consideration of these conditions, authorised consumption from the IWA water balance is replaced by the component Authorised Supply Q_S and its two components Flat-Rate Billed Authorised Supply Q_{BS} and Unbilled Authorised Supply Q_{US}. The Flat-Rate Billed Authorised Supply Q_{BS} comprises the two components Consumption Q_{BSC} and Wastage Q_{BSW}, as part of the supplied water volume might be wasted due to overflowing private storage tanks or emptying of these tanks in order to get fresh water.

The methodologies to quantify or estimate the volumes of the above mentioned balance components also have to be adapted. In a WDS with initially unmetered customers, a monitoring system has to be implemented to measure Flat-Rate Billed Authorised Supply Q_{BS}, Consumption Q_{BSC} and Wastage Q_{BSW} of a sample of households with water meters installed upstream of the customers' premises and downstream of the customers' roof tank. Applying statistical methods such as simple sampling or post-stratified sampling along with auxiliary information of a comprehensive household survey, the volumes of Flat-Rate Billed Authorised Supply Q_{BS}, Consumption Q_{BSC} and Wastage Q_{BSW} of the total population can be estimated. In contrast to the IWA water balance, the deduction of the revenue and non-revenue water is not straightforward, as the customers are not billed according to their actual consumption but with a flat-rate tariff often related to a certain fixed (theoretical) water volume. Thus, the Revenue Water Q_{RW} might be higher, equal or smaller than the actual Flat-Rate Billed Authorised Supply Q_{BS}. All three scenarios are also considered and depicted in the adapted water balance.

The application of the outlined approach is demonstrated for a DMA with approximately 710 household service connections in the medium-sized city of Tiruvannamalai in South India. The implemented monitoring system to estimate Flat-Rate Billed Authorised Supply Q_{BS}, the Consumption Q_{BSC} and the Wastage Q_{BSW} covers a sample of 42 household service connections. The statistical methods applied to quantify the Flat-Rate Billed Authorised Supply Q_{BS} of the DMA show that additional information of household occupancy increases the precision of the estimate and should therefore be acquired by a household survey or census data. The results of the adapted water balance show the volume of Water Losses Q_L being about 25% and the volume of Wastage Q_{BSW} within the customers' premises about 26% of the System Input Volume Q_{SIV}. The volume of Non-Revenue Water Q_{NRW} is considerably high and about 74% of Q_{SIV}. Two-thirds of Q_{NRW} are due to the inadequate flat-rate tariff, as the utility charges far less volume than actually supplied to the customers.

The application of the adapted water balance in the case study shows that this approach can be used to initiate a continuous monitoring and assessment of the water losses and non-revenue water for WDS which charge a flat-rate tariff without metering and billing of the actual consumption. Based on the statistical analysis of supply and consumption volumes of a metered household sample, the adapted water balance focuses on the most relevant components for water losses in WDS described above. In a next step, developing indicators derived from the adapted water balance in addition to the internationally recognised and applied performance indicators, for example, introduced by the IWA and comprehensively described by Alegre *et al.* (2006), would be a valuable help for the water loss management in the given cases. Operational indicators, for example, could provide information whether water loss reduction measures should be concentrated on the network or the customers' premises along with financial indicators helping to interpret the subcomponents of Revenue Water Q_{RW} and Non-Revenue Water Q_{NRW}. With the adapted water balance and performance indicators, the developed approach could serve as a tool for many water utilities worldwide, especially in developing countries, to assess and tackle water losses in their distribution systems.

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