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An approach to measure parameter sensitivity in watershed hydrological modelling

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Abstract

Hydrological responses vary spatially and temporally according to watershed characteristics. In this study, the hydrological models that we developed earlier for the Little Miami River (LMR) and Las Vegas Wash (LVW) watersheds in the USA were used for detailed sensitivity analyses. To compare the relative sensitivities of the hydrological parameters of these two models, we used normalized root mean square error (NRMSE). By combining the NRMSE index with the flow duration curve analysis, we derived an approach to measure parameter sensitivities under different flow regimes. Results show that the parameters related to groundwater are highly sensitive in the LMR watershed, whereas the LVW watershed is primarily sensitive to near-surface and impervious parameters. The high and medium flows are more impacted by most of the parameters. The low flow regime was highly sensitive to groundwater-related parameters. Moreover, our approach is found to be useful in facilitating model development and calibration.

Keywords

Sensitivity analysis; HSPF; NRMSE; flow duration curve; model development; model calibration

Introduction

1.1 Sensitivity analysis in watershed hydrological modelling

Watershed hydrological models are a simplification of reality, and they are mostly based on conceptual representations of the physical processes that govern the flow of water through and over the soil. Parameters for such models are generally related to soil properties, vegetation characteristics, topographic properties, stream characteristics, crop characteristics, climate, and atmospheric conditions (Bergström and Graham 1998). Typically, there are two types of parameters: “physical” parameters and “process”

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parameters. Physical parameters represent physically measurable properties of the watershed, such as the area of the watershed, stream length, surface slope, and impervious surface percentage. The watershed properties that are not directly measurable are characterized as process parameters. Examples of such properties include near-surface soil moisture storage, groundwater recession rate, deep percolation to the groundwater storage, and lateral interflow rate (Sorooshian and Gupta 1995).

Since the hydrological responses in a watershed vary both spatially and temporally, it is important for water resource managers and planners to identify the dominant characteristics and processes controlling watershed hydrology. One approach to gain this understanding is through sensitivity analysis. In watershed hydrological modelling, sensitivity analysis evaluates the hydrological influences of certain hydrological parameters on simulation outcomes of the models (Hornberger and Spear 1981, Freer *et al.* 1996, Wagener *et al.* 2001, Liang and Guo 2003, Hall *et al.* 2005, Sieber and Uhlenbrook 2005, Pappenberger *et al.* 2006, Tang *et al.* 2007).

Traditionally, sensitivity analysis is performed at the beginning of model development to facilitate the identification of the most influential and the least important model parameters (Hamby 1994). As such, they are valuable tools for simplifying and improving model structure (Cariboni *et al.* 2007). Besides, they can be used to test model adequacy, relevance, and conceptualization, as well as to examine if the model behaves according to underlying assumptions (Ma *et al.* 2000, Wagener *et al.* 2003, Tang *et al.* 2007). They can also provide valuable information on model calibration by allowing the modeller to identify the parameters that are most responsible for the hydrological behavior of the watershed (Christiaens and Feyen 2002). In addition, sensitivity analysis can be used in post-processing to identify the hydrological impacts from any alteration of watershed properties. These analyses are useful in devising watershed protection strategies by helping to identify any unrecognized problems that affect watershed hydrology. Furthermore, sensitivity analyses can enhance the efficiency in model application and facilitate the determination of priorities for future research and field measurements (Sieber and Uhlenbrook 2005, Bahremand and De Smedt 2008). As Doherty and Hunt (2009) noted, another possible use of the sensitivity analysis is in evaluating the potential use of a complex, detail model in addressing one or more issues facing a particular study area.

1.2 Comparing parameter sensitivities to different watersheds and different flow regimes

In many studies, sensitivity analyses are conducted in one watershed, and the model parameter sensitivity is analysed over the entire flow regime for the simulation period or for a specific season. However, to have a better understanding of the intricate relationships of watershed hydrological processes under different environments, there is a need to compare the sensitivities of the parameters in different watersheds and in different flow regimes. Since stream flows in different watersheds are not the same, the sensitivity of each parameter in the model may vary between different watersheds with different flow regimes. Besides, different watersheds may have different forms of time series data. Hence, it may not be feasible to directly compare and capture the level of sensitivity of model parameters between multiple watershed models. The same problem can also arise when comparing

sensitivity between different flow regimes in one model. For this limitation, it is necessary to apply a standardization method.

In hydrological modelling, the root mean square error (RMSE) (Chu and Shirmohammadi 2004, Singh *et al.* 2005, Vazquez-Amábile and Engel 2005) is a commonly used error index for evaluating the local sensitivity of model parameters. In general, the lower the RMSE value, the better the model performance. However, the value of RMSE is also dependent on the magnitudes of each occurrence, such as the daily flow values in our study.

To standardize the error index, Moriasi *et al.* (2007) has applied baseline standard deviation and used the RMSE-observations standard deviation ratio (RSR). Another similar approach is normalized RMSE (NRMSE). It is a standardization method for estimating the ratio between RMSE and a range of baseline data by normalizing all the RMSEs to a comparable scale. As a powerful index, which generates a standard value for time series with different levels of magnitudes, NRMSE has been widely applied in various fields, such as artificial neural network analysis (ANN) (Plutowski 1994), climatology (Kim and Valdés 2003), hydrology (Kourgiyalas *et al.* 2008, Su *et al.* 2008), market predictability analysis (Qian and Rasheed 2004), and image analysis (Nayak *et al.* 2004, Guizar-Sicairos *et al.* 2008). In this study, we used NRMSE as an index to estimate the relative sensitivity of the parameters among different hydrological models and to evaluate and compare the parameter sensitivities among different flow regimes in each of these models.

