PAPER 5

Stochastic daily time-step conjunctive water use model for municipalities

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ABSTRACT

South Africa has a broadly-developed water infrastructure based mainly on surface water, localised groundwater and occasional desalination or reuse. However, most suitable surface water sites are already utilised and with increasing demands and climate variability it is projected that South Africa will experience water deficiencies by 2025. To mitigate water scarcity, more conjunctive water use solutions need to be investigated at municipal level.

To implement more conjunctive management of the scarce water resource at a local authority scale, an excel based model is developed for a combination of surface water, groundwater, desalination and reuse using daily time-step. The model is stochastically driven by synthetically generated streamflow sequences using Stochastic Model of South Africa (STOMSA). Monthly streamflow is disaggregated into daily streamflow and a streamflow-rainfall relationship is established to generate corresponding synthetic rainfall sequences. Surface water is modelled using conventional dam balancing equations with daily streamflow. Groundwater is modelled using a similar approach as the Aquifer Firm Yield Model with the saturated volume fluctuation equation as the stochastic link between rainfall, recharge and water levels. This model is paired with the Cooper-Jacob model and data from Groundwater Resource Assessment Phase 2 – project (GRA II). Desalination and Reuse is modelled as a source which provides water at 100% assurance of supply at different operational capacity levels over fixed three-monthly time-step.

An overall system balancing approach will be used to estimate the available yield of the system whereby surface water is used first corresponding to availability after which groundwater is utilized and then desalination or reuse. A control is built in which shuts down the desalination plant if the dam capacity reaches safe user-defined levels (80% of Full Supply Capacity). The model allows for multiple alternative water resources, based on consumer defined input. Additionally, the short-term and long-term assurance of supply is graphically presented and management suggestions and tools are provided. An analysis of the historical water supply system is produced while suggestions for improved water management are also provided.

INTRODUCTION

South Africa is classified as a semi-arid region. The current water supply system is based on 77% surface water, 11% return flow, 9% groundwater and less than 1% desalination (Department of Water Affairs, 2013). Water availability in South Africa varies greatly in space and time. While the West is dry with winter rain and mean annual rainfall as low as 100 mm, the East and Southeast receive rainfall throughout the year with a mean annual rainfall of up to 1,000 mm. Much of the runoff is lost through flood spillage thereby making surface water resource fairly limited. Climate variability might additionally influence the availability of water due to a persistent shift in rainfall patterns and the frequency of rainfall events. Although groundwater is limited due to geologic conditions, it is utilized in rural areas but remains under-used in urban areas. Population growth is a further factor which causes an increase in water demand.

According to the Municipal Structures Act (Act 117 of 1998) and the Water Services Act (Act 108 of 1997), responsibility for the provision of water and sanitation services lies with water services authorities, which the Water Services Act defines as the municipalities. The Acts place responsibility on municipalities to have an uninterrupted water supply at a high quality. Water supply from a variety of sources could be used in conjunction, to reduce the risk of failure of the supply system.

Different conjunctive use combinations have been developed to provide water for urban and irrigational demands which include combinations of surface water, desalination, groundwater and reuse. The most prominent conjunctive use combination is that of surface water and groundwater (Pulido-Velázquez et al. 2006).

This paper highlights the findings on the fundamental links between surface water, groundwater and desalination to model them conjunctively. To assist a municipality in managing its water supply sources an Excel based model has been developed for proactively managing the available resources based on both historical data as well as stochastically generated data. The aim of developing the conjunctive water use model is to assist in managing water resources with daily considerations.

LITERATURE REVIEW

To develop a conjunctive use model, modelling methodologies and considerations from existing South African water simulation and analysis models were identified. Separate conjunctive model components such as surface water, groundwater, desalination and reuse were investigated to identify significant modelling concepts and inter-linkages.

Review of Water Resource Models

Developing a model involves reducing the number of factors governing the real-life system to a manageable size by identifying the most significant interactions in the system while assuming other factors to be negligible (Xu, 2002). According to Seago and McKenzie (2008), Models can have different functions, namely; descriptive, predictive and optimization. Descriptive models aid the understanding of the system, predictive models are used as a "what-if" analysis tool to evaluate the effects of different scenarios; while optimization models make use of mathematical principles to establish the best scenario from a number of possible scenarios based on a criterion (Seago et al. 2008). Water resource models are mainly used for either operations and management, planning or data management. Further technical classifications of water resource models are deterministic, stochastic or system simulation.

