Developing a Surface Water - Groundwater Interaction Model for Letaba River System in South Africa

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Abstract

There is a constant increase in water demand and a pressing need to conserve the environment in the Letaba River system. This is leading to a situation where the demand for water may have outstripped the capacity of the existing resources to sustainably meet them. In the past dams were constructed and boreholes drilled as a strategy of reconciling demand and supply and this is evidenced by the numerous dams and boreholes in the Letaba River system. There are five major dams; three of which have a capacity exceeding 60 million cubic meters and also more than 3000 boreholes in the river basin. Currently, all the dams are stressed and the releases from Tzaneen Dam, intended to meet the water requirements of downstream users including Kruger National Park fail to meet these requirements substantially. Although these demands are high and probably exceed the system's capacity, it is likely that the reliability of supply can be improved significantly if the surface water - groundwater (sw/gw) interactions within the basin are modelled comprehensively and then incorporated into system operation. This paper reports on an ongoing development of a sw/gw model of the Letaba River System. The model development intends to maximize the use of the relevant available information and data and recognizes the existence of an interaction zone which forms a major link of many of the processes that will be included in the model. It has been found that the scale of monitoring processes in the river system is inadequate and is a significant constraint to the development of the model that is expected to impact on the level of confidence in model implementation and application. Incorporation of uncertainties will therefore be an integral part of the modelling.

Keywords: Maximizing data/information usage, surface water - groundwater interaction modelling, uncertainty quantification

1 Introduction

In the Letaba River system (Figure 1) there is constant increase in water demand due to increase in social, economic and environmental activities. These include increase in irrigation activities, mining activities, industries, recreation and the need to maintain the minimum flow requirement for ecological concern. In the past the strategy to reconcile demand and supply was to build dams, hence the government of South Africa constructed

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several dams in the area which include Tzaneen Dam, Ebenezer dam, Middle Letaba dam and Nsama dam for the purpose of storing water for supply during periods of low flow and drought (Katambara and Ndiritu, 2006). Between the year 1995 and 2001, many boreholes were drilled to abstract groundwater. Currently more than 3000 boreholes exist in the area (DWAF 2006). The construction of dams may no longer be a viable option due to several reasons including: limited of availability of funds (Cui and Kuzera, 2003), lack of suitable sites for construction of large reservoirs (Ndiritu, 2005) and increasing mobilization of opposition to large storage project in developing countries (Labadie 2004). The over-use of groundwater is causing the groundwater level to fall below the stream bed level most of the time hence a decline in base flow contribution to streamflow in the area (DWAF, 2006). The effects of over utilization of one source over the other have been discussed (Winter (1995) and Sophorous (2002)). The focus now is on how to optimally operate these two resources in a sustainable manner for the benefit of the current and future generations. Considerations towards this have been done by the South African government by enacting a law (National Water Act 1998) which prioritizes some water uses over others in the country. The human reserve has been given the highest priority followed by the ecological reserve over other commercial water uses. The ecological reserve is the minimum instream flow requirement (IFR) determined at specific sites along the river and it tries to mimic the natural flow for the purpose of ecological sustainability.

In general the dams in the system are stressed, however the releases from Tzaneen Dam are meant to meet the ecological requirements downstream in particular KNP. There have been instances where dam releases to downstream users in the system have been lost before reaching the intended users. One explanation for these losses is the surface water - groundwater interactions which are not well understood and are not allowed for in the operation of the Tzaneen Dam (Katambara et al, 2007). It is envisaged that the comprehensive modelling of the sw/gw interaction and their incorporation in the operation of the Tzaneen Dam will improve the reliability of the supply in the areas downstream of the dam. This paper reports on the current stage of the development of the model for the Letaba River system.

