Simulator for NRW and real loss estimation in water distribution systems for developing countries

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Abstract

NRW (Non-revenue water) in water distribution network is an important issue which affects water utilities worldwide. In developing countries, due to an ageing infrastructure, many water utilities face issues of NRW around 45%. This higher value of NRW affects the financial viability of water utilities through loss of revenue. At an initial stage of any NRW reduction program, performing water balance is a necessary step. In such situations, especially in developing countries, estimation of NRW and real loss is challenging due to missing and uncertain data. For this kind of data conditions, traditional water balance software is not sufficient because it increases efforts and assumptions in water balance work. To overcome this challenge, we developed water balance simulator (WBS) which include inbuilt missing data estimation models for water supply, consumption and unbilled authorized consumption. Additionally, customized methodologies for estimation of water theft (unauthorized consumption) and customer metering inaccuracies are proposed. This approach can help utilities in developing countries having limited data availability to obtain realistic results with reduced assumptions in water balance.

Keywords: NRW estimation software; Real losses; Apparent losses estimation

1. Introduction

Due to increasing urban populations and expanding service areas, many water utilities in developing countries continue to struggle with providing clean drinking water to their consumers. NRW (Non-Revenue Water) is one of the major issue affecting performance and economic situation of water utilities. NRW is the difference between the amount of water put into the distribution system and the amount of water billed to consumer. The comprehensive water audit help to determine the amount of NRW, detailed profile of the distribution system and water users, thereby facilitating easier and effective management of the resources with improved reliability. It helps in correct diagnosis of the problems faced to suggest achievable and practical solutions (Dighade et al., 2014)

To estimate NRW and real losses the standardized IWA (International Water Association) water balance provides an appropriate corresponding basis. At initial stage top down approach of water balance is preferred to estimate NRW because it is based on available data/records and can be compiled quickly (Water Audits and Loss Control Programs, 2009). To perform top down approach in developed countries (advanced water utilities) is not challenging, due to availability of AMR (Automated Meter Reading) and AMI (Advance Meter Infrastructure) at supply and consumption side. The AMR data collection helps to reduce uncertainties and real time online NRW estimation is possible. In developing countries most of water utilities works with intermittent water supply (Frauendorfer, 2010).

To reduce wastage of water and to access performance by volumetric tariff, as initial stage utilities in developing are improving extent of consumer connection metering (PAS, 2014). The consumption meter reading collection occurs manually on bimonthly or monthly basis (depends on utility).

It has observed that, to estimate total billed consumption at end of month, utilities face problem due to missing data in consumption due to not-working meter connections. The percentage of this missing consumption data varies from utility to utility. City level developed utilities use MDM (Meter Data Management) software which provides estimate for missing consumption for not -working meter connections based on past and historic consumption data (using rule based methods). In such estimations, an accuracy becomes uncertain when not-working meter replacement is not well managed. In case of long meters replacement time around 1 year or 2 years, using past consumption data may not be a suitable option. In some small-scale utilities (town), its observed that, for not-working meters connections there are no estimates due to unavailable records and history data, so history based estimation techniques are not applicable in these cases. Considering this challenge suitable missing data (due to not-working meters) estimation technique is necessary for obtaining monthly total billed metered consumption. To estimate water supply in most of utilities face issue due to absence of bulk flow meter at downstream of ESR (Elevated Storage Reservoir) and at boundaries of zone in such case water supply data is completely missing. To overcome this situation selection of specific experimentation technique for water supply estimation is necessity (CPET, 2010). In case of bulk meter is present daily water supply volume can be available. However due to malfunction of meter can create missing data problem.

