TRACING THE EVOLUTION OF RECONSTRUCTED WATERSHEDS USING THE PARAMETERS OF THE SYSTEM DYNAMICS WATERSHED MODEL

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Tracing the evolution of reconstructed watersheds using the parameters of the system dynamics watershed model

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Abstract

The oil sands industry in northern Alberta, Canada, is committed to reclaiming disturbed watersheds by placing soil caps over the mined-out overburden, and thus forming reconstructed watersheds. The reconstructed watersheds evolve hydrologically over time due to many factors; freeze-thaw cycles are the most important one. The hydrologic evolution causes the reconstructed watershed to be unstable, and therefore it is challenging to simulate it in the traditional way. In this paper, the system dynamics watershed (SDW) model, previously developed for reconstructed watersheds, is used to trace the watershed evolution by studying the inter-annual trend of the calibration parameters. This study shows that the evolution hypothesis could help reduce the number of possible parameter sets that fit the observational data. This approach has the future potential to provide insights into the problems of non-uniqueness (equifinality) as well as the predictive uncertainty of watershed models by limiting the possible number of calibration parameter sets.

Keywords: reconstructed watersheds; watershed evolution; system dynamics; calibration parameters.

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Introduction

In northern Alberta, Canada, oil sands are extracted from large open pits extending to nearly 100 meters in depth and covering large areas. The result is the disturbance of the natural environment over more than 100 km^2 for any individual mine site (Leskiw, 2004). Reclamation in these cases requires that entire landforms and drainage systems be reconstructed from the mine overburden and that soil covers that replicate the performance of the natural A, B, and C soil horizons be layered over these landforms (Kelln et al., 2006). The oil sands industry is committed to restoring functioning landscapes by designing reclaimed watersheds to restore the various functions of natural watersheds (Black, 1996).

The interrelationships among different variables and hydrological processes in reconstructed watersheds define the watershed response and develop a closed-loop network that tends to mimic natural watersheds. During the initial stages of the development of the watershed, soil moisture in the upper layers of soil plays a greater role in vegetation growth, but as the watershed matures, runoff and lateral flow may dominate (Jutla et al., 2006). This process can be further complicated by time and scale factors. A simulation model that captures the short-term behavior of the reconstructed watersheds and that has the potential to predict the long-term hydrologic performance is essential for the mining industry. The watershed simulation model can maximize the benefits gained from the monitoring program and enable different scenarios to be tested to help direct the design of the reclamation landscape and further monitoring (Elshorbagy, 2006). A system dynamics watershed (SDW) model was developed within

STELLA environment for the above-mentioned purposes by Elshorbagy et al. (2005). STELLA is an efficient simulation environment that has been used for various environmental applications (e.g., Elshorbagy and Ormsbee, 2006; Zhang and Mitsch, 2005; Voinov et al., 2004) and has been evaluated against other commercial packages (Rizzo et al., 2006).

The SDW model (Elshorbagy et al., 2005; Elshorbagy, 2006; Jutla et al., 2006) is unconventional compared to traditional watershed models because of its simulation environment and system structure that is based on combinations of empirical and physics-based formulations. The suitability of such formulations is interrelated; i.e., they work best as a system even though each formulation may not be the optimum one when evaluated as a stand-alone estimator of a specific hydrologic process. However, the SDW model is a traditional model in the sense that, once calibrated, it can simulate stable watersheds that do not encounter physical changes over time. In modeling terminology, such a stability is represented by a fixed (time invariant) set of calibration parameters.

In order for the SDW model to fulfill its objective as a decision aid tool for the oil sands mining industry, it has to have the ability to evaluate and predict the hydrologic performance of the reconstructed watersheds over time. Reconstructed watersheds (soil covers) are subjected to a number of physical, chemical, and biological processes that can alter performance over time including freeze/thaw and wet/dry cycling, erosion, root penetration, and bioturbation (MEND, 2004). These processes ultimately affect key properties of the soil cover such as the hydraulic conductivity and moisture retention characteristics. It is extremely difficult to predict the rate of evolution of the reconstructed watershed, especially the long-term changes. The reconstructed watershed under consideration for this study was constructed in 1999 and has been undergoing natural evolution. In modeling terminology, the SDW model needs a time-varying set of parameters to adapt to the continuous evolution of the watershed.