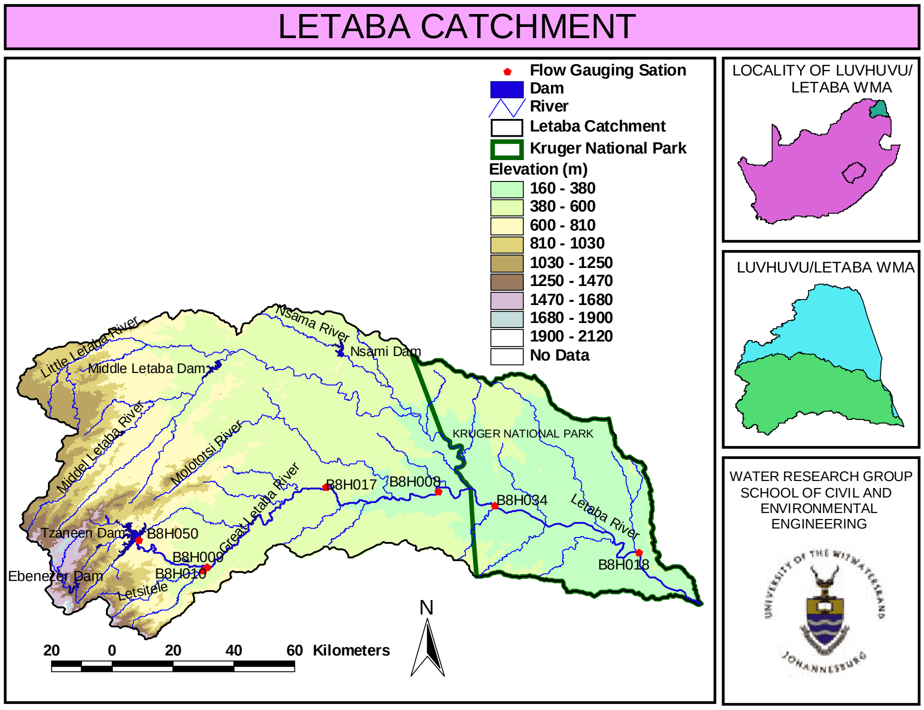


Figure 1: location of the Letaba River system

2 Description of the study area

(a) Location

Letaba catchment as shown in Figure 1 is located in a semi-arid region in the north-eastern part of South Africa and covers an area of 13 669 km^2. The western part of the catchment is a mountainous region with an altitude higher than 2 000 m above mean sea level and gradually decreases towards the eastern part of the catchment to slightly lower than 450 *masl*. The main rivers (i.e. Groot Letaba River and Middle Letaba River) originate from this mountainous region and flow towards lower part of the catchment in the eastern part.

(b) Hydrogeological regions

The catchment can divided into several hydrogeology regions (Figure 2) characterized by fractured aquifers formed mainly by metamorphic basement rocks. Intergranular aquifers with unconsolidated to semi consolidated materials, with primary porosity occur on the Letaba River (DWAF, 2006). The regions are:

- *Escarpment Zone*

The main aquifers in this zone are from fractured rooks which are highly permeable although the storage in these aquifers is very limited. The annual rainfall is above 1000 *mm* and the steep slope of more than 15% causes a high initial contribution in baseflow of 200 *mm/a* and declines rapidly as the larger joints and fractures are dewatered. This has caused about 40% of the boreholes in this area to dry inspite of the fact that there is high recharge rate in the area. The aquifer yield varies from 0.5 *l/s* to 1.5 *l/s* (DWAF, 2006).

- *Drakensberg Foothills and Valleys*

The geology is similar to the Escarpment zone and with slopes generally less than 15%. Annual rainfall in this region ranges between 500 *mm*/a to 1000 *mm/a* and for well sited boreholes, the yield is up to 3 *l/s* but generally ranges from 0.5 *l/s* to 3.0 *l/s* and less than 30% of the bore holes are dry during dry periods (DWAF, 2006).

- *Bandelierskop*

The main aquifer is formed by deep weathering (fractures and faults) at various deformational phases. The rainfall ranges between 500 *mm* and 1000 *mm* annually and the slopes range from 5% to 15%. The borehole yield (mainly for water supply in the region) can go up to 1.5*l/s* and the higher yield are associated with faults zone in the area (DWAF, 2006).

- *Giyani-Gravelotte*

The aquifer is dominated by local fractured materials as a result of the intense folding and associated fracturing. The rainfall lies between 500 *mm* to 600 *mm* annually and the topography is generally flat and also it is steep in ridge where quartzite and ironstone formations outcrop. The boreholes yield varies between 0.5 and 5 *l/s*, with the highest yields occurring in brittle quartzites and is used mainly for human basic requirements (DWAF, 2006).

- *The Plains*

The plains cover 50% of the catchment and are characterised by fractured rocks. The rainfall ranges between 500 *mm* to 600 *mm* annually and the groundwater yields generally vary between 0.5 and 2.0 *l/s*, with localized zones where yields range between 2.0 *l/s* to 5.0 *l/s* and occasionally more than 5 *l/s*. It is in this area where large scale of groundwater abstraction for irrigation purposes takes place. The crops grown includes citrus, mango, avocado, banana, litchi and macadamia nuts. The abstraction has an impact on the groundwater levels resulting in levels that are generally below streambed, hence baseflow is unlikely to be generated (DWAF, 2006).