From Indian water audit reports, it observed that UBAC (Unbilled Authorized Consumption) is generally around 1 to 3% range. Estimation of unmetered unbilled authorized consumption is challenging due to unavailable records (Dighade et al., 2014). Apparent losses (Commercial / nonphysical water losses) consist of unauthorized consumption (Water theft), customer metering inaccuracies and systematic data handling errors (Vermersch, 2016). According to AWWA (American Water Works Association) (Water Audits and Loss Control Programs 2009), in developed countries water theft can be considered as 0.25% of water supply. In India, due to socio-economic divide, this percentage is higher than 0.25% of water supply. From water audit report on Kalol city in Gujarat, it is observed that water theft is 16 % of water supplied (CPET, 2010). Customer metering inaccuracies is another important component of apparent loss. To estimate metering inaccuracies data of connection diameter, flowrate and age of the meter is important information (Cruz, 2016).

The methods currently available to estimate apparent losses without online monitoring and AMR (automatic meter reading) system has challenges to use it commercially, e.g. For metering inaccuracies estimation in non -automatic meters, methods are available but commercial usefulness of these method in large site has challenges due to time-consuming experimentation **(**Fontanazza et al.,2013). For water theft estimation, the technologies available are based on online monitoring of demand curves. In offline systems, estimation of water theft is still uncertain. To estimate NRW and real loss Many versions of free water balance software have been developed since year 2000. They are customized for local circumstances and traditional terminology, but they always follow the foundation principles of the IWA Water Balance. Free water balance software's like "AWWA water balance" and "CheckCalcsNZ" provides top down approach for NRW and real loss estimation with better presentation of water loss KPIs. In these software's top down NRW estimation is based on final value of estimated supply and billed consumptions entered by user. The inbuilt compensation techniques for missing data in consumption and water supply is not provided. Additionally, apparent loss components are assumed. In developing countries apparent loss estimation is necessary because it varies from utility to utility.

By considering these all motivations and challenges mentioned above, for estimation of NRW and real loss in developing countries, the objective of research is to develop a simulator with inbuilt models based missing data estimation and methodology for apparent loss estimation.

2. Methodology

Conventional free water balance software's does not consider detailed data. It considers single value for water balance component and user entered confidence interval for that values. Due to this reason utility with missing data component cannot decide proper single value for water balance component. In addition, many software's do not have inbuilt apparent loss estimation technique. Considering this challenge to estimate missing data by considering detailed actual data, and to provide inbuilt apparent loss estimation facility WBS (Water Balance Simulator) has been developed. This simulator can also help for effectiveness analysis of NRW reduction solutions, to propose suitable NRW reduction plan. Figure 1 shows structure of simulator and its features.