South Africa hydrological planning models consist of three main modelling tools. A deterministic tool relating rainfall to runoff which is developed in the Water Resources Simulation Model (WRSM2000). In this model, rainfall and runoff data is used to determine the volume of water that moves through an interlinked water system. It also provides the basis in which streamflow extension and natural streamflow generation takes place by using calibration processes and subtracting manmade influences respectively (Seago

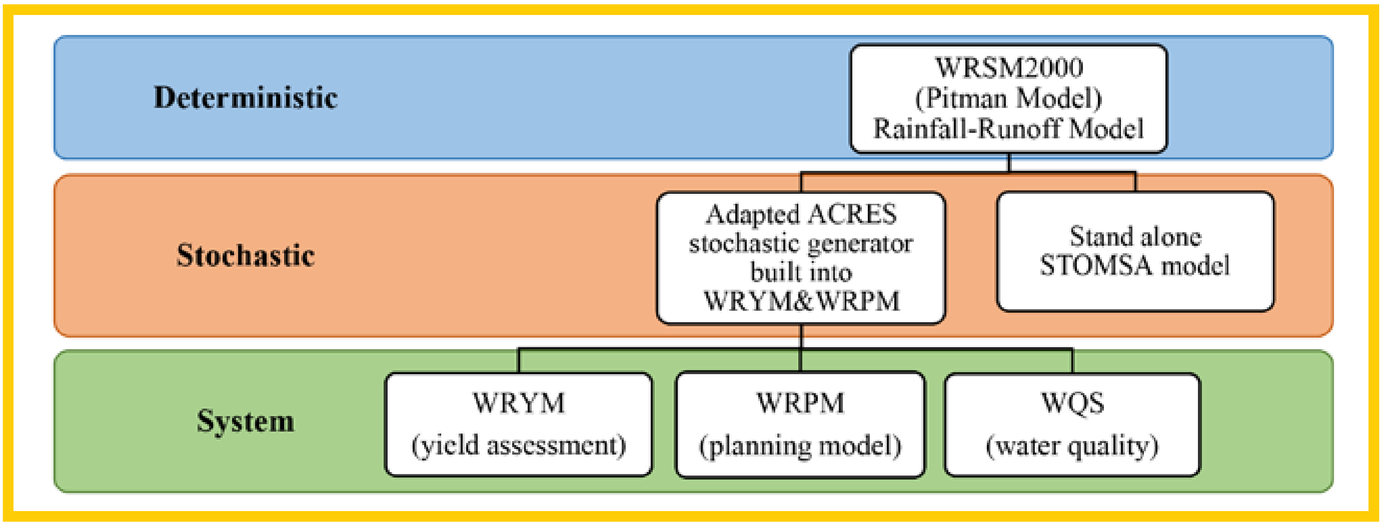

FIGURE 1: South African water resources models in technical classification groups and interconnections

et al. 2008). Deterministic outputs from the WRSM2000 are used as input in stochastic models.

The second group of modelling tools encompass stochastic modelling whereby probabilistic and deterministic parameters of historical sequences are used to generate stochastic sequences which represent climatic variations. The third group of modelling tools consists of system modelling including the Water Resource Yield Model (WRYM), the Water Resources Planning Model (WRPM) and the Water Quality and Sulphates Model (WQS) which make use of the stochastic sequences (Seago et al. 2008). Figure 1 illustrates the technical classification groups for water resource models as well as the available South African water resource models making in each in each group and their inter-relationships.