1.3 The use of sensitivity analysis in HSPF models

Among the many watershed hydrological models in use today, the Hydrological Simulation Program–FORTRAN (HSPF) (Bicknell *et al.* 2001) is one of the most common ones (see for example the work of Johnson *et al.* 2003, Albek *et al.* 2004, Singh *et al.* 2005, Donigian and Love 2007, Mishra *et al.* 2007, Fonseca *et al.* 2014). To attain a more accurate simulation of watershed hydrology using the HSPF model and to assist the HSPF modellers in their model development and calibration, it is imperative to have a better knowledge of the model parameters, their influences under different flow conditions, and their relative sensitivities to the overall watershed hydrology. There have been some studies on analysing parameter sensitivity in HSPF. There are also studies that estimate parameter sensitivity under different flow regimes using other watershed models, such as the Soil and Water Assessment Tool (SWAT). Cijin *et al.* (2010), for example, have shown that the SWAT model that they have developed is more sensitive to soil evaporation coefficient under low streamflow conditions than under high streamflow conditions. However, relative parameter sensitivities between different flow regimes and among different watersheds in the HSPF model are yet to be elucidated.

1.4 Research objectives

In our earlier studies (Tong *et al.* 2012, Ranatunga *et al.* 2014), we developed two HSPF models for two watersheds with different watershed hydroclimatic settings, the Little Miami River (LMR) watershed and the Las Vegas Wash (LVW) watershed. (Fig. 1 shows the spatial locations and land use/land cover of these two study areas.) The original HSPF hydrological models were used to study the hydrological impacts of climate and land-use changes. The

results reveal that the hydrological effects of different watershed characteristics and processes are different in different watersheds with different climate and land-use conditions. In this study, in order to improve our original models and to attain better information for water resource management for the study areas, we investigated the relative sensitivity of various parameters in our models. Since the distributions of flow regimes in these two watersheds are not the same, we also evaluated the relative sensitivities of the model parameters under different flow regimes. To further our understanding of the relationships between watershed characteristics and the hydrology of these two watersheds, we compared the differences in the relative sensitivities of the model parameters in each watershed by using the NRMSE index, an index that will not be affected by the magnitudes of stream flows.

When compared with other methods of sensitivity analysis for measuring local and global sensitivities, the approach used in this study is innovative in the way that the parameter sensitivity under different flow regimes is considered. Moreover, the sensitivity index was used to compare the hydrological responses in different watersheds. Hence, our approach provides a more comprehensive and detail analysis. The specific aims of this study were to evaluate the relative sensitivity of each model parameter for the watershed processes: (a) under two hydroclimatic conditions, and (b) over different flow regimes.

With this analysis, the most appropriate watershed characteristics and properties for managing the hydrological behavior in each watershed were identified. These results can help to further our understanding of the watershed hydrology in the study areas. Besides, they can help to improve our hydrological models and any future modelling activities, especially in model development and calibration, in the study areas or other watersheds with similar climatic and watershed characteristics and settings. The results can also be used to obtain information on the behavior of HSPF parameters as well as on other related parameters in other watershed models (such as SWAT) under different flow regimes.

2 Methods

2.1 HSPF hydrological modelling

The most important step in watershed hydrological simulation is to select an appropriate hydrological model based on the scale of application, data demand, and computing requirements. In our earlier studies, we used the HSPF model (Bicknell *et al.* 2001) from the Better Assessment Science Integration Point and Nonpoint Sources (BASINS) (USEPA 2012).

The HSPF model is a continuous, watershed-scale hydrological model developed to simulate the hydrological and water quality processes in natural and manmade water systems (Bicknell *et al.* 2001). The model combines a set of parameters relating to different factors, such as the time series of rainfall, temperature, and evapotranspiration, and other parameters related to land-use patterns, soil characteristics, and agricultural practices, to simulate the processes that occur in a watershed. By representing a watershed as a collection of land segments and channels (reaches) and subdividing the watershed into sub-watersheds, HSPF uses a mass balance approach, where water and its quality constituents are routed through

appropriate pathways. It is a lumped parameter model with a modular structure. As such, it has several modules and submodules to simulate various processes in each sub-watershed. The module PERLND is used to simulate the processes that occur on pervious land areas, which have an appreciable amount of water infiltrating the ground. The IMPLND module is used for impervious land areas, such as paved urban surfaces, where infiltration is negligible. The RCHRES module is used to simulate processes occurring within the water bodies, such as streams and reservoirs. The submodules PWATER and IWATER simulate runoff from PERLND and IMPLND, respectively; and the submodule HYDR routes water through the RCHRES. Figure 2 illustrates the conceptual hydrological model in HSPF. It depicts the processes and properties included in the three modules and submodules (Johnson *et al.* 2003).

In the HSPF model, most parameters are process parameters. They represent the physical properties of various variables and/or processes among these variables and their properties. Derived from the Stanford Watershed Model (UESPA 1999), these parameters and their relationships with other parameters and physical and hydrological variables are summarized in various formulae. For example, the parameter INFILT is the mean soil infiltration rate index. It is used as an indicator to represent the effective moisture from surface precipitation and subsurface flow and storage. A high INFILT value will add more water into the lower zone and groundwater and will result in a lower surface flow. Whereas a low INFILT value will produce more upper zone and interflow storage and a higher direct surface flow (Equation (1)):

$$PERC = 0.1 * INFILT * INFFAC * UZSN \left[\frac{UZS}{UZSN} - \frac{LZS}{UZSN} \right]^3 \quad (1)$$

where PERC is the infiltration volume in the topsoil (mm/interval), INFILT is the infiltration index (mm/h), UZSN is the nominal upper zone storage (mm), and UZS and LZS are upper and lower zone storage (mm), respectively.