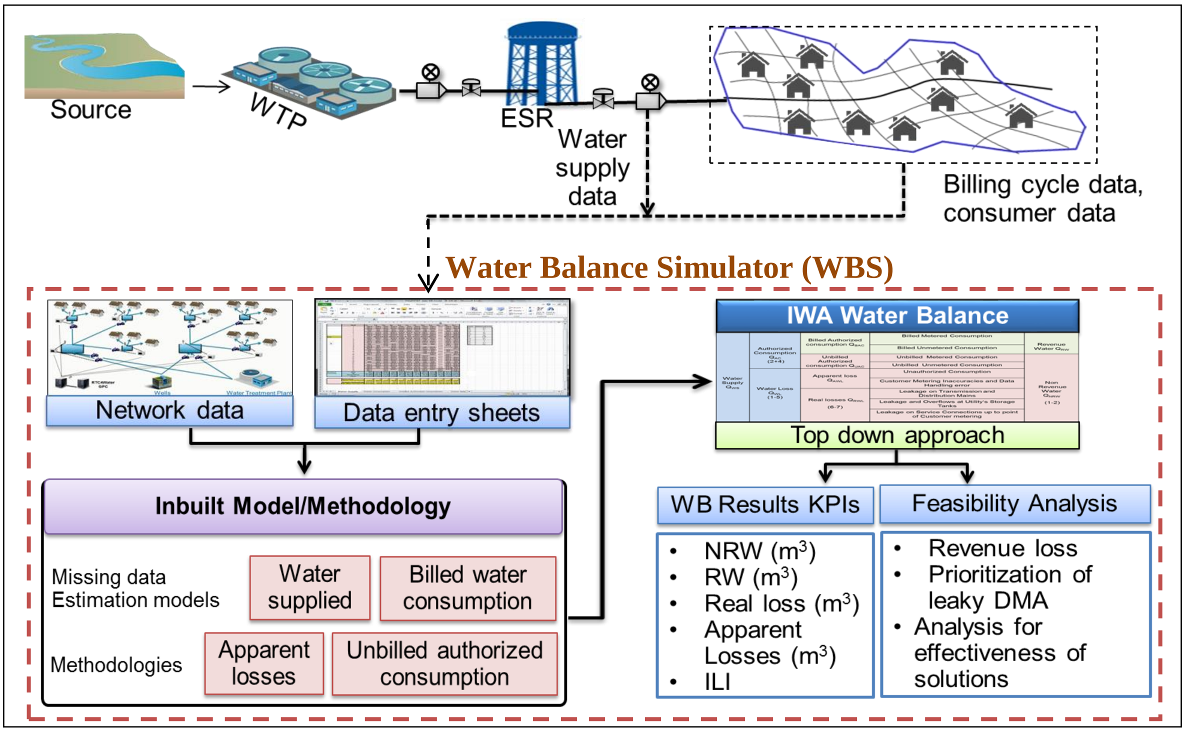


Figure 1 Structure of WBS (Water Balance Simulator)

As shown in Figure **1**, the data related to selected network area (separated by system boundary) can be provided in the data entry sheets of WBS. The input data includes available data for water consumption, system input volume, information about unbilled authorized consumption and apparent losses. The inbuilt models and methodologies help to estimate these components (water consumption, system input volume, apparent loss and unbilled authorised consumption) with better accuracy. Based on these components using IWA top down water balance approach NRW, real loss and KPIs for selected area has estimated. To propose reduction strategy WBS can be used to estimate effectiveness of solutions like pressure management and apparent loss reduction on NRW, based on feasibility study inputs. Following part of paper shows details about models and methodology for water balance.

2.1 Billed authorized consumption (BAC)

BAC includes two types of consumptions, metered and unmetered consumption. In developing countries collection of metered consumption data occurs manually by meter reader on monthly or bimonthly basis. In billing cycle data due to not-working meters missing data occurs. Many utilities use consumption history data of that connection to estimate this missing consumption values. However, in most of the cases, damaged meters are not replaced for many billing cycles and same consumption value from history data is repeated. Some utilities do not have history data records for not-working meters, in this case billing occurs on flat rate basis for those connections and in place of consumption value (m^3/billing cycle) no estimates are available. To estimate consumption by not-working meters connections by onsite experimentation and test is time consuming and needs customers support (Apoorva, 2018). Therefore, the proposed compensation technique to estimate the missing data in metered consumption is by developing a model using obtainable customer details like household population data. Generally household population and water consumption shows better correlation coefficient.

Initially based on available data for normally working meters, WBS creates consumption model (example regression model) for each month (billing cycle data). The equation (1) shows example of it.

$$\boldsymbol{y_{(Missing)} = \beta_1 x + \beta_0 + e} \quad \textbf{(1)}$$

y = Metered consumption, x= Household population

$\beta_1, \beta_0 = Model\ parameters\ (Inclination, intercept)$, *e = noise variable*

The model parameters are estimated using suitable statistical techniques. To estimate consumption data by not-working meter in month, it uses household population of connection and parameters of (monthly) consumption model. Model provides standard error of estimate and initial estimate about confidence interval in billed consumption, this helps user to consider final extent of confidence interval for total billed metered consumption in water balance results. This consumption estimation technique helps to avoids use of assumptions, estimates based on inference from current month available data and suitable for utility to understand.