As is demonstrated through Figure 1, the South African water system models take all three modelling tools into consideration. The WRYM is used to determine the historic and stochastic water resource supply capability (yield) of a system. Historic sequences are used for the historical yield analysis while stochastically generated sequences are used to evaluate stochastic yield in which case assurance of supply for different yields is determined (Nkwonta, et al. 2017). The WRPM expands on the stochastic analysis to forecast the capability of the water system to provide for water requirements that change with time. Yield-Draft curves are used to illustrate the historical firm yield of a system. Draft is considered as the target withdrawal volume from a water supply system, while yield is defined as the annual actual volume of water that can be supplied (Basson et al. 1994). To determine the reliability of supply, the yield of a set of stochastically generated sequences is evaluated for different target drafts. A failure occurs when the yield of a sequence is not equal the target draft. Therefore, long-term risk of failure is calculated as the number of failure sequences over the total number of sequences. Consequently, the reliability of supply is evaluated as the inverse of long-term risk of failure (Basson et al. 1994).

Literature on stochastic streamflow generation and disaggregation provides better understanding for future model development.

Stochastic Streamflow Generation and Disaggregation

The time period in which a reservoir is emptied from a full supply level to the minimum operating level (empty) till the point in time when it is again filling up to full supply level, is termed a critical period (Basson et al. 1994). For water supply systems in semi-arid regions critical periods can be as long as eight years. Accroding to Basson et al., a longer hydrological record length is neccessary for reliably assessing a water system with a longer critical period (1994). Synthetically generated sequences provide alternative hydrological sequences that can be used to evaluate the water system at different supply reliabilities.

According to Maas and Du Plessis (2017) there are a number of stochastic models that exist in the field of hydrology. According to literature findings by Maas et al. (2017) a stochastic model that represents the most realistic varied stochastic flow sequences, is one that identifies historical statistics, uses pseudo random number generation as well as cross-correlation. The Stochastic Model of South Africa (STOMSA) is a model that satisfies the requirements investigated by Maas et al. (20017) Historical statistics are used together with pseudo random number generation and cross-correlation to produce annual stochastic flows. The annual time-steps are then disaggregated into monthly time-steps by matching the yearly flow to the closest yearly flow in the monthly historic input data. STOMSA is a widely applied model used for stochastic sequence generation.

Daily stochastic streamflow is particularly difficult to generate because of non-linear responses to channel characteristics. Therefore, to model daily streamflow, monthly flow is disaggregated into daily flow (Xu, 2002). Acharya and Ryu (2014) developed a simple method for disaggregating monthly flow into daily flow through maintaining historical flow characteristics. The flow at the target station is based on monthly flow records and at a source station in the same catchment consists of historical monthly and historical daily flow. Flow classes are established by using a 3-month window, in which seasonal patterns are identified and monthly flow is disaggregated by using linear deterministic methods.

Having considered components and processes followed in stochastic streamflow generation as well as streamflow disaggregation, the surface water reservoir simulation processes are researched.

Surface Water Reservoir Simulation

Surface water reservoirs are evaluated on the basis of a mass balance approach. System storage capacity is simulated by considering inflow and outflow volumes of the water system for every time-step. The sequential reservoir storage equation is given by Equation 1 as adopted from (Waldron & Archfield, 2006):

$$S_{t+1} = S_t + Q_t - D_t - E_t - L_t - O_t \quad (1)$$

Where:

S_{t+1} = Storage capacity at the end of the time-step (mil m^3)
Q_t = Storage capacity at the beginning of the time-step (mil m^3)
S_t = Inflow volume per time-step (mil m^3)
D_t = Demand per time-step (mil m^3)
E_t = Evaporation losses per time-step (mil m^3)
L_t = Losses due to seepage and environmental releases per time-step (mil m^3)
O_t = Overflow/spillage losses (mil m^3)

Each surface reservoir component is evaluated with constant time-steps, conventionally a monthly time-step is used, but studies have also been performed using daily time-steps to manage drinking-water supply systems (Waldron et al. 2006). Inflows into the reservoir can either be total river channel inflow or inflow from an abstraction weir. Over every time-step, the demand volume is extracted from the reservoir and is deemed the main outflow. The losses from the dam are namely: evaporation, seepage, environmental releases and spillage. In South Africa, Symons-pan factors are used to convert mean annual evaporation to open water evaporation (Du Plessis, 2017).

Surface water components used to simulate storage behaviour of surface water reservoirs have been identified. Groundwater-surface water interactions need to be explored to further build the conjunctive model.