The parameter LZSN is the nominal soil moisture storage in the lower zone of the soil layer. This parameter is related to both regional precipitation patterns and soil characteristics. When LZSN is high, the infiltration increases, and surface runoff decreases:

$$I = \frac{INFILT}{\left[\frac{LZS}{LZSN} \right]^{INFEXP}} * INFFAC \quad (2)$$

where I is the mean infiltration capacity, INFILT is the infiltration parameter, LZS is the lower zone storage (mm), INFEXP is the exponent parameter that is greater than 1, and INFFAC is the factor that accounts for frozen ground effects (when applicable). The parameter AGWRC is the groundwater recession rate. It is the ratio of current groundwater discharge to that from 24 hours earlier when the groundwater recession flow (KVARY) parameter is set to zero. AGWRC can be represented by the following formula:

$$AGWO = KGW * AGWS * (1.0 + KVAR * GWVS) \quad (3)$$

where AGWO is the baseflow generated from a land segment (mm), AGWS is the active groundwater storage (mm), GWVS is the antecedent index increased by drainage to AGWS, KVAR is the groundwater recession flow parameter that describes nonlinear groundwater recession rate, KGW is represented as $1.0 - (AGWRC)^{dt/24}$ and dt is the change in time. Further descriptions of the other parameters and their formulae can be found in the BASINS technical and training documentation (USEPA 1999, 2000).

2.2 Development of the LMR and LVW watershed models

As Tong *et al.* (2012) and Ranatunga *et al.* (2014) have already discussed in detail the development, calibration, and validation of the LMR and LVW HSPF hydrological models, in this paper we only provide a summary description of the model development procedures.

2.2.1 The LMR hydrological model—Originating to the southeast of Springfield in southwestern Ohio, the 169.78 km long LMR is a major tributary of the Ohio River. Its watershed is predominantly agricultural with a draining area of about 5840 km². The watershed has a cool temperate climate; summers are warm and humid with a high temperature of 30°C and a low temperature of 15°C, while winters are moderately cold with a few winter frosts and an average annual snowfall of 50–76 cm. The average annual precipitation for the area ranges from 90 to 110 cm; about one-third of the precipitation becomes surface runoff (Debrewer *et al.* 2000, Tong *et al.* 2012). Most of the area in the watershed is flat to gently rolling with steep-walled river valleys. The northern portion of the watershed is characterized by gently sloping land, low gradient streams, and areas of fertile soil. In the southernmost areas, the terrain is mostly dissected and hilly with a higher stream density and more drainage problems (Debrewer *et al.* 2000). Formed from silt, alluvial, and residual materials from the glacial deposits, the soils are deep and highly productive but susceptible to erosion (Lerch *et al.* 1975). Soils in the southeast older till plain are less extensively cultivated than the younger till-derived soils in the northwest. Figure 3 is a soil map of the LMR watershed.

To develop the base HSPF model for the LMR watershed, various data were first retrieved from the metadata sets through the BASINS interface. The watershed was then delineated using the eight-digit hydrological unit code (HUC), stream reach file coverages (RF3), and digital elevation model (DEM) at 30 m × 30 m resolution. The meteorological data (from January 1980 to December 1984), soil data, and land-use/land-cover data of the delineated watershed were compiled and imported to the HSPF model to run the simulation. The model was calibrated by comparing the simulated results with the observed daily flow records from the USGS gauging station near Milford, OH, and adjusting the model parameters, including lower zone nominal soil moisture storage (LZSN), index to infiltration capacity (INFILT), base groundwater recession (AGWRC), fraction of groundwater inflow to deep recharge (DEEPR), upper zone nominal soil moisture storage (UZSN), interflow recession parameter (IRC), length of overland flow (LSUR), Manning's n (roughness) for overland flow (NSUR), and retention (interception) storage capacity (RETSC), iteratively by trial and

error until acceptable results were attained. After many attempts, the calibration results of the LMR model finally showed a correlation coefficient between simulated and observed flows of 0.88 and a Nash-Sutcliffe model efficiency coefficient, E (Nash and Sutcliffe 1970), of 0.69. The validation period for the model was from January 1985 to December 1989. The validation results showed a 0.91 correlation coefficient and an E statistic of 0.72.

2.2.2 The LVW hydrological model—Located in southern Nevada, the LVW is the main channel conveying water from the Las Vegas Valley to Las Vegas Bay, an arm of Lake Mead. The flow of the LVW is mostly composed of treated domestic and industrial wastewater effluents. However, the amount of point source discharge is rather constant; as such, this input of water can be regarded as “baseflow”, and the fluctuations in the flow regime are basically attributed to dry and wet weather runoff and groundwater seepage (Piechota and Bastista 2003).

The LVW watershed is a predominantly urbanized watershed of approximately 4850 km² in aerial extent. The climate of the valley is hot and arid. The average annual precipitation is about 106 mm, and it occurs mostly as high-intensity, short-duration storms in July and August and low-intensity rainfall in winter months. The average monthly temperature ranges from 9°C to 34°C, and the normal average annual temperature is about 21°C. The average daily relative humidity ranges from 32% to 56% in mid-winter and from 11% to 28% in mid-summer. Evapotranspiration is high because of the high summer temperatures, high solar radiation, cloudless skies, low humidity, and the frequent high summer wind (Morris *et al.* 1997, Stave 2001). The soils of the Las Vegas Valley are composed of gravel, windblown sands, and fine grained silts and clays (Fig. 4). The soils on the valley floor typically have low field capacity and high permeability (BLM 2004).

Similar to the LMR model, the base LVW HSPF model was developed by delineating the watershed according to the eight-digit HUC watershed boundaries, RF3, and DEM at 30 m × 30 m resolution. Data, including the meteorological records for 1991 to 2002 water years (starting from October), soil data, land-use/land-cover information, and point source discharge were imported into the HSPF model and run as the base model. After the LVW model had been developed, it was further calibrated. The calibration period for the model was from October 1991 to 1995. This period was chosen because it represented both dry and wet years. Model calibration was performed by comparing the simulated flow with the observed daily flow records from the USGS gauging station at the Las Vegas Boulevard, Henderson, NV, and iteratively adjusting the values of the parameters, such as LZSN, INFILT, AGWRC, DEEPFR, UZSN, IRC, NSUR, LSUR, and RETSC.