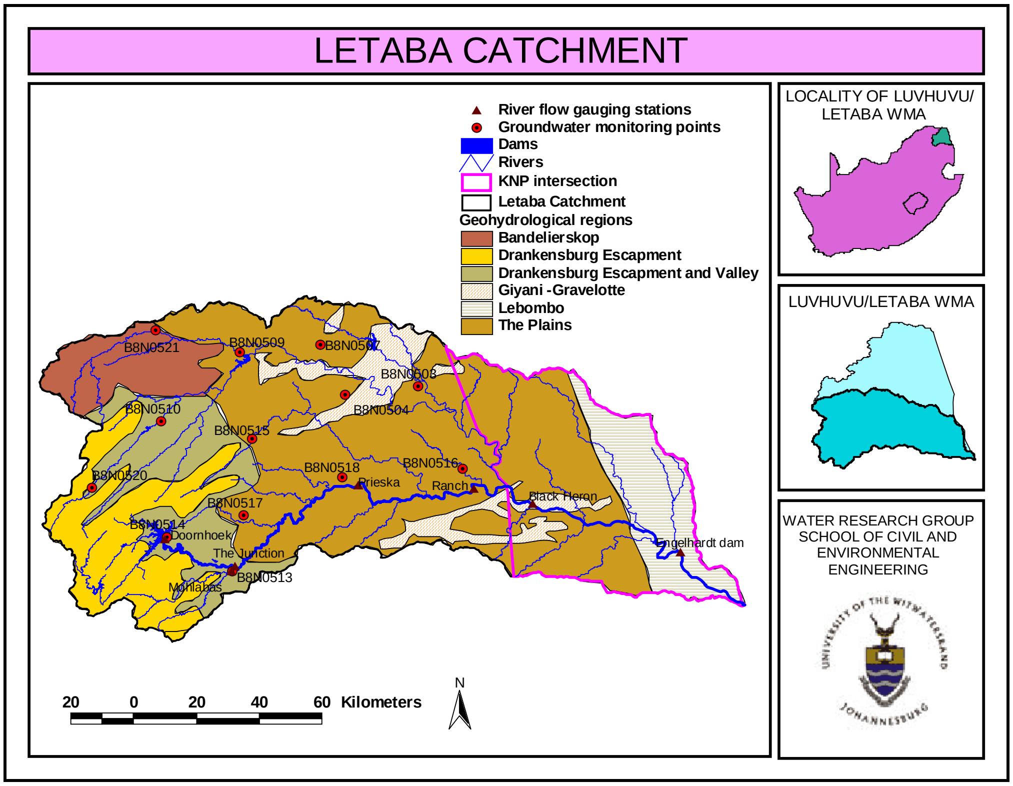


Figure 2: Geohydrological regions of the Letaba Catchment

- *Lebombo*

The eastern part including KNP is underlined by this aquifer and it characterized by thin basal sequence of Clarens formation sandstone overlain by basalts and rhyolites. The borehole yields are generally less than 0.5 to 1.5 *l/s* and a large fraction of the boreholes are dry.

- *Alluvium*

These aquifers are characterized by a saturated alluvium and they exist along the major rivers drainage systems and are composed of unconsolidated clayey silts to coarse gravels and boulders. The aquifer properties are highly variable within short distance (WRC, 2004). The aquifers cover a width of up to more than 500 *m* and a thickness of up to more than 10 *m*. This provides a maximum flow width which controls the opportunity for infiltration during high flow (Alderwish and Dottridge, 1995). The average borehole yield of this aquifer is more than 5 *l/s* and during the rainy season the yield can reach 20 *l/s*. However, the yield diminishes during the dry season if the volume of storage is limited or if there is not enough recharge from the host rock. These aquifers form isolated local aquifers along major river courses and are recharged during periods of high stream flow and discharge to the river once stream stage drops. A delicate equilibrium exists between the surface water and ecosystems present along the river course.

3 Mechanisms of surface water – groundwater interaction

Surface - groundwater water interaction occurs by lateral flow through unsaturated zone, by exfiltration of the subsurface water from saturated zones and by infiltration of the surface water into the subsurface. The mechanism varies both spatially and temporary and it involves water exchange and solute transfer (Newman et al, 2006). Sophocleous (2002) and Rushton and Tomlinson (1995) discussed four conditions necessary for surface water and groundwater interaction to occur. These are:

- The stream is gaining as a result of the groundwater head above the level of river flow
- Neither the stream or groundwater is gaining and the groundwater head and the stream head are at the same elevation
- The stream is losing as a result of groundwater head being slightly below the stream elevation
- The stream is losing due to the groundwater head being below the stream and an unsaturated zone separates the groundwater and the stream flow.

There are times when the stream and groundwater are not connected due to the existence of an impermeable layer below the stream. In such reaches, surface water - groundwater interaction does not exist (Ivkovic, 2004).

The conditions discussed above do not comprehensively represent the situation in semiarid regions like Letaba River system where the catchments are characterised by erosion and deposition along the stream hence creating an alluvium aquifer. Newman et al (2006) discussed four other conditions necessary for surface - groundwater interaction in a semiarid region. These conditions are:

- In the first condition, an alluvium aquifer does not exist along a river reach and all the conditions discussed above can take place.
- In the second condition the alluvium aquifer does exist but the groundwater head is below the stream bed and there is no surface water flowing along the river hence surface water - groundwater interaction does not exist. This condition occurs after or before the next two conditions and is influenced by excessive groundwater abstraction in this zone.
- In the third condition the stream flow replenishes the alluvium aquifer. This can occur when under perennial flow condition, or when episodic flow is initiated in the stream either through a flood pulse coming from upstream tributaries or local overland flow.
- In the forth condition the aquifer contributes to the stream flow as a result of direct lateral input to the alluvium aquifer either from overland flow, riparian zone infiltration, subsurface runoff or spring and seepage contributions. The condition is most likely to be found at the wetter end of the semiarid climate spectrum like higher annual precipitation and higher elevations.

There is no doubt that the last two conditions can occur along the same river reach or can switch back and forth with time at the same location. Hence some reaches can be looked at as a combination of the last two. The second condition can also exist for longer dry periods. A numerical or analytical approach for quantification of these sw/gw interactions requires an assessment of the hydrologic regime (e.g. runoff magnitude, duration, and frequency), the geomorphologic properties of the watershed (e.g. river lengths, widths and drainage density) and the geologic characteristics of the streambed and underlying aquifer (Newman et al., 2006, Sophocleous, 2000).