2.2 Water supply estimation

Case 1 – Area with available bulk flow meter at supply points.
The availability of water supply data for selected zone or prefecture depends on availability of bulk meters at system boundary. It can provide daily water supply data. In developing countries if bulk flow meter is available then most of the times data collection occurs manually. Sometimes because of malfunction of bulk flow meter, supply data consist missing data. This missing data percentage in supply data varies from utility to utility and based on maintenance of bulk flow meter. To estimate missing daily water supply data, in WBS models can be generated using available water supply data, weather condition and atmospheric temperature data. In case of missing water supply for a day, estimate is provided based on model parameters and weather data of that day. The total water supply is estimated by sum of estimated (for missing data days) and actual water supply data.

Case 2 – Area without bulk flow meter at supply points.

In this case estimation of water supply flow rate in supply hours is necessary. For this use of ultrasonic portable (clamp-on) flow meter is preferred for initial estimate. Based on flowrate and water supply hours as user input WBS provides estimate for water supplied. Based on water supplied and billed authorized consumption NRW is estimated.

2.3 Unbilled authorized consumption estimation methodology (UBAC)

Unbilled authorized consumption involves water consumption by utility and district government, which is not billed. Unbilled authorized consumption consists of two types, metered and unmetered consumption. Metered consumption includes government offices, schools, hospitals, stand post and public toilets. Unmetered consumption includes use of truck tanker for drinking water supply and firefighting. Water used for flushing of mains ESR cleaning is also part of unmetered consumption. Developing a model for missing data estimation in metered consumption is challenging because affecting factors (Intendent variables) are different for each type. Therefore, for missing value average of last three consumption values is used as estimate. In case of unavailability of last three-month data, consumption data of connections alike in size, hours of operation, type of use in same month has been used as estimate. To estimate unmetered consumption for drinking water tankers and firefighting tankers user entered information about truck tanker capacity and number of tankers used in month has used for estimation equation 2 shows example of it.

$$\boldsymbol{C_{water\ Tankers}}\left(\frac{\boldsymbol{m^3}}{\boldsymbol{month}}\right) = \boldsymbol{T_{Capacity}} * \boldsymbol{N_{Tankers}} \qquad \textbf{(2)}$$

$C_{water\ tankers}$ = Consumption by truck water tanker supply, $T_{Capacity}$ = Truck tanker capacity, $N_{Tankers}$ = Number of tankers used in a month.
For estimation of water used for flushing of mains and ESR cleaning, flowrate and time (hours/ day/month) information has been considered in WBS (Water Audits and Loss Control Programs, 2009).

2.4 Apparent loss estimation

a) Customer meter inaccuracies

Water loss due to customer meter inaccuracies is mainly due customer meter under-registration (negative error). The error of the meter can be calculated from the following formula (Fontanazza 2013).

$$\varepsilon = \frac{V_m - V_a}{V_a} * 100 \qquad (3)$$

Where, V_m = is the measured (registered) volume (known from billing cycle data), V_a = is the actual volume, ε = Percentage error. For new meters, according to Indian standards for minimum (Q_{min}) to transition flow (Q_t) error should be within $\pm 5\%$ and for transition (Q_t) to maximum (Q_{max}) it should be ± 2%. However, actual on field working meters error is $\varepsilon = f(Flow\ rate,\ meter\ age)$ (Cruz, 2016). As age increases error increases for meter (Arregui, 2006). To estimate losses due to meter errors first step is meter error curve generation. It needs experimental data of random sample meters by testing at different flowrates. In WBS based on user entered experimental testing data (for particular meter diameter and meter age) error curve and function can be generated. Using this function and customer connection data related to daily average flowrate, age of meter and monthly consumption value the initial estimate about loss due to each metered connection can be estimated. The challenges for obtaining the data for daily flowrate need to compensate by hydraulic model support with prioritization of meter age and pressure in area.

b) Water theft / unauthorized consumption.
In developing countries, the extent of unauthorized consumption varies from area to area due to socio-economic divide. The water theft can be categorized in two following types as shown in Table **1**.