At each step, model performance was evaluated, and the calibration proceeded until the simulated values closely matched the monitored records. For the LVW model, the final calibration results show a correlation coefficient of 0.97, and the Nash-Sutcliffe model efficiency coefficient, E , is 0.94. The model was further validated for the water years of 1998 to 2002. The validation results show a correlation coefficient of 0.9 and an E of 0.89.

2.3 Model parameter selection

The parameters that we used to calibrate the LMR and LVW models (see Section 2.2, as well as Tong *et al.* 2012 and Ranatunga *et al.* 2014) were further employed in this study for sensitivity analyses. Altogether, there were nine HSPF model parameters. According to the information provided by the HSPF model technical notes (USEPA 2000) and literature (Abdulla *et al.* 2009, Donigian and Love 2007, Mishra *et al.* 2007, Fonseca *et al.* 2014), these parameters were the most important ones to capture the major hydrological processes that occur in the watersheds. Among the nine module parameters, six were from PERLND, and three were from IMPLND. Table 1 summarizes the selected parameters, their definitions, and the range of values (minimum to maximum) for each parameter. The category of the watershed processes (for example, groundwater, soil, land use, climate, geology, topography, and surface conditions) is also given. Moreover, the calibrated parameter values used in the model for each watershed are listed. These were the values derived by the iterative process of parameter evaluation and adjustment. The models with the values of these calibrated parameters were considered as the base models, and their simulation results were defined as the “base case”. The parameter sensitivities were estimated in reference to these base cases.

2.4 Parameter sensitivity estimation

To examine the relative sensitivities of these nine selected parameters to watershed hydrology, both the LMR and LVW models were run by changing the values of each chosen parameter separately while holding the base values of the rest of the parameters. The values of each chosen parameter were changed by 25% increments, starting from its minimum and up to its maximum. As such, this is the 25% perturbation from the mean values, increases and decreases, for each model parameter. Thus, each model parameter was tested six times, including the base model value. Since there were nine parameters to be tested, we performed 54 model scenario runs for each watershed model. The daily flow outputs were recorded for each run for these 54 runs.

2.5 Defining flow regimes using flow duration curve analysis

River flow regimes can be defined using qualitative descriptions or a wide range of quantitative values. The latter is referred to as flow duration curve analysis. It is a method involving the analysis of historical flow data. A flow duration curve generally illustrates the percentage of time, or probability, that flow in a stream will equal or exceed a particular value. Consequently, the duration curve approach allows for characterizing streamflow into different flow regimes based on their probability of occurrence. A basic flow duration curve measures high flows to low flows. The *x*-axis represents the percentage of time (known as duration or frequency of occurrence) that a particular flow value is equalled or exceeded. The *y*-axis represents the quantity of flow at a given time step, for example cubic metres per second (m^3/s), associated with the duration. Flow duration intervals are expressed as percentages of exceedence, with zero corresponding to the highest stream discharge in the record (i.e. flood conditions) and 100 to the lowest (i.e. drought conditions). For instance, a flow duration interval of 60% associated with a stream discharge of $10 \text{ m}^3/\text{s}$ implies that 60% of all observed daily average stream discharge values are equal to or have exceeded 10

m³/s. Typically, low flows (flow during prolonged dry spells) are exceeded a majority of the time, while high flows, such as those resulting in floods, are exceeded infrequently (USEPA 2007).

In this study, observed flow data during the modelled time period in each watershed were used in generating flow duration curves. Using the USEPA guidelines (USEPA 2007), the observed flow data were first arranged in descending order and ranked from 1 to N . Then the frequency of occurrence (exceedence probability) was estimated using the following formula:

$$F = 100 * \frac{R}{N + 1} \quad (4)$$

where F is the frequency of occurrence (expressed as percentage of time a particular flow value is equalled or exceeded), R is the rank, and N is the number of observations.

In every model setup, there can be outliers, especially from the extremely high peak flow values, that can have an impact on the general trends of flow in a watershed. In order to reduce bias, we ranked the flow values and removed the highest and the lowest 1% of them. After eliminating the outliers, the sorted flow rate was plotted against the exceedence probability in a semi-log curve to generate the flow duration curve. A common way to examine the duration curve is by dividing it into five zones based on percentage exceedence, representing high flow (10% exceedence), moist condition (10–40% exceedence), mid-range flow (40–60% exceedence), dry condition (60–90% exceedence), and low flow (90–100% exceedence) (USEPA 2007). Figure 5 is an illustration of a standard flow duration curve with the five flow regime zones. In this study, based on the USEPA guidelines of flow duration curve development (USEPA 2007), we only defined three different flow regimes: high flow, medium flow (which included the typical moist condition and mid-range condition), and low flow (including dry flow and low flow), representing percentage exceedence of 10%, 10–60%, and 60%–100%, respectively. Using this criterion, for each model sensitivity run the flow outputs were separated according to these three flow regimes.

2.6 Sensitivity index

In this study, the relative sensitivities of parameters, or the relative influence of the parameters on model output, were measured using the RMSE estimation technique. It is a measure of the difference, or residuals, between the values predicted by each sensitivity scenario run and the values actually observed from the base case model. Equation 5 depicts the formula for RMSE estimation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (X_{base,i} - X_{scenario,i})^2}{n}} \quad (5)$$

where x is the flow value, and n is the number of observations.

The total RMSE for the entire flow range as well as for each flow regime was calculated by summing the individual RMSEs. By aggregating the individual RMSEs, the total RMSE therefore provides a single measure of predictive power. For our analysis, we calculated the RMSEs for the output daily flow values of all the sensitivity runs with respect to the base model outputs.

In order to standardize the RMSE values into a common and comparable scale between each flow regime, it is essential to normalize the calculated RMSEs. In this study, the flow range for each flow regime was used as the denominator in normalization.

The total RMSE of each flow regime was divided by the range of the flow values in the base model under each regime. The equation for normalized RMSE (NRMSE) is as follows:

$$NRMSE = \frac{RMSE}{(X_{base,max} - X_{base,min})} \quad (6)$$

where x is the flow value.