Stochastic Modelling of Groundwater

Groundwater is defined as water stored in the pore spaces of sands, rocks crevices and fractures. According to Heath (2004), "an aquifer is a rock unit that will yield water in a usable quantity". South Africa has both high yielding and low yielding aquifer systems that can be used to augment supply systems (Woodford et al. 2005).

Conventionally borehole yield tests are performed to determine the safe yield of a particular borehole and aquifer system. The water level response to the pumping is used to estimate the hydrogeological parameters of the borehole and give an indication of the boundary conditions of the aquifer system. According to Gelhar (1993) groundwater not only varies with space but also with time. Therefore, available abstraction estimate at a single time consideration is not deemed sustainable over long periods of time. Gelhar (1993) further states that water level response of aquifer systems follows natural recharge events dependent on precipitation. The challenge with groundwater quantification and modelling is the extreme variability of material properties over small distances and time-periods (Gelhar, 1993).

A model that, according to Gelhar (1993), best describes the dominant behaviour patterns of large-scale systems, is one that incorporates the limited observed data from boreholes as well as physical laws. Physical laws include the mass and momentum continuum equations that govern the effects of inflow and outflow of the groundwater system. Aquifer models consider average hydraulic parameters specific to their region as well as time variations of recharge (Woodford et al. 2005). To establish time-variability linked to precipitation, recharge methods are identified that are used in aquifer modelling.

Recharge Determination

Recharge is water that increases the water table through vertical infiltration and lateral flow. Recharge occurs through; rainfall events, interconnected aquifer system, surface- and ground-water interactions as well as through artificial means. Chemical and physical approaches are used to estimate recharge (Xu & Beekman, 2003). Chemical approaches make use of isotropic tracer elements to estimate recharge. Groundwater Resources Assessment

TABLE 1: Recharge estimation methods adapted from Xu & Beekman (2003)

Method	Approach and Zone	Main Principles
CRD	Physical approach Saturated-Unsaturated Zone	Groundwater water levels at a point in time are affected by the sum of previous rainfall events. Recharge is determined to be a fraction of the cumulative rainfall.
SVF	Physical approach Saturated Zone	Water balance approach modelling inflow and outflow of a system using time-steps and averaged groundwater levels available from monitoring borehole data.

Phase 2 (GRA II) makes use of this method to determine recharge percentages. Physical recharge estimation approaches identify the dominant variable of precipitation which is time-dependent. Different recharge methods are applicable to one of two zones; saturated and unsaturated (Xu et al, 2003). A saturated zone describes soil with a high moisture content while unsaturated refers to dry soil.

Table 1 presents a brief summary of two physical recharge determination methods that are applicable to semi-arid and arid regions: Cumulative Rainfall Departure (CRD) and Saturated Volume Fluctuation (SVF).

The CRD method is widely applicable for aquifers where water levels fluctuate, nonetheless an extensive borehole dataset is necessary. The SVF method presents both hydrogeological parameters as well as time-varied parameters in a mass balance equation. While potential recharge can be determined for unsaturated zones, actual recharge is determined for saturated zones.

The SVF is considered the most appropriate for this research and is defined in Equation 2 as adapted from (Murray et al. 2011):

$$h_{t+1} = h_t + \frac{\%R*MAP_t}{Sy} + \frac{In_t - Out_t}{Sy*A} - \frac{Abs_t}{Sy*A} \qquad (2)$$

Where:

h_{t+1} = Water level end of the time-step (mbgl)
h_t = Storage capacity at the beginning of the time-step (mbgl)
%R = Recharge percentage of Mean Annual Precipitation (%)
MAP_t = Mean Annual Precipitation per time-step (m)
In_t = Inflow per time-step (m^3)
Out_t = Evapotranspiration and baseflow outflow per time-step (m^3)
Abs_t = abstraction per time-step (m^3)
S_y = Specific yield (%)
A = Area of Aquifer (m^2)

It is evident from Equation 2 that water level drawdown in meters below ground level (mbgl) will increase as water is depleted from aquifer storage. This can either be due to evapotranspiration losses or high abstraction rates. Water levels will increase with the opposite scenario (Murray et al. 2011). A model that makes use of the SVF equation is the Aquifer Firm Yield Model.