The aim of this paper is to analyze and trace the evolution of the reconstructed watershed using time-varying parameters for the model that was calibrated and validated in Elshorbagy et al. (2005); Jutla (2006); and Jutla et al. (2006).

The system dynamics watershed (SDW) model

The SDW model is a lumped watershed model that simulates the various hydrologic processes occurring in the reconstructed watershed shown in Figure 1. The model is conceptualized as a control volume that simulates and takes into account the water balance components among the three soil layers (peat, till, and shale) as well as the evapotranspiration and runoff on daily basis (Jutla et al., 2006). The developed SDW model makes optimum use of the extensive monitoring program established for the study site and uses climatic and hydrologic factors to evaluate the hydrologic processes. The dynamics of the watershed under consideration were captured in a causal-loop diagram with multiple feedback loops that govern the entire water-balance system. A combination of physically based formulations (e.g., Green-Ampt for infiltration and soil moisture distribution, and Penman equation for potential Evapotranspiration) and empirical (fitted-parameter) formulations (e.g., actual evapotranspiration based on simulated soil moisture index and infiltration into frozen soil) was employed in formulating the model (Elshorbagy et al., 2005).

Evolution of the reconstructed watersheds

The glacial soil of the reconstructed watersheds is comprised of 60 to 75% fines (particle diameter less than 0.045 mm), of which 25 to 40% are clay size particles. It can be classified as medium plasticity clay with a plastic limit of 28% (Kelln et al., 2006). The field saturated hydraulic conductivity (K_s) was measured each year from 2000 to 2005 using a Guelph Permeameter (Reynolds, 1993). The Guelph permeameter testing involves maintaining a constant water head in an uncased cylindrical auger hole to measure the steady state infiltration rate. The Guelph permeameter may provide more realistic estimates of bulk hydraulic conductivity than laboratory derived K_s because it tests a larger soil volume. Larger soil volumes allow macro scale features such as fractures or secondary structures to be captured. Approximately 30 measurements were conducted on the reconstructed watershed covers and underlying shale every year (Meiers et al., 2003; Kelln et al., 2006).

The average values of in-situ saturated hydraulic conductivity (K_s) of the peat/mineral mix, the glacial till soil, and the shale overburden are presented in Figure 2. The glacial till soil layer experienced the largest increase in K_s (from around 2×10^{-8} m/s to 2×10^{-6} m/s). The K_s value of the underlying shale increased from 2×10^{-9} m/s in 2000 to 10^{-8} m/s in 2002, whereas the K_s value of the peat/mineral soil increased from 8×10^{-6} m/s to 7 x

10^{-5} m/s. It can be noted that the saturated hydraulic conductivity stabilized in subsequent years; ignoring the marginal decrease in the case of the glacial till soil.

The evolution of the hydraulic conductivity, which is a sign of the reconstructed watershed evolution, was attributed to the freeze-thaw effects (Meiers et al., 2003). The effect of the freeze-thaw effect on the K_s of clay-rich soils has been suggested by other laboratory and field studies (Benson et al., 1995; Chamberlain et al., 1995). Othman and Benson (1993) explained that the increase in K_s occurs due to water migration towards the freezing front, which induces cracking, and the formation of ice lenses, which alters the structure of the soil.

The evolution of the reconstructed watersheds is reflected in the relative amounts of water distributed through the various hydrologic processes. The increase of the saturated hydraulic conductivity and the change of the soil structure may lead to an increase in the total amount of water infiltrating from the surface into the top peat/mineral layer and also to the downward movement of water from the top soil to the till and shale layers. This change in the soil moisture dynamics is expected to affect the amount of water stored in the soil and made available to the plants for evapotranspiration. In other words, some of the dominant hydrologic processes in the reconstructed watersheds and their interrelationships become time-varying (nonstationary) over years of evolution. Such nonstationarity poses great difficulties on any stationary watershed model, such as the SDW model. Most watershed models are calibrated and validated using a set of parameters that are assumed to be invariable over years.

Methodology

Based on the discussion provided in the previous section, the research hypothesis to be tested in this study is as follows: *the parameters (coefficients) of the SDW model representing the evapotranspiration from the peat and till layers (c_P and c_T), the evapotranspiration exponent (λ), the downward movement of water from the peat layer to the till layer (I_{cT}), and the downward movement of water from the till layer to the shale layer (I_{cS}) should be time-varying over years to reflect the reconstructed watershed evolution*.