This NRMSE value was then used as the sensitivity index (SI) to determine the relative sensitivity of model parameters to watershed hydrology in each HSPF model. For this index, higher SI values imply a higher influence on watershed hydrology, and lower index values are related to a lower influence. Using this index, we identified the most influential parameter in each watershed on its hydrology for the entire flow range. In order to determine the hydrological responses of the parameters in the two watersheds, the sensitivity indices were plotted against each parameter perturbation for the entire range of flow values. To measure the magnitude of the response change, the average slope was estimated for each parameter in the two watersheds. The average slope of a sensitivity curve is useful as it depicts the degree of variation in sensitivity across the entire parameter range. Furthermore, the trend of hydrological response to the increase of parameter values from lowest to maximum can also be derived by observing the shapes of the sensitivity curves.

Then, the SI of each flow regime, which was obtained based on the above flow duration curve analysis, was calculated for each sensitivity run. Thus, three SI values for the three flow regimes were obtained for one perturbation in each model parameter. When these SI values were plotted against each perturbation for each parameter separately, the sensitivity of the changing parameter values to watershed hydrology in these three flow regimes could then be identified by observing the shapes of the curves and the magnitudes of the slopes as the parameter values increased from minimum to maximum.

3 Results and discussion

3.1 Flow duration curves and flow regimes of the two watersheds

The flow duration curves developed for the two watersheds are shown in Figure 6. For the LMR watershed, high, medium, and low/dry flow regimes correspond to flow discharge rates of greater than 129 m³/s (10% exceedence), 129 to 19 m³/s (10–60% exceedence), and

less than $19 \text{ m}^3/\text{s}$ (60–100% exceedence), respectively. For the LVW watershed, they correspond to greater than $6 \text{ m}^3/\text{s}$ (10% exceedence), 6 to $5 \text{ m}^3/\text{s}$ (10–60% exceedence), and less than $5 \text{ m}^3/\text{s}$ (60–100% exceedence), respectively (Table 2). From the flow rates recorded during the study periods, it is evident that the LMR watershed is characterized by higher flow rates than the LVW watershed (Fig. 6). The flow rates of the LMR watershed span a wider range, from 3 to $673 \text{ m}^3/\text{s}$, while in the LVW watershed, the range of flow rates is relatively narrow, from 3 to $23 \text{ m}^3/\text{s}$. Thus, in the LVW watershed, the flow rates do not show much variability across the three flow regimes. But in the LMR watershed, the flow values are highly varied when compared to LVW flow regimes. These variations between flow regimes also cause different levels of sensitivity to model parameters. For example, the parameter sensitivity between medium and low flow regimes in the LVW watershed is not as apparent as in the LMR watershed.

Although the areal extents of the LMR and LVW watersheds are very similar (5840 and 4850 km^2 , respectively), the differences between flow rates in these two watersheds are quite large. These may be attributed to their watershed characteristics. The LMR watershed is predominantly agricultural, and it has a cool temperate climate regime. Since a large portion of the watershed is covered by vegetated lands, the inflows are predominantly from naturally occurring overland flow, subsurface runoff, and groundwater seepages (Wang 2001). The frequent wet weather events in the LMR watershed may therefore lead to a higher discharge rate (Tong *et al.* 2012). On the other hand, the LVW watershed is under a hot and dry climatic regime, with few wet weather events throughout the year (NOAA 2013). As the watershed is mostly urbanized, the discharge in LVW is mainly from treated wastewater from the urban centres in Las Vegas (SNWA 2009). But, as discussed in Ranatunga *et al.* (2014), for the LVW there are 14–20 average annual flash rain events; these events may have contributed to the high flow portion of the duration curve.

3.2 Parameter sensitivity in the LMR and LVW hydrological models

The sensitivity indices used in this study provide qualitative and quantitative assessments of the impacts of the HSPF parameters on the model output in different watersheds. They can assist in identifying the parameters most and least sensitive to the hydrology of the watershed. The two-dimensional curves between sensitivity index and perturbations of each parameter (Fig. 7) and the average slope of each curve (Fig. 8) are used to explain the relationships of each parameter to the model output. In the LVW watershed, eight out of nine parameters are sensitive to the watershed hydrology, whereas in the LMR watershed, only six parameters are sensitive. The results also show that almost all the parameters have a nonlinear relationship to the model output in both watersheds. According to Muleta and Nicklow (2005), this nonlinear relationship between parameter values and output values is typical in hydrological models.

In the LMR watershed, DEEPFR, INFILT, and AGWRC are the three most sensitive parameters among the nine chosen hydrological parameters. Among these three parameters, DEEPFR and INFILT have decreasing sensitivity and AGWRC has increasing sensitivity to watershed hydrology as their parameter values increase. According to the average slope of the sensitivity curve, DEEPFR (average slope 0.034) is the most sensitive parameter,

followed by INFILT and AGWRC. DEEPFR is the fraction of infiltrating water that is lost to deep aquifers. It also represents any other losses that may not be measured at the flow gauge used for calibration (SJRWMD 2012). This high sensitivity implies that if the watershed properties associated with the DEEPFR parameter are disturbed, the corresponding changes in watershed hydrology can be substantial. The deep permeable soil layers and limestone and shale bedrock associated with the LMR watershed (Wang 2001) may influence the relationship of this parameter to watershed hydrology. The shape of the DEEPFR curve (Fig. 7) shows a linear decrease of sensitivity as the parameter value increases. It also indicates that the values towards the higher end of the parameter are more appropriate in simulating hydrology in the LMR watersheds or other watersheds similar to the LMR.