Aquifer Firm Yield Model

Following the recommendations by Gelhar (1993), lumped-parameter water-balance models consider the linear rate in change in storage depending on the inflows and outflows of the aquifer system. These models are based on a steady state whereby the water level responds to the main variable of interest which in the case of stochastic modelling is recharge. The Firm Yield Aquifer Model (Murray et al, 2011) is a lumped-parameter box model that considers critical water levels for managing abstraction. It is used to estimate available abstraction volumes as well as aquifer yields and assurance of supply.

The water balance concept of the Aquifer Firm Yield Model (AFYM) is illustrated by Figure 2. The Aquifer reserve storage is the volume of water below

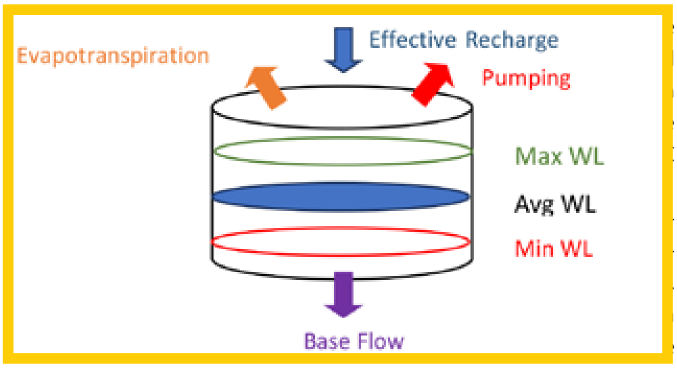

FIGURE 2: Aquifer Firm Yield model concept adapted from Murray et al. (2011)

water level drawdown at single boreholes and combined borehole effects in wellfields. The Cooper-Jacob Wellfield Model can be used for this evaluation.

The Cooper-Jacob Wellfield Model considers uses numerical equations to describe radial flow at boreholes induced by pumping. The Cooper-Jacob method is used in scenarios when borehole and aquifer parameters such as storativity, transmissivity, recharge and boundary conditions are known (Murray et al., 2011). It is applicable to porous aquifers and interconnected fractured aquifers, which form part of the main aquifer structure in South Africa (Woodford et al., 2005). It was found by Cooper & Jacob that the drawdown at a borehole is predominantly affected by the pumping rate and the transmissivity, while storativity, pumping duration and radius of borehole affect the drawdown less. Each borehole has a maximum depth to which it may be drawn down to. It is important to note that according to the SVF evaluation, seasonal fluctuation does occur at borehole and aquifer level and thus has to be considered when determining the sustainable abstraction. Abstraction potentials would fluctuate together with seasonal fluctuation (Murray et al., 2011).

Desalination and Reuse

Desalination and reuse are water resources that are climate-resilient thus having the potential to provide water at 100% of the time. There are two types of desalination: seawater desalination and brackish groundwater desalination. Large capital costs are required for desalination and reuse plants since membrane technology is predominantly used (Du Plessis et al. 2008). Additionally, operational and maintenance costs are higher than any other water resource because of the high energy requirements of the plants.

An economic evaluation of seawater desalination as part of an effort to augment the City of Cape Town's water supply was carried out by Blersch and du Plessis (2017). A desalination plant was modelled as a constant inflow channel in the WRYM and WRPM. According to Blersch et al. (2017), the most economically effective way to incorporate a desalination plant into the existing supply scheme is as a continuously operational base supply. The reason for continuous use is that membrane deterioration increases when the desalination plant is not used continually. Similarly, reuse plants also make use of membranes and follow similar operational guidelines. In terms of total usage, it was found that electricity costs for seawater desalination constitutes around 50% of the total operational and maintenance costs while electricity consumption of reuse plants is between 10% and 25% (Du Plessis et al., 2008).

South Africa has six small operational seawater desalination plants that were built as emergency supply source. The Sedgefield desalination plant is used as a seasonal water augmentation scheme in peak water demand periods. Even though the optimum scenario would be to use desalination as a constant supply, using it for high peak water demand periods at regular intervals can still maintain membrane life span. Reuse is practiced in Windhoek (Namibia) and provides 25% of the water supply (de Villiers, 2018).