Table 1 Categories of unauthorized consumption

Sr. No	Categories of unauthorized consumption
1	Unauthorized consumption by unregistered consumer connections (illegal connection in slums area)
2	Unauthorized consumption by registered consumer connections by meter bypass

To identify the theft by registered user's, analysis of billing cycle data and inferences from consumption model can be used to highlight suspect connections with working meter based on repeating zero or abnormally low consumptions. Based on site survey this suspect connection can be confirmed. To estimate consumption by the suspect connection, the connection details and parameters of consumption model for same month can been used. The challenge for this approach is uncertainty in consumption data collection. The validation of this method is necessary it has not tested on field. To identify unauthorised consumption by unregistered consumers, site survey is recommended. To estimate water theft in slums without public stand posts, the estimate about total population of slum and parameters of consumption model has been used with additional multiplication factor. Multiplication factor has considered because the consumption in slums can be more less than average per capita consumption in normal areas. The accuracy of this method need to validate.

c) Systematic data handling error
Systematic data handling errors can include errors due to data acquisition process and error in data estimation. In data acquisition error includes data handling and data transfer error in water supply, billed authorized consumption and unbilled authorized consumption. In WBS user can enter the estimate about losses due to data acquisition process error based on available information. For data estimation error, MSE (mean squared error) of model for missing data estimation is used to estimate initial confidence interval for total billed consumption. The uncertainty about other components like water supply, unbilled authorized consumption and apparent loss is defined based user entered confidence interval. Based on standard formulas confidence interval for real loss and NRW has estimated.

3. KPIs (Key performance indicators)

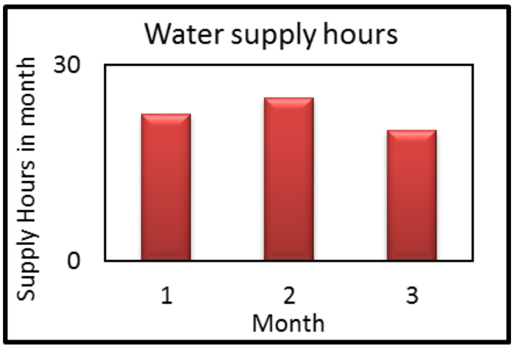
The KPIs section of WBS provides following KPIs.

- Real loss (m^3), Apparent loss (m^3)
- ILI (Infrastructure leakage index) using
  UARL = $\boldsymbol{UARL\,(liters/day) = \left(18 * L_m + 0.8 * N_c + 25 * L_p\right) * P_S}$
  L_m = length of mains [km], N_c = Number of Service Connections, L_p = length of private service pipes from property boundary to the meter [km], P_s = average Pressure [m]

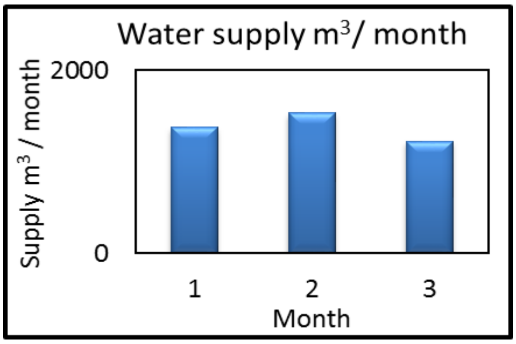
- Annual revenue loss (INR/Year)

4. Case study – Utility 1

The case study has performed on small town area about 2 km in Indian utility. The three-month data for water balance has acquired with discussion with utility. The population in selected area is around 500 and number customer connection 80. In which 77 are domestic connections and 3 are commercial connections. At initial stage it observed that monthly billing cycle data has 40% is missing due to not working meters. At supply side bulk flow meter was not available. The age of pipe network is around 25 to 30 years. To estimate NRW at initial stage estimation of SIV (system input volume) was necessary. The water exported in selected area is 0. Therefore, SIV is equal to water supplied. Due to absence of bulk flow meter, the supply flowrate has estimated by experiment. Using supply flowrate value and available hours of supply data in month (from log books) water supplied volume has been estimated. Figure 2 shows water supply hours and estimate of total water supplied in month.