The parameter INFILT is the second most sensitive parameter with a slope value of 0.0267 (Fig. 8) in the LMR watershed. INFILT is the parameter that effectively controls the overall division of the available moisture from precipitation (after interception) into surface and subsurface flow and storage components (USEPA 2000). It has comparatively higher sensitivity at the lower values of the parameter than at the higher values, as the sensitivity reduces drastically with the increase of parameter value. This relationship implies that any decrease in infiltration in the watershed, for example by altering the soil properties, could lead to considerable changes in watershed hydrology of this basin. This result also indicates that careful adjustment of the parameter values between the minimum and first perturbation is important during the calibration process. High values of the infiltration parameter are more appropriate for this watershed, which is in accordance with the fact that soils of the watershed have high infiltration capacity (Debrewer *et al.* 2000).

The third most sensitive parameter for the LMR watershed, AGWRC, is the groundwater recession rate, which controls the shape of the hydrograph after a storm event (USEPA 2000). The overall AGWRC is a complex function of watershed conditions, which include climate, topography, soil condition, and land use/cover. The results of the analyses show that the sensitivity of AGWRC increases with increasing parameter value, especially towards the high end of the parameter values, where a significant increase can be observed. This relationship indicates that increasing the groundwater recession rate is not appropriate for this watershed, as the higher values of AGWRC have a higher impact on the hydrology. The higher sensitivity in the AGWRC parameter in the LMR watershed may be attributed to the fact that most of the area in the LMR watershed is under either forested or agricultural land use. Also, it has a moist climate. Hence, a considerable fraction of the water from precipitation percolates, some becoming groundwater, and some becoming lateral flows. This fraction of water will be released slowly to streams.

In other HSPF modelling studies, LZSN is often found to be one of the most sensitive parameters in hydrology (Donigian and Love 2007, Mishra *et al.* 2007). But, surprisingly, in our analysis LZSN shows a relatively small impact on the hydrology of the LMR watershed. This may be because LZSN is mainly a climate (precipitation) dependent parameter (Marsalek and Ng 1989, USEPA 2000), and previous studies have suggested that the hydrology in the LMR watershed is affected more by land-use variations than climate change (see, for example, Tong *et al.* 2012). Furthermore, the thick layer of fertile soil in the watershed (Lerch *et al.* 1975) may have a higher level of moisture storage capacity.

Therefore, the parameter values may vary substantially without showing significant impact on the flow in the watershed.

The two other parameters recommended by the HSPF modelling community to be considered in the development and calibration of the model are UZSN and IRC. However, our analysis for the LMR watershed indicates that these two parameters show a relatively small impact on the hydrology of the watershed as the values of the parameters vary from minimum to maximum (Figs. 7 and 8). For UZSN, the convention is to use 10% of the value of LZSN as its value (SJRWMD 2012). Since the sensitivity of LZSN is low in the LMR model, UZSN also shows low sensitivity. Depending on the agricultural conditions, tillage, and other practices, UZSN may change over the course of the growing season (SJRWMD 2012). The mixed land-use nature of the watershed (although we considered LMR as an agricultural watershed) and high moisture-holding capacity of the soil layers could be the reasons for the lower sensitivity for this parameter.

From our results, it is obvious that all impervious parameters, including LSUR, NSUR, and RETSC, are insensitive in the LMR watershed. This may be related to the fact that the LMR watershed does not have a large urban area. Hence, the impacts from changing the impervious surfaces are negligible. Regarding the LVW watershed, INFILT, DEEPFR, and LZSN are the three most sensitive parameters. AGWRC and RETSC parameters also show considerable degrees of sensitivity to the hydrology of the watershed, but in comparison with INFILT, DEEPER, and LZSN, their sensitivities are lower. According to the average slope of the sensitivity curve (Fig. 8), INFILT is the most sensitive parameter to watershed hydrology with a value of 0.0396 within its parameter range, whereas the average slopes of the curves are 0.0361 and 0.0177 for DEEPFR and LZSN, respectively. The sensitivity of INFILT drastically changes within the first two perturbations and stays more or less constant with further increase in parameter value, implying that lower levels of infiltration have a higher impact on watershed hydrology than high infiltration values. But, when compared to the LMR watershed, the magnitude of the impact of INFILT is higher in the LVW watershed. This is true in most of the watersheds with more impervious surfaces, as in this situation the infiltration will be reduced, and the amount of runoff will increase. An increase of INFILT reduces the immediate surface runoff; therefore, lower INFILT values are more sensitive in this watershed. Overall, infiltration-related watershed processes play an important role in the hydrological condition in this watershed.

According to the HSPF technical notes (USEPA 2000), LZSN is one of the main factors that contributes greatly to evapotranspiration. Several studies also suggest that INFILT, LZSN, and DEEPFR are highly sensitive to annual streamflow (Singh *et al.* 2005, Mishra *et al.* 2007). In the LVW watershed, evapotranspiration is usually high, and it is an important factor affecting watershed hydrology. Furthermore, because the LVW watershed has sandy soils with low water storage capacity (BLM 2004), it is more sensitive to the LZSN parameter. A small change to the factors related to LZSN would have a considerable impact on the hydrological behaviour of this watershed.

Contrary to the LMR watershed, all of the three impervious parameters (I-LSUR, I-NSUR, and RETSC) in the LVW watershed show some degree of sensitivity to the hydrological

outcome of the watershed. Moreover, in the LVW watershed, the overall sensitivities of almost all the parameters are comparatively higher than those in the LMR watershed. This indicates that when the impervious parameter values are altered, the impacts on the model output are higher in the LVW watershed than in the LMR watershed.

Since the average annual stream discharge in LVW is less than in LMR (5.3 and 52.2 m³/s, respectively), the results from this study seem to imply that the sensitivity in a watershed with a small stream may be higher than in a watershed with a large river. This finding is reasonable. In a small stream, because of the smaller volume of flow, any change in the watershed hydrological properties and processes can have non-proportional impacts on the flow. In our study, not only is the LVW smaller, but also its watershed is highly urbanized. Its climate is hot and dry, and storms are usually torrential in nature. As a result, a large portion of rainfall can easily become surface runoff. Any changes in INFILT, DEEPER, LZSN, and impervious parameters would have a high impact on flow.