MODEL METHODOLOGY

The research methodology incorporates the concepts that were identified within the literature review to develop each conjunctive water resource component and the combination of each in a comprehensive conjunctive use model. Two main data sources are used: WR2012 and the GRA II. Surface water and groundwater are linked through rainfall, and stochastic analysis is performed using stochastic sequences generated by STOMSA. A system balance is performed on surface water, groundwater, desalination and reuse. The conjunctive use model is developed in Microsoft Excel 2016 for easy use in a municipal setting.

Overview

The conjunctive water resource model uses a deterministic data from WR2012 as generated by WRSM2000, together with stochastic streamflow generation in the STOMSA software to evaluate the yield of the conjunctive use system. Figure 3 displays the links between input data, processes, system components and their integration. The WR2012 quaternary hydrological data sets, hydrogeological parameters from GRA II, specific municipal reservoir and demand information are all input data into the conjunctive use model.

The conjunctive use model process involves the application of stochastic links between surface water and groundwater as indicated in Figure 3. WR2012 data is fed into STOMSA to generate stochastic monthly sequences. Monthly streamflow sequences are disaggregated to daily sequences using historical flow categories. The daily sequences are then used to model inflow into the surface water reservoir. Runoff-rainfall relationships are used to generate daily rainfall to evaluate net evaporation. Stochastic rainfall is also used in the groundwater component together with catchment data from the GRA II.

Catchment aquifer parameters are used to evaluate average available abstraction on monthly time-step using the SVF and the principles from the lumped-parameter Aquifer Firm Yield Model (Murray et al, 2011). Desalination and reuse are taken as a single component which follows identical operational rules since both operate in 3-month periods dictated by high demand or triggered by low dam levels. These three components are integrated in the daily system balance analysis that is used to determine the yield and reliability of supply of the system.

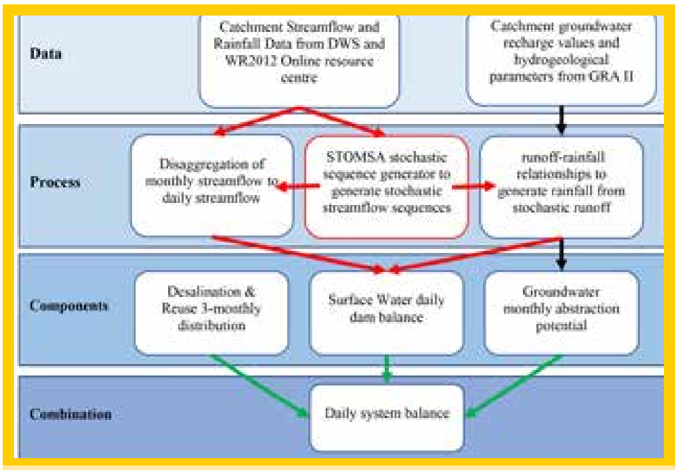

FIGURE 3: Conjunctive use model setup with data used, processes followed and combination of components

Surface Water Component

Two processes are outlined within the surface water component. The first is the process followed to disaggregation monthly streamflow to daily streamflow and the second is the surface reservoir mass balance.

The disaggregation of streamflow is done using a similar procedure to the one followed by Acharya and Ryu (2014) in that it uses an existing historical daily streamflow sequence to disaggregate monthly streamflow. While there are a number of streamflow gauges throughout catchments, the streamflow gauge that has daily historical data, situated within the closest proximity and in the corresponding catchment of the surface water reservoir is chosen as source station.

The historical daily streamflow sequence from the source station is obtained from the DWS website (DWS, 2019) and is used to extract high, medium and low flow categories for each month. Each month contains a dominant daily distribution in each category, which is expressed as percentage of daily flow over monthly flow.

Since stochasticly simulated data sequences are in monthly time-steps, monthly classsification boundaries are established as percentage monthly flow over mean monthly flow. To disaggregate the stochastic monthly sequence, each month in the stochastic sequence is expressed as a percentage of mean monthly flow of the respective stochastic sequence.