4 Quantification of surface water - groundwater interaction

The sw/gw interaction for hydraulically connected stream aquifer system is a function of the head difference between the river stage and aquifer head (Sophocleous, 2000). The mechanism is based on Darcy’s law which can be expressed as

$$q = k(h_a - h_r) \tag{1}$$

Where q is the flow between the river and aquifer $(m^3/day/km)$, h_a is the aquifer head (m), h_r is the river stage (m) and k is a constant representing the streambed leakage coefficient $(m^2/day/km)$. During stream flow recession the volume of water has been found to be independent of the leakage coefficient and during high recharge the leakage calculated from equation 1 is much greater than would occur in practice and takes no account of the increased resistance of passage of water as its volume increases (Sophocleous, 2000). Rushton and Tomlinson (1976) suggested a nonlinear relationship to account for increase in resistance at high flows as

$$q = k_1[1 - \exp(-k_2(h_a - h_r))] \tag{2}$$

Where k_1 and k_2 are constants. For small changes in head, equation 2 produces high flow and postulates a maximum flow which can be exceeded as long as the head difference becomes larger (Sophocleous, 2000). Equations 1 and 2 both have different merits with regard to the description of the linkage hence Rushton and Tomlinson (1976) proposed a combination of the linear and nonlinear relationships:

$$q = k_1(h_a - h_r) + k_2[1 - \exp(-k_3(h_a - h_r))] \tag{3}$$

Where k_1, k_2 and k_3 are constants.
High rates of infiltration are experienced in semiarid regions where stream seepage is the source of recharge and the groundwater level is below the streambed most of the time. Equation 2 is the appropriate for such situations. The precise quantification of infiltration and exfiltration depends on the detailed understanding of how these interactions occur and also what controls the interaction (Newman et al., 2006).

5 Uncertainty in modelling

Some physically based models have analytical solutions which involve numerical solutions of systems of partial differential equations (e.g. MIKE SHE). The obtained solution is regarded as an approximate solution due to unaccounted for uncertainty (Brardossy at el, 1995). Loucks and van Beek (2005) classified uncertainty into three main categories: knowledge uncertainty, natural variability and decision uncertainty (Figure 3). The knowledge uncertainty is a combination of the structural uncertainty due to model setup as a result of over simplification and parameter uncertainty due estimation techniques and differences in scale. The natural variability is about the spatial and temporal variability of the model input values (rainfall, evaporation, recharge, groundwater level) due to inadequate monitoring within the catchment and the time variability of the records.. Decision uncertainty is concerned with the future changes in the goals, objectives and the preference in values needed.

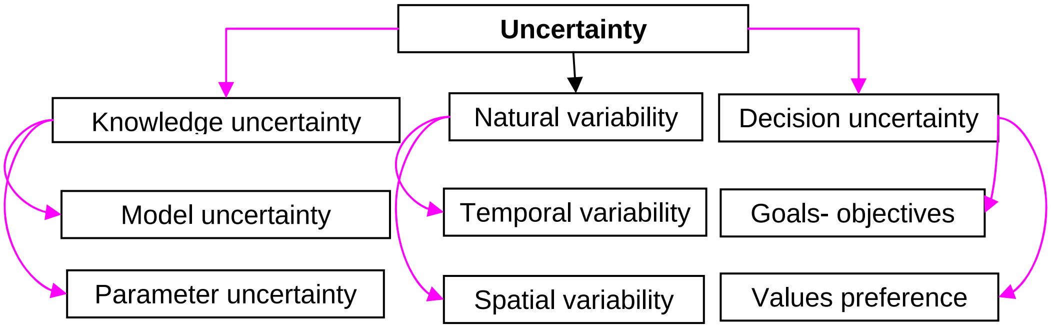


Figure3: Categories of uncertainty

In the Letaba River system, several factors that are likely to affect the model results exist including inadequate scale of monitoring of the stream flow and groundwater. The contribution of the Molototsi river and Klein Letaba river into the Groot Letaba river are not measured and few groundwater monitoring points exist only close to the Letaba River. Traditional uncertainty analysis utilizes probability theory that requires distributional assumptions concerning random variables to be made. Kagoda and Ndiritu (2007) applied the Bayesian inference in modelling extreme rainfall in South Africa in a study that incorporated uncertainty in the analysis. The estimates obtained from Bayesian method were higher than those obtained from Regional Storm Index Method (RSIM) for higher return periods. Lloyd and Atkinson (2001) applied ordinary kriging and indicator kriging in assessing uncertainty in estimates of elevation. It was observed that Indicator Kriging with locally adaptive indicator threshold provided a more accurate guide to uncertainty on local basis than ordinary kriging. Elfeki (2006) coupled Markov chain, a stochastic technique with numerical groundwater flow and transport models applied in the Central Rhine Meuse delta in the Netherlands. The probability distributions used in the coupled Markov chain where generated from the available information. Hence precision of the model depends on the amount of the data available to generate the distributions. The drawbacks with these techniques are the amount of data required to estimate the distribution and computational difficulties arising from multiple convolutions in the usual case of dealing with several non-normal dependent random variables (Bardossy at el, 1995 and Tayfur et al 2003).These drawbacks have provided impetus to opt for a less limiting alternative approach. Heuristic methods like artificial neural networks and fuzzy logic algorithms have been applied in modelling of hydrological processes and could provide alternative approaches. In the field of hydrological processes, artificial neural networks (ANNS) have been employed in modelling rainfall-runoff (Chen and Adams, 2006), water quality (Yoon, 2007) and groundwater (Samani, et al, 2007). The main advantage with artificial neural networks is that the hydrological processes can be synthesized without making use of the detailed and explicit knowledge of the underlying processes. Use of ANNS with limited or noisy training data sets, however, may result in an inconsistent and meaningless output (Tayfur at el 2003). The fuzzy logic algorithm which has the ability to describe the knowledge in a descriptive human-like manner in the form of simple rules using linguistic variables can be used to provide a frame work to deal with uncertainty and vagueness at various levels (Zimmermann, 2001, Xiong et al, 2001). It is less computationally intensive and it can be linked to a numerical or analytical model (Xiong et al, 2001). In hydrological processes, fuzzy logic algorithms have been employed in the estimation of sediment transport from bare soil surface (Tayfur at el 2003). Jacquin and Shamseldin (2006) developed a rainfall-runoff model using Takagi–Sugeno fuzzy inference systems. Superior results were observed from fuzzy inference as compared to a simple linear model.