The findings also show that the sensitivity index developed in this research can be used to compare the sensitivity of parameters between different watersheds. To compare the relative sensitivities of the parameters in the LMR watershed with the LVW watershed, the sensitivity of each parameter in each watershed is ranked in relation to other parameters in the same watershed. A summary of the ranking is presented in Table 3. Here, the parameters with the largest differences in sensitivity between the two watersheds are LZSN and the three impervious parameters mentioned above.

3.3 Parameter sensitivity under different flow regimes

As described in Section 3.2, changing the values of certain parameters can result in different levels of response in the overall watershed hydrology. In this research, in addition to analysing the entire flow regime, we further explored the relative sensitivity of the parameters under different flow regimes (high, medium, and low). This is because we wanted to understand whether the impacts of watershed properties and processes over the entire flow range are the same as those on individual segments of the flow regimes. Figures 9–12 illustrate the sensitivity index of each parameter for the three flow regimes in the two watersheds.

In the LMR watershed, according to the slope of each curve (Fig. 9), high flow is the regime most affected by all parameters. Similar to the behavior for the entire flow regime explained in Section 3.2, among all the parameters, DEEPFR shows the highest impact under the high flow condition, followed by INFILT, AGWRC, UZSN, IRC, and LZSN. Based on the shape of the SI curve (Fig. 9), altering the groundwater recession rate, or DEEPFR, near its low values, will greatly change the runoff of the watershed for all three flow regimes. But when the values of DEEPER are high, any alteration will not have as much impact on the flow conditions. This is the case for all three flow regimes. According to the HSPF technical notes (USEPA 2000), decreasing the DEEPFR value will increase overland flow, especially during wet weather events, which usually create high flows. Figure 9 further shows that the impact of this parameter on the medium and low flow conditions is moderate when compared to the sensitivity of other parameters under the same flow conditions. Hence, it is

likely that the overall high sensitivity of DEEPER for the entire flow range described in Section 3.2 above is due to impacts of high flow sensitivity.

As the second most sensitive parameter, INFILT shows similar sensitivity at both high and medium flow regimes and low sensitivity to the low flow conditions. Both high and medium flow conditions indicate the same pattern (the graph in Fig. 9 shows a sudden drop at the beginning and then the curve gradually decreases), while the low flow condition indicates a gradual decrease throughout. It therefore indicates that the impacts of the INFILT parameter are mainly confined to medium and high flows. These results can help in parameter value selection in future modelling for different flow simulations. The hydrological response in all three flow regimes is low when the parameter value decreases up to the second perturbation. Further decreases in the parameter values show a substantial impact on the high and medium flows. This behavior further indicates that higher values of the INFILT parameter are more suitable for the LMR watershed in simulating the hydrology for all flow conditions. Based on the average sensitivity to the INFILT parameter, the model provides a better simulation for high and medium flows than for low flows.

For the AGWRC in LMR, the sensitivity increases gradually in all three flow regimes (Fig. 9). The change in AGWRC values has more impact on the high flow conditions than the other two flow conditions; medium flow has the lowest impact from the change, whereas low flow shows a comparatively high response. Furthermore, lower values of the parameter are appropriate for simulating all three flow conditions.

In general, if the purpose of modelling is to simulate high flow conditions in the watershed, DEEPFR, INFILT, and AGWRC will be the appropriate parameters for investigation. Although LZSN, UZSN, and IRC did not show a huge impact on model output for any flow regime, their behavior is important in simulating the detailed patterns of watershed hydrology. According to Figure 9, LZSN shows a similar pattern of sensitivity to all three flow regimes. But, interestingly, it shows relatively higher sensitivity to the low flow condition compared to the other two flow regimes (Fig. 10). This implies that LZSN is a parameter that mostly affects low flow conditions in watersheds similar to that of LMR. In a similar manner, IRC is a parameter that affects the high and low flows. Moreover, similar to sensitivity of the entire flow range, all three impervious parameters show almost no sensitivity to any of the flow regimes.

As illustrated in Figures 11 and 12, in LVW, the impacts from each parameter in the three flow regimes are different from those in the LMR watershed. There is a distinct variability of response between each flow regime. It is noticeable that the impacts of most of the watershed parameters, such as INFILT, DEEPFR, and LZSN, on the model output are less apparent under the low flow regime than under the other two flow conditions. This could be related to the fact that a large portion of LVW baseflow (low flow) is from point source discharges, such as the effluent from wastewater treatment plants (SNWA 2009). Therefore, altering watershed properties will instigate little variation under the low flow conditions. On the other hand, since AGWRC shows a very high sensitivity to low flows, an increase in the groundwater recession rate in this watershed can have a significant impact in stream baseflows. According to the SI curve for AGWRC (Fig. 11), high values of the parameter

show high sensitivity, whereas low to medium range values show more or less no sensitivity. Of the three impervious parameters, RETSC shows comparatively higher sensitivity to all three flow regimes. The LVW watershed is an urban watershed. It is sensitive to the impervious module parameter. However, the relative impacts from these parameters are still less than pervious parameters. These results therefore show that hydrological simulation of the LVW watershed (and other watersheds with similar hydroclimatic conditions) is a complicated process, as parameter sensitivities could vary substantially between the three flow regimes.

4 Conclusions

The goal of this study was to use a simple and effective analytical approach to evaluate and compare the relative sensitivities of various hydrological parameters to the hydrology of different watersheds under different hydroclimatic settings and to different flow regimes in one watershed. For this purpose, we used NRMSE as the index to estimate the influence of parameters in the HSPF hydrological model. The index provides a standardized value that can be used to compare the parameter sensitivity in different watershed model outputs. To measure the parameter sensitivity under different flow regimes in one watershed model, we combined the NRMSE index approach with a flow duration curve analysis technique. This approach is an improvement on other local sensitivity analysis methodologies, which usually measure the parameter sensitivity of the entire flow regime. The results from this study have determined the capability of this approach in generating a sensitivity index to compare the impacts of watershed processes in different watersheds as well as under different flow regimes in one watershed. The information derived from this research is useful not only in model development but also in model calibration.