This is then matched to the historical flow category for that month, and the daily distribution is applied to each month. For example: October 1994 in the stochastic data set is expressed over the mean flow of each October in the stochastic data set (October 1920 to October 2008). The percentage is then compared to the percentages bounding the categories and the corresponding October high-, medium- or low-flow category is chosen that matches the daily distributions. The daily distribution for the corresponding category in October is then used to distribute the October's montly flow into daily flows.

With reference to Equation 1, the reservoir balance equation is used to simulate storage capcaity behaviour of the surface water reservoir. Daily stochastic streamflow sequences are used as inflow to the dam balance equations. The dam is classified as either an in-channel dam or off-channel dam. In the case of an in-channel dam, the entire inflow from the daily stochastic streamflow is considered. Conversely, off-channel dams receive inflow through abstraction canals and/or through pipelines which provide a constant supply unless daily flow is insufficient.

Runoff-rainfall relationships are established using the historic streamflow and historic rainfall sequence of a specific station. The mean historcial monthly rainfall is expressed as a percentage of mean monthly streamflow. The assumption is that the mean monthly percentage applies to each individual day. Daily average rainfall values are used to determine the net evaporation from the dam. Evaporation values are taken as mean monthly evaporation as per the Symons-pan readings for the different evaporation zones that are converted into open water evaporation. Monthly rainfall is used to connect the surface water and groundwater components.

Groundwater component

Available groundwater abstraction rates are calculated using concepts from two models: the Aquifer Firm Yield Model (Murray et al., 2011) with the Saturated Volume Fluctuation Equation (SVF) and the Cooper-Jacob Wellfield Model (Murray et al., 2011).

The SVF expressed by Equation 2 is used to iteratively determine the available abstraction on a monthly time-step. Recharge percentages of mean annual precipitation from the GRA II together with the stochastically generated average monthly rainfall are used to determine the actual recharge experienced in saturated zones of primary unconfined aquifers. Since water level is influenced by hydrogeological parameters, the average catchment specific yield is used (retrieved from GRA II data set). The catchment aquifer system is balanced by assuming that the average of inflow from recharge is matched by an average outflow consisting of baseflow and evapotranspiration. Uniform abstraction is introduced over the catchment aquifer with incremental time-steps. The maximum abstraction rate is established by setting the maximum average allowable water level drawdown of the catchment aquifer to 5 m above the lowest natural water level. Although different groundwater professionals recommend different allowable maximum average aquifer water levels, 5m below lowest natural water level is considered as a sufficiently conservative approach (reference needed).

The SVF approach is especially useful when limited borehole or wellfield parameters are known, because it uses existing hydrogeological and hydrological data to estimate the average catchment aquifer fluctuation behaviour. When hydrogeological parameters of boreholes and wellfields are known, the Cooper-Jacob Wellfield model is used to determine the drawdown that will occur at the boreholes when pumping. Borehole interference is discouraged and warnings will be given when this occurs.

Desalination Component

Based on literature findings, desalination and reuse are modelled as constant inflow channels. The capacity of the plant is taken as an input parameter. A number of options are considered for integrating desalination and reuse into the water supply scheme:

1. Operating at a constant capacity throughout the year.
2. Operating at varying capacities throughout the year provided that one capacity is maintained for a minimum three-month period, respectively.
3. Operating at three-monthly periods triggered by dam levels; for example, the plant (desalination and or reuse) switches off when dam capacity is more than 70% for at least three months. If the dam capacity becomes lower than 50%, the capacity of the plant is sequentially increased for three-month periods depending on the amount of membrane units present.

System Combination

Each component of the conjunctive use model is integrated into a single daily time-step model. The conjunctive system is evaluated on daily basis to simulate water availability. In order to perform a system balance, inflows from the different components are balanced to the demand. Demand is given in monthly percentages of the draft which are distributed evenly over the days of each month. The order in which the components are used is determined by their associated cost implications as well as environmental constraints.

Therefore, as illustrated by Figure 4, surface water is considered as primary supply source, groundwater as secondary and desalination and reuse as tertiary. After evaluating the dam equation (Equation 1), available surface water is used to satisfy the demand. If demand is not met by surface water, the available abstraction amount from groundwater is used to supply the demand. If both the surface water and the groundwater are insufficient to satisfy the demand, then desalination or reuse will be switched on at a specific starting capacity for three-months.