Other hydrological process studies which have employed fuzzy logic include modelling rainfall-runoff (Vernieuwe, et al 2005), stage discharge relationships (Lohani, et al 2006) and flood forecasting (Xiong et al, 2001).This development of a fuzzy logic algorithm to model the sw/gw interaction acting along the Letaba River is now described.

6 Conceptual Fuzzy logic algorithm for Letaba River

Generally the components of a fuzzy system (Figure 4) are, input data set, fuzzification, fuzzy base rule, fuzzy output engine, difuzzification and output data. Input data sets are prepared, and this involves fixing concurrent dates and filling the gaps using simple methods (e.g. seasonal mean, linear regression). Fuzzification is a process where each input data piece is converted to degrees of membership by applying membership functions. The degree of membership ranges between 0 and 1 inclusive. This allows for the partial belonging of any input data to different subsets rather than to completely one set. There are several ways of assigning the value to membership functions but the intuition approach is most commonly used inference because it is simply derived from the innate intelligence and understanding of human beings (Tayfur et al, 2003). The membership function can take different forms but simple linear functions such as triangular ones are preferable.

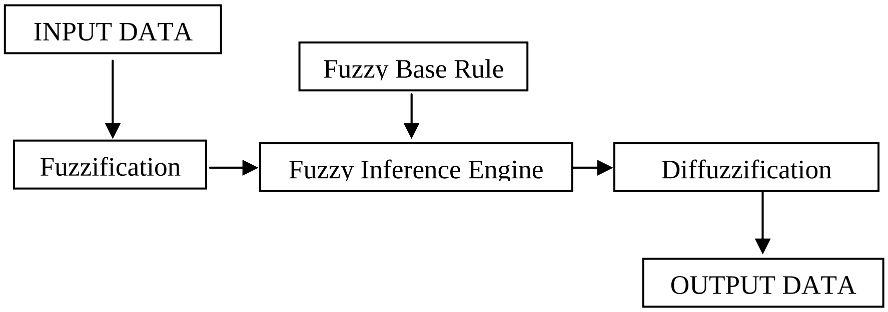


Figure 4 Diagram of fuzzy logic algorithm

Fuzzy base rule contains fuzzy rules that include all possible fuzzy relations between inputs and outputs. There are no mathematical equations and model parameters, however, all the uncertainty and model complications are included in the descriptive fuzzy inference procedure in the form of IF-THEN statements. Fuzzy inference engine takes into account all the possible rules in the fuzzy rules in fuzzy base rule and learns how to transform a set of inputs to corresponding outputs. Deffuzification converts the resulting fuzzy outputs from the fuzzy inference engine using either, weighted average, maximum membership, average maximum membership or center of gravity into a number (crisp output).

7 Model setup for Letaba River system

The objective of the model is to provide the outflow from a reach given the inflow, the rainfall, the evaporation, the groundwater levels and water abstractions in the reach. The Letaba River system is subdivided into reaches to account spatial variability and to optimize on data utilization. Considering Tzaneen dam releases as the inflows in the first reach, the outflows obtained from an upstream reach then become inflows for the neighbouring downstream reach. The setup of the fuzzy logic model for the Letaba River is described in the schematic of Figure 5.

This model will be setup for the whole river section from the gauging station B8H050 which measures releases from the dam to the out flow in the KNP. The four units will be linked, the outflow from B8H054-B8H009 will be an inflow to the link B8H009-B8H010-B8h017. The outflow from B8H009-B8H010-B8h017 will be an inflow to B8H017-B8H008 and an outflow from B8H017-B8H008 will be an inflow to B8H008-B8H034. The last reach of the model, B8H008-B8H034 is used to explain how the fuzzy logic modelling will be set up.