Even though the SDW model and its formulations are detailed in Elshorbagy et al. (2005) and Jutla et al. (2006), the equations that entail the parameters under consideration are provided below:

$$AET_P = c_P S_{mP}^{\lambda} T_a \qquad (1)$$

$$AET_T = c_T S_{mT}^{\lambda} T_{sP} \qquad (2)$$

$$f_T = \frac{\theta_P}{\theta_T}\frac{S_P}{\Delta t} I_{cT} \qquad (3)$$

$$f_S = \frac{\theta_T}{\theta_S}\frac{S_T}{\Delta t} I_{cS} \qquad (4)$$

where AET_p is the actual evapotranspiration from the peat layer (mm/day); c_P is the evapotranspiration constant (mm/^{o}C-day) from the peat layer; λ is an exponential coefficient; S_{mp} is the effective moisture saturation in the peat layer (dimensionless); T_a is the air temperature (^{o}C); AET_T is the actual evapotranspiration from the till layer (mm/day); c_T is the evapotranspiration constant (mm/^{o}C-day) from the till layer; S_{mT} is the effective moisture saturation in the till layer; T_{sP} is the depth-averaged peat layer temperature (^oC); f_T is the rate of the downward water movement into the till layer (mm/day); θ_P, θ_T, θ_S are the volumetric moisture contents in the peat, till, and shale layers, respectively (%); S_P is the peat layer storage (mm); Δt is the solution time interval; I_{cT} is the coefficient of downward movement of water from the peat layer to the till layer; f_S is the rate of the downward water movement into the shale layer (mm/day); S_T is the till layer storage (mm); and I_{cS} is the coefficient of downward movement of water from the till layer to the shale layer.

The amount of water moving between the various soil layers depends on the total amount of water available through rainfall as well as the rainfall patterns. Sequences of dry and wet periods affect such movement of water since a storm that deposits an amount of precipitation in one day can cause soil saturation and downward movement of water, whereas a precipitation event of the same amount distributed over a number of days may not have the same effect due to the water consumption through evapotranspiration. However, the fact that all the SDW model parameters are time-lumped parameters (i.e., invariable within each year) make them encapsulate and represent the overall (total annual) values and patterns of the hydrologic processes more precisely than daily patterns. The parameters were derived, as it is the case with most watershed models, so that the overall (average) error over the entire year is minimized. Therefore, it is important to neutralize the effect of the input variable (i.e., total rainfall), which changes every year, before investigating the annual trend of the model parameters.

The SDW model, which was calibrated and validated using the traditional calibration approach (i.e., the same values of model parameters are used during both calibration and validation), is used in the proposed further analysis. The model of each sub-watershed is executed to simulate the hydrologic processes without applying any constraints on the parameter values. The model parameters are changed every year using the same approach of trial and error until a reasonable agreement between the simulated and observed series (i.e., soil moisture and overland flow) is achieved. The model parameters I_{cT}, I_{cS}, $c_{P,}$ c_T, and λ for the each sub-watershed is recorded. Expectedly, multiple sets of parameter values can be deemed appropriate; however, a limited number of such sets could lead to accepting the research hypothesis, whereas the other sets may result in rejecting the hypothesis. In order to negate some of the effects of the meteorological variability, the values of the parameters are normalized by dividing each parameter value by the total depth of summer rainfall in the year under consideration. Some of the parameters may assume small values; therefore, the parameter values are multiplied by an arbitrarily large number (e.g., 10000) before dividing by the rainfall depth. The annual trend of the normalized parameters is investigated to test the study hypothesis.

Results and analysis

Neutralizing the effect of the total rainfall on the water movement and evapotranspiration, and thus the relevant model parameters, is a straightforward task since it can be achieved by dividing the model parameters by the total annual (or summer) rainfall. However, the intra-annual rainfall patterns are more complicated to capture and investigate. In this paper, the cumulative rainfall over the summer season

(May 15th till October 15th) of every year and the frequency curves are analyzed and used to investigate the intra-annual rainfall patterns. Figure 3 shows the cumulative summer rainfall for each one of the five years (2000 – 2004) under consideration. With the exception of 2003, there is a reasonable visual similarity in the patterns of rainfall accumulation over the summer for 2000, 2001, 2002, and 2004. The differences between the curves can be attributed to a shift that is caused by the amount of the rainfall rather than the rainfall pattern.