Evaluating the yield of the system as well as the reliability of supply is crucial to managing water resources sustainably in current and future scenarios. The firm yield of the conjunctive system is determined by iteratively increasing the draft and evaluating the system yield for each draft. This iterative process is used to plot a draft yield line where the historic firm yield point represents the capacity of the system under historical conditions.

The reliability of supply is determined by using the stochastic streamflow sequences. Similar to the firm yield evaluation, the draft is incrementally increased. However, each draft is evaluated for all of the stochastic sequences.

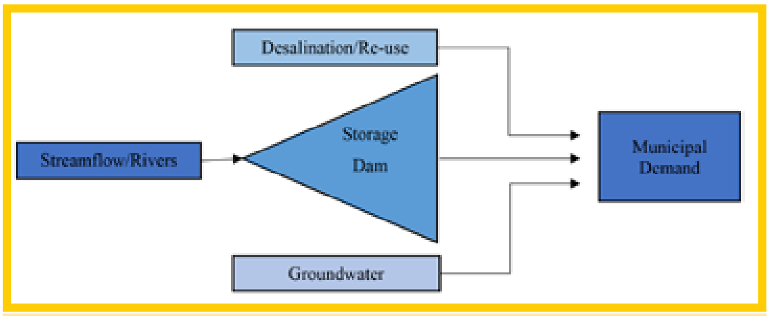

FIGURE 4: Model components to be used in conjunctive water resource model for municipal use

When the draft cannot be supplied by the system, it is considered a failure. The sequences are ranked according to their supply capacity and plotted on a yield reliability curve. After evaluating the system for different drafts for all stochastic scenarios, a long-term reliability of supply can be established for the system.

CONCLUSION AND FURTHER CONSIDERATIONS

Municipalities are the local water service authorities and sole providers responsible for water service delivery. Municipalities are faced with increasing populations, variable climate conditions on finite resources and limited internal management capacity. To relieve some of these challenges, a stochastic, daily time-step conjunctive water resource model was developed. The purpose of the conjunctive use model is to act as a advisory tool capable of analysing the yield and reliability of resources in a municipal supply system.

Modelling principles were identified in the literature review that guided the process of developing the conjunctive use model for surface water, groundwater, desalination and reuse. Monthly streamflow data from WR2012 was used as input to STOMSA software in order to generate monthly stochastic streamflow. The stochastic monthly streamflow sequences were disaggregated into daily flow sequences using high-, medium- and low-flow categories.

The challenge in combining the different water resources was to establish the dominant stochastic links between surface water and groundwater. Groundwater was taken as a recharge dependent resource driven though rainfall events. Rainfall, being stochastic in nature, could be generated from stochastic streamflow using runoff-rainfall relationships. The SVF method was used to describe water level fluctuations due to recharge over a catchment area. The catchment aquifer was taken as a lumped-parameter box-model similar to the Aquifer Firm Yield Model, in which inflow and outflow balance the system and abstraction rates are evaluated by using maximum allowable water level drawdown restrictions. Surface water storage capacity simulation was governed by the dam balancing equation developed for daily time-steps using both historic and stochastic streamflow disaggregated into daily streamflow. Desalination and reuse were incorporated by modelling them as constant supply inflow depending on the monthly operational capacity as percentage of total desalination plant or reuse plant capacity.

The priority ranking in which water resources are utilized to satisfy demand is the following: (1) surface water, (2) groundwater if surface water does not suffice, and (3) desalination and reuse. A series of operational scenarios were developed in order to incorporate the different water resources.

Daily supply storage simulations assist municipalities to manage water resources on a daily basis. Yield and reliability of supply analyses are provided to evaluate the system capacity and assurance of supply so that planning and operational management can be implemented before municipalities experience water supply deficits.

The conjunctive use model remains to be tested and validated on various municipalities to provide reliable results. Further developments include developing full user-friendly interfaces. As first trial, the model will be limited to primary unconfined aquifers that include unconsolidated shallow aquifers as well as fractured and porous aquifers. Recommendations for future additions to the conjunctive use model are aquifer recharge systems.

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