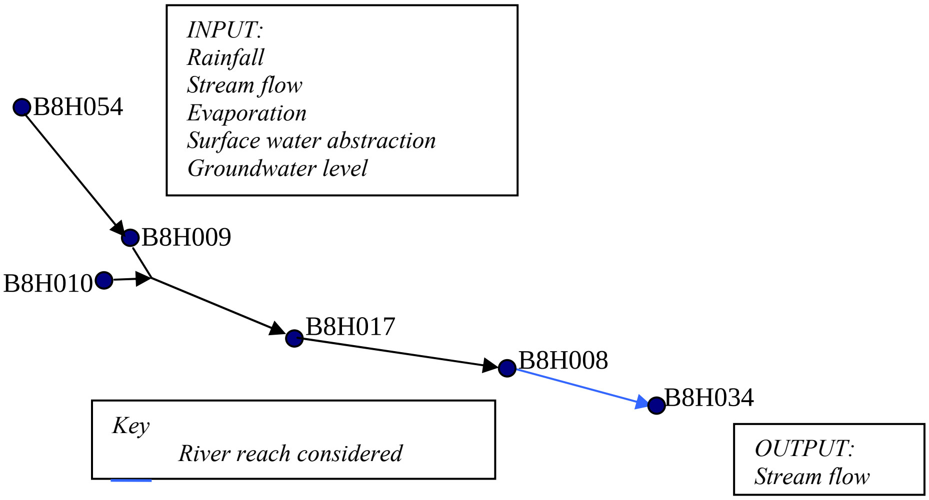


Figure 5: Sketch of the network for model in the Letaba River system

The rainfall, groundwater, and evaporation data sets were obtained from stations 0681249W, B8N0516 and B8E008 respectively (see Figure 2). Linear triangular functions are selected for modelling the degree of membership and the stream flow dataset recorded at Black Heron (Figure 6) is used to illustrate their formulation. Any flow less than 2.5 m^3/s is considered very low (VL) and the degree of membership is higher for flows records close to zero (Figure 7a). Other subsets includes low (L), medium (M), high (H) and very high (VH). This will also be done to the total stream flow abstraction along the given river reach.

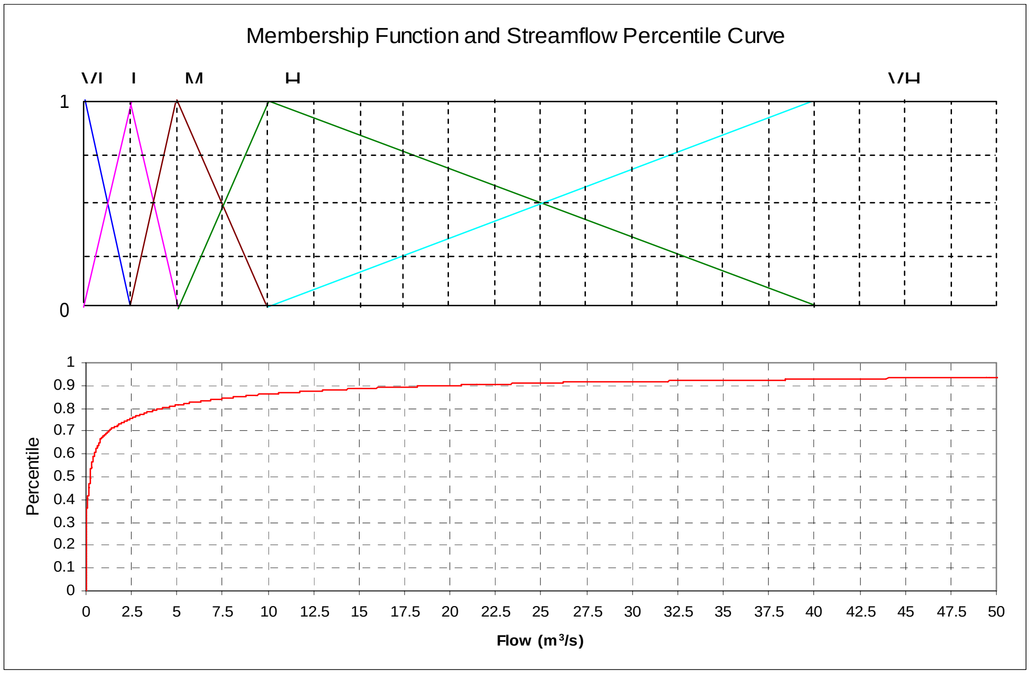
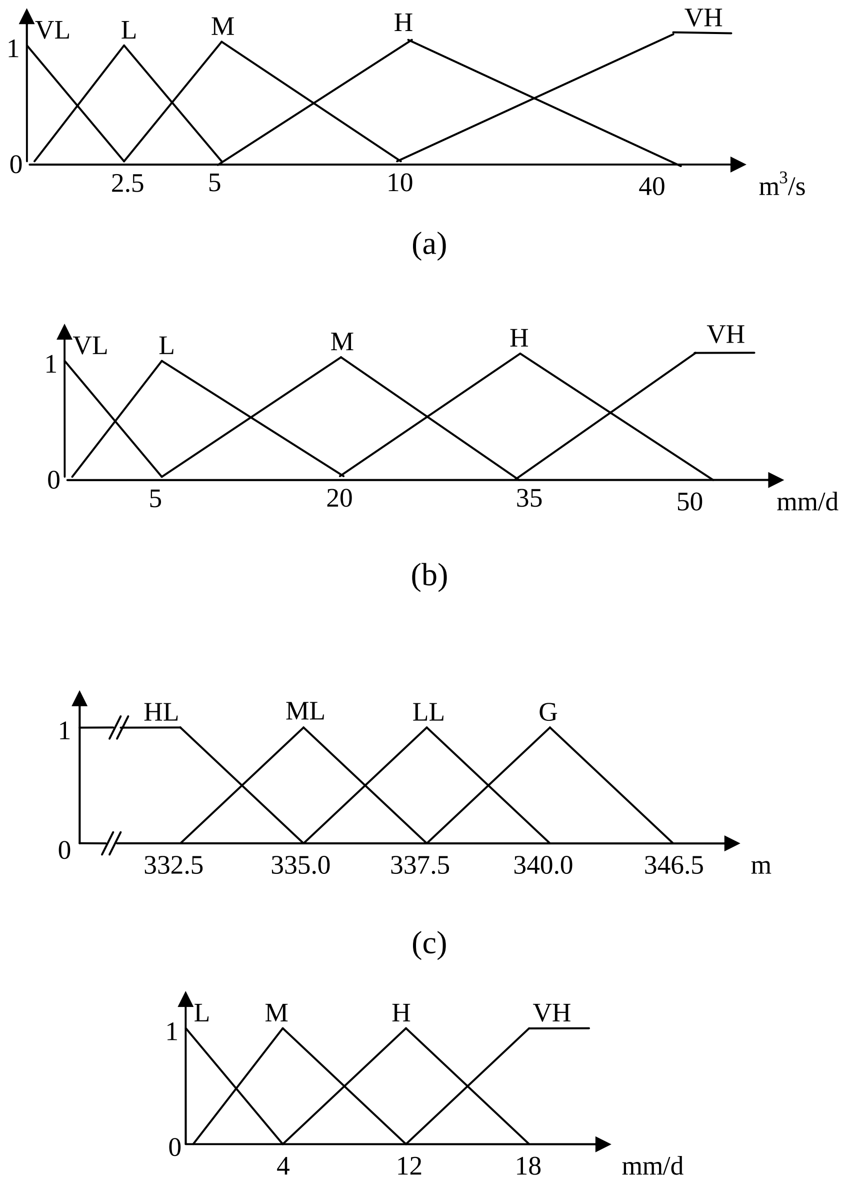