a)



b)

Figure 2 a) water supply hours b) water supply (m^3/month)

In selected site, water billing cycle period is 1 month. In billing cycle data it observed that estimate for not-working meter connections is not available. To develop consumption model the household population data for each connection has collected during meter reading. Based on available consumption and household population data for 48 working meter connections, consumption model has developed. The model has been used for estimation of consumption by not-working meter connections. Figure 3 shows estimated billed metered consumption.

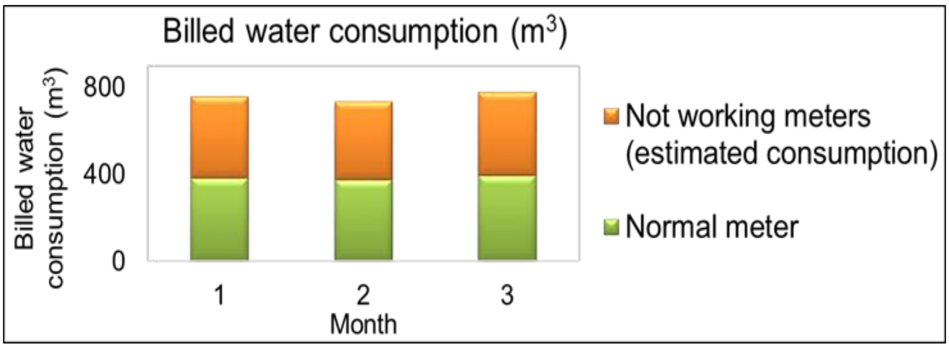
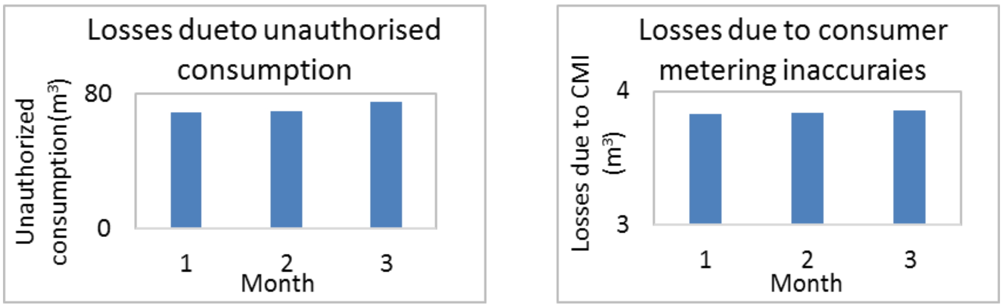


Figure 3 Billed water consumption for three months



a) b)

Figure 4 a) Losses due to unauthorized consumption b) Losses due to consumer metering inaccuracies

Based on water supply and water billed consumption non-revenue water for three months has estimated. In selected area due to absence of unbilled authorized connections in this case water loss is equal to NRW. To estimate losses due to unbilled authorized consumption, a site survey performed and observed 3 domestic connections and 1 commercial unauthorized connection. The selected area did not has slum area. The losses due to unauthorized estimated using household population of observed connection and consumption model. To estimate customer metering inaccuracies error curve has assumed due lack experimental data of sample meters. Using customer data of metered connections and assumed flowrate values, initial estimate for losses due to customer metering inaccuracies has obtained. Figure 4 shows the estimate for customer metering inaccuracies and unauthorized consumption. For losses due to data handling error is assumed as 1% of water supply because water supply is estimated without bulkflow meter. Based on apparent loss and water loss value real loss for each month and aggregate has estimated. Figure 5 shows view of WBS for and results of NRW for month 1.