Using this tool, we have derived some useful information that may contribute to the literature of hydrological modelling, not only for HSPF but also for other hydrological models, such as SWAT. The information is particularly useful in selecting the most appropriate watershed processes for hydrological modelling. For example, parameters related to groundwater processes should be used in modelling the LMR watershed or other similar watersheds.

This research has also provided some useful findings for the LMR and LVW watersheds (and also other watersheds that are under similar hydroclimatic conditions). By furthering our understanding of the most and least important watershed characteristics and processes in the LMR and LVW watersheds that affect their hydrological behavior, this new knowledge can be instrumental for water resource managers and government agencies as they devise appropriate watershed management plans for these areas.

The results from the analyses also show that, although the LMR and LVW watersheds have different hydroclimatic conditions and flow regimes, the sensitivity index that we have employed is capable of identifying the relative sensitivities of different hydrological parameters. Based on the sensitivity index analysis for the entire flow range, eight out of the nine parameters used in model development in the LVW watershed are sensitive to watershed hydrology, whereas only six parameters are sensitive in the LMR watershed. This

study also shows that almost all the parameters show a nonlinear relationship with the hydrology in both watersheds. For the LMR watershed, the order of the hydrological impact of the parameters from highest to lowest is DEEPFR, INFILT, AGWRC, UZSN, IRC, and LZSN. For the LVW watershed, the parameters that have the highest to lowest hydrological effects are INFILT, DEEPFR, LZSN, AGWRC, RETSC, I-NSUR, I-LSUR, and UZSN (Table 3). Overall, this study shows that the groundwater-related parameters (DEEPFR and AGWRC) are more important to the LMR watershed than near-surface parameters, whereas LVW is primarily sensitive to near-surface parameters (INFILT and LZSN) and the impervious parameters.

In the LVW watershed, the overall sensitivity of almost all the parameters is comparatively higher than in the LMR watershed. This shows that, if the parameter values are changed, the impacts on the model output are higher in the LVW watershed than in the LMR watershed. This study further reveals that the parameters for the impervious module (LSUR, NSUR and RETSC) are not sensitive in watersheds with less urban surface, as these impervious parameters are insensitive for the LMR watershed, but they are sensitive for the LVW watershed.

Using the sensitivity index, we were able to identify the model parameters that have the highest to the lowest impact in each of the three flow regimes in the LMR and LVW watersheds. Regardless of the differences between land-use classes, soil, and hydroclimatic conditions, most parameters, except AGWRC, usually affect the high and medium flows more than the low flows. Compared with other parameters, AGWRC has a relatively higher impact under low flow conditions. This indicates that AGWRC is an important parameter to use when simulating low flow conditions in these two watersheds.

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Figure 1.
Maps of the study areas: the LMR and LVW watersheds

Figure 2.
Conceptual model of HSPF hydrologic simulation

Figure 3.
Major soil types of the LMR watershed

Figure 4.
Major soil types of the LVW watershed

Figure 5.
Flow regimes of a Flow Duration Curve (FDC)

Figure 6.
Flow duration curves for the (a) LMR watershed; (b) LVW watershed

Figure 7.

Comparison of parameter sensitivity for the entire flow ranges of LMR and LVW watersheds

Figure 8.
Average slope of the SI curves for the entire flow range

Figure 9.
LMR model parameter sensitivity in three flow regimes

Figure 10.
Average slope of the SI curves of three flow regimes in LMR watershed

Figure 11.
LVW model parameter sensitivity in three flow regimes

Figure 12.
Average slope of the SI curves of three flow regimes in LVW watershed

Table 1

HSPF parameter descriptions

	Parameter	Units	Function of	Possible Values ¹		Model Parameter Values	
				Min	Max	LMR	LVW
PWATER	LZSN - Lower Zone Nominal Soil Moisture Storage	mm	Soils, climate	50.8	381	162.56	127
	INFILT - Index to Infiltration Capacity	mm/hr	Soils, land use	0.028	12.7	12.7	31.75 ²
	AGWRC - Base groundwater recession	None	Base flow recession	0.85	0.999	0.85	0.92
	DEEPFR - Fraction of GW inflow to deep recharge	None	Geology, Groundwater recharge	0	0.5	0.45	0.7 ²
	UZSN - Upper zone nominal soil moisture storage	mm	Surface soil conditions, land use	1.27	50.8	20.32	12.7
IWATER	IRC - Interflow recession parameter	None	Soils, topography, land use	0.3	0.85	0.75	0.45
	LSUR - Length of overland flow	meters	Topography	15.24	76.2	76.2	91.44 ²
	NSUR - Manning's n (roughness) for overland flow	None	Surface conditions, residue, etc.	0.01	0.3	0.05	0.08
	RETSC - Retention (Interception) Storage capacity	mm	Retention potential of impervious surfaces	2.54	12.7	2.54	2.54

¹Range of possible values for each model parameter (USEPA 2000)²Due to the local hydrologic characteristics, some parameters may have values beyond the recommended range (USEPA 2000).

Table 2

Flow rates for each regime in the LMR and LVW watersheds

	Flow rates (m ³ /s)		
	Low (>60%)	Medium (10%–60%)	High (<10%)
LMR	<19	19–129	>129
LVW	<5	5–6	>6

Table 3

The ranking of the parameters in the LMR and LVW watersheds according to their sensitivities

Parameter Sensitivity	Watershed Parameters	
	LMR	LVW
High	DEEPFR	INFILT
	INFILT	DEEPFR
	AGWRC	LZSN
	UZSN	AGWRC
	IRC	RETSC
	LZSN	I-LSUR
	RETSC	I-NSUR
	I-LSUR	UZSN
Low	I-NSUR	IRC