Figure 6 Membership function and the percentile curve for streamflow (m^3/s) at Black Heron.

Membership functions for rainfall, evaporation groundwater level and the output stream flow are formulated in a similar manner and are also presented in Figure 7. Water abstraction data is not yet available and is therefore currently not included.



(d)

Figure 7 Fuzzy subsets for a section between the Ranch and Black Heron for (a) stream flow, (b) rainfall (c) groundwater level and (d) evaporation

The fuzzy rules relating the input (e.g. rainfall, stream flow, groundwater level, surface water abstraction and evaporation) and output (stream flow) are developed based on the available data. The rules are expressed in the IF-THEN format where the antecedent part (control variable) of the rule starts with the IF and the consequent part (output variable) starts with THEN. Equation 4 is an example of a rule.

R_r: IF(inflow is L AND rainfall is L AND evaporation is L AND gw level is LL) THEN outflow is L (4)

where R_r is the inference rth rule, inflow, rainfall, evaporation and gw level are variables in fuzzy inference and each value corresponding to a particular portioned domain (e.g. stream flow: VL, L, M, H, VH). In the case of equation 3, the number of input variables is four (stream flow, rainfall, gw elevation) and the output (outflow) of the *r*th IF_THEN inference rule R_r. is portioned into portions as the input.

The portioning of the input variables x_i is based on the subsets membership value $m_r^{(1)}$ within the particular subset. Hence for every inference rule the variables used have some degree of membership within the particular subset. Then, the degree of membership which can be represented by a symbol α_r for a given inference rule is defined as the minimum values for the degrees of membership from the subsets within the rule.

$$\alpha_r = \min\left(m_r^{(1)}(x_1), m_r^{(2)}(x_r), \dots m_r^{(p)}(x_p)\right) \tag{4}$$

Fuzzy logic assumes that for every given rule there is an output which can be represented as a linear function. The output value dependents on the input values and can be represented as

$$y_r = f\left(x_1, x_2, \cdots, x_p\right) = a_r(0) + a_r(1)x_1 + a_r(2)x_2 + \dots + a_r(p)x_p = a_r(0) + \sum_{j=1}^{p} a_r(j)x_j \tag{5}$$

where a_r are coefficients of the output function. The coefficient can be obtained by the method of least square or be optimized using any optimization technique.

The final process, defuzzification, converts the output from the fuzzy inference rules into a crisp output y using weighted mean and is given as

$$y = \frac{\sum_{r=1}^{k} \alpha_r y_r}{\sum_{r=1}^{k} \alpha_r} \tag{6}$$

9 Concluding remarks

The river losses associated with sw/gw interaction tend to reduce the reliability of a river system. The quantification of the losses sometimes poses challenges to the river system operators and modellers as well. This is especially so in cases where the available data is inadequate in terms of the scale distribution. The hydrological processes acting along the river are complex but if their mathematical representation in model is simplified there is risk of failure to capture the relevant components adequately. Zimmermann (2001) noted that as the complexity of a system increases, the ability to make precise and yet relevant statements about the system diminishes until the precision and relevance becomes mutually exclusive beyond a certain point. Furthermore, he recommended on the application of the fuzzy set theory in modelling complex systems because of its capability to provide a frame work to deal with uncertainty and vagueness at various levels of modelling. The application of the fuzzy logic algorithm in modelling the sw/gw interaction and evapotranspiration losses discussed herein is because the data and the monitoring in the system are inadequate. It is envisaged that the completion of this model will further demonstrate the application of fuzzy logic in hydrological process modelling.