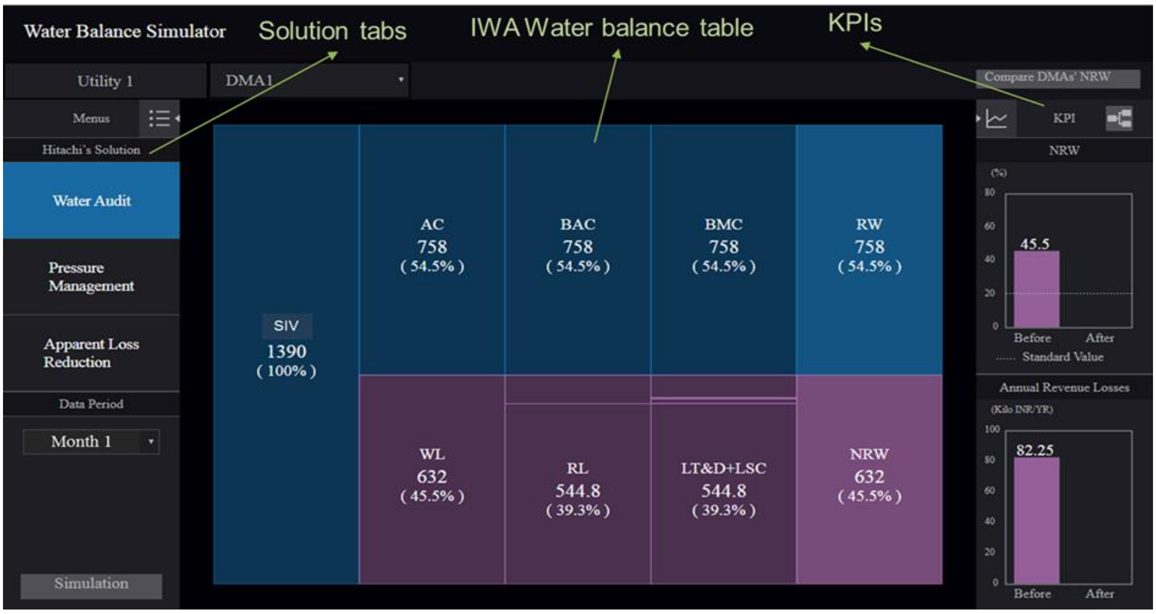


Figure 5 WBS for and results of NRW for month 1

5. Results and discussion

Figure *5* shows the WBS GUI view. On left side it has solution names and centre it has IWA water table and at right side of table it shows KPIs. The components name of water balance has shown with their short forms. The height of component column is automatically adjusted based on value of component. In Figure 5 NRW results for month 1 is show in water balance table. The results for other two months and aggregate for three-month can be obtained by selecting the data period tab. The NRW % in month 1 is 45.5 % of SIV. The estimated amount of real loss is 39.3% and apparent loss is 6.2 %. The estimated NRW for month 2 and 3 is 51 and 33% respectively. The value of NRW in month 3 is less compared to other months, because water supply hours are less in month 3 but consumption is almost same to the other months. The estimate of losses due to customer metering inaccuracies need to validate based on actual meter error curve generation. The estimated ILI for area is 20 which show poor KPI, this is could be due to old pipe network.

Conclusion

The estimation of NRW and real loss in developing countries is challenging due to data availability. For better estimate of total billed consumption, suitable techniques for estimating consumption by not-working meters is necessary. Due to absence of bulk flow meters, in supply estimate uncertainty can be higher. The inbuilt estimation methods in WBS provides ease to user in water balance estimation. The reliable, less time-consuming and less assumption in NRW is preferable to utility. The methodology proposed for apparent loss estimation is based on developing countries utility data availability and infrastructure condition the validation of method with multiple case studies is necessary. The solution effectiveness analysis in WBS can help utility to understand benefits of NRW reduction in better way.

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