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References

Alderwish, A., Dottridge, J., (1995) Modelling infiltration from ephemeral wadi flows in the Sana's basin, Yemen. In: Younger PL (ed) Modelling river-aquifer interactions. British Hydrological Society Occasional paper 6, ISBN 0 948540 70 2, pp 4-16.

Bardossy, A., Bronstert, A., and Merz, B., 2005, 1- 2- and 3-dimensional modelling of water movement in the unsaturated soil matrix using a fuzzy approach, Advances in Water Resources 18 (4) 237-251.

Chen, J. and Adams, B. J. (2006), Integration of artificial neural networks with conceptual models in rainfall-runoff modeling, Journal of Hydrology, 318 232–249.

Cui L and Kuczera, G., (2003), Optimizing urban water supply headworks using probability search method, Journal of Water Resources planning and Management ASCE 129 (5) 350-387.

Department of Water Affairs and Forestry (DWAF) (2006), Letaba catchment reserve determination study, Report RDM/B800/01/CON/COMP/1304.

Elfeki, A. M. M, (2006), Reducing concentration uncertainty using the coupled Markov chain approach, Journal of hydrology 317 1-6.

Ivkovic, K. M., Letcher, R. A. and Crooke B. F. W., (2004) Groundwater-river interactions in the Namoi catchment, New South Wales (NSW) and their implications water allocation, 9th Murray –Darling Basin Groundwater Workshop, Australia

Jacquin, A. P. and Shamseldin, A. S., (2006), Development of rainfall-runoff models using Takagi-Seguno fuzzy inference system, 329 154-173.

Jacquin, A. P., and Shamseldin A.Y., (2006), Development of rainfall–runoff models using Takagi–Sugeno fuzzy inference systems, Journal of Hydrology 329 154– 173

Kagoda and Ndiritu (2007), Assessment of Bayesian inferential techniques for rainfall frequency analysis in South Africa, Proceedings of the 13th SANCIAHS Conference, Cape Town, South Africa.

Katambara Z. and Ndiritu J.G (2006), Optimizing the operation of the Letaba River system including comprehensive surface/groundwater interaction, Proceeding of the 2nd Water Research Showcase, Pretoria, South Africa, 2 25-27

Katambara, Z., Hattingh, L., Mwaka, B., Sinha, P., Boroto, R.J., and Ndiritu J. G., (2007), Challenges in operating the Letaba River System in South Africa: A way forward, Proceedings of the 13th SANCIAHS Conference, Cape Town, South Africa.

Labadie, J.W., (2004), Optimal operation of multireservoir systems: State- of-the-art review, Journal of water Resources Planning and Management, ASCE 130 (2) (93-111).

Lohani, A. K., Goel, N. K. and Bhatia, K. K. S. (2006) Takagi –Sugeno fuzzy inference system for modelling stage-discharge relationship, Journal of Hydrology 331 146-160.

Loucks, D.P., and van Beek, E., 2005, Water resources system planning and Management: An introduction to methods, model and application, United Nation Educational, Scientific and Cultural Organization, Delft, Netherlands, ISBN 92-3-103998-9.

Ndiritu, J. G., (2005), Maximising water supply yield subject to multiple reliability constraints via simulation-optimization, Water SA, 34 (4) (423-433).

Newman, B.D., Vivoni, E. R., and Graffman, A. R., (2006) Surface water-groundwater interaction in semiarid drainages of the American southwest, Hydrological Processes, 20, 3371-3394.

Parson, R., (2004), Surface water-groundwater interaction in a Southern Africa context, Water Resources Commission, WRC report No TT218/03.

Republic of South Africa, (1998), National Water Act 1998 No. 36 of 1998, Government Gazette 398 19182.

Rushton, K. R., Tomlinson, L. M., (1979), Possible mechanisms for leakage between aquifers and rivers. J Hydrol 40:49–65.

Samani, N.,. Gohari-Moghadam, M., and Safavi, A. A., (2007), A simple neural network model for the determination of aquifer parameters, Journal of Hydrology 340, 1– 11.

Sophocleous, M., (2002), Interaction between groundwater and surface water: the state of science, Hydrogeology Journal 10 (52-67).

Tayfur, G., Ozdemir, S. and Singh, V. P., (2003), Fuzzy logic algorithm for runoff-induced sediment transport from bare soils surface, Advances in Water Resources 26 1249-1256.

Vernieuwea, H., Georgievab, O., De Baetsa, B., Pauwelsc, V. R. N., Verhoestc, N. E. C. and De Trochc, F. P., (2005), Comparison of data-driven Takagi–Sugeno models of rainfall–discharge dynamics, Journal of Hydrology 302 173–186.

Winter, T.C., 1995. Recent advances in understanding the interaction of groundwater and surface-water. Rev. Geophys. 33, 985–994.

Xiong, L., Shamseldin, A. Y. and O'Connor, K. M., (2001), A non-linear combination of the forecast of rainfall-runoff models by the first-order Takagi-Seguno fuzzy system, 245 196-217.

Yoon, H., Hyun, Y. and Lee, K (2007), Forecasting solute breakthrough curves through the unsaturated zone using artificial neural networks, Journal of Hydrology 335, 68–77.

Zimmermann, H. J., (2001), Fuzzy set theory and its applications, Kluwer academic Publisher, USA ISBN 0-7923-7435-5.