Further analysis of the intra-annual rainfall pattern is conducted by investigating the frequency curves of rainfall for the five years under consideration (Figure 4). The figure presents the nonexceedance probability of any rainfall quantile. The frequency curves are not representative of the chronological sequence of rainfall (unlike the cumulative curves in Figure 3). However, the curves indicate the percent of time a certain rainfall amount is exceeded. With the exception of 2003, the other four curves are almost parallel to each other for most of the rainfall range, indicating that they originate from similar populations (distributions) with different mean values. The differences in the mean values are represented by the downward or upward shifts. 2003 departs significantly from the other four years. When probability distributions are fitted into the rainfall data for each year, the same probability distribution (Beta General distribution) is found to be the best-fit for 2000, 2001, 2002, and 2004. Exponential distribution was found to be the best fit for the data of 2003. This result supports the preliminary conclusions made, using the cumulative curves, about rainfall similarity over the period of study except 2003. Based on the argument provided in this section using the cumulative and frequency curves of daily rainfall within the summer months, it is considered that the intra-annual rainfall patterns for most of the study period can be ignored, assuming that the total amount of the summer rainfall is the distinctive inter-annual criterion. Apparently, this assumption simplifies the analysis for this study but needs further verification for future studies.

Evolution of sub-watershed D1 (50 cm)

The SDW model, which was calibrated and validated using the data from 2001 and 2002, respectively (Elshorbagy et al., 2005), was used to simulate the hydrologic processes in each year (2000 – 2004) individually. Minimizing the difference between the observed and simulated values of the various processes (soil moisture, runoff, and evapotranspiration) was set as the objective function while changing the values of the calibration parameters freely every year. A set of model parameter values of the developed SDW model for sub-watershed D1, which was obtained using the trial and error methodology, are given in Table 1. During the trial and error process, it was noticed that three of the parameters (c_i, T_{Imax}, and m_F) have marginal effect on the results and thus, can be kept out of further analysis. This is useful because it helps ensure that the analysis of watershed evolution is focused on the parameters that can be better physically explained. The remaining five parameters (I_{cT}, I_{cS} c_P, c_T, and λ) exhibit dynamic variation over time.

In order to analyze the hydrologic evolution of the watershed, the parameters I_{cT}, I_{cS}, $c_{P,}$ $c_{T,}$ and λ were multiplied by an arbitrarily large number (10000). In order to negate some of the effects of the meteorological variability, the values obtained were normalized using the total depth of summer rainfall in each year. The summer rainfall in each of the five model years is 298, 273, 272, 278 and 257 mm, respectively. Figure 5 shows the trend in the normalized actual evapotranspiration (AET) parameters (c_P, $c_{T,}$ and λ). These results indicate that sub-watershed D1 may still be evolving over time, although there is a modest indication that the watershed is stabilizing more in regards to λ than to the other two parameters. The increasing trend of c_P (Figure 5a) may indicate the growth of vegetation, and thereby the need for more water for evapotranspiration (see Eq. 1). The fact that c_T (Figure 5c) is nearly constant may indicate that the roots penetrate into the till layer but may not be benefiting from the till moisture except in drier years. This is not surprising since the top 20 cm of the peat/mineral mix layer can provide most of the moisture needed for vegetation.

According to the data presented in Figure 2, an increase in the normalized till infiltration parameter (I_{cT}) and the shale percolation parameter (I_{cS}) values over time should be expected. Figure 5 validates the expectation and the hypothesis where the normalized I_{cT} and I_{cS} values are plotted over five years. The figure reveals that the watershed is still evolving over time and that the moisture dynamics in the soil layers have not stabilized yet. This is possible because the watershed is experiencing freeze-thaw cycles and decomposition of the organic peat layer, which in turn increases water intake (Haigh, 2000). The effect of the different rainfall pattern of 2003, discussed earlier, is sometimes reflected as unexplained pattern (Figures 5a, 5c, and 6a) in 2003.

Evolution of sub-watershed D2 (35 cm)

The set of the optimum model parameter values of the developed SDW model for sub-watershed D2, which was obtained using the trial and error methodology, is given in Table 2. Similar process and analysis to those followed with sub-watershed D1 were conducted with sub-watershed D2. Figure 7 shows the increasing trend in c_P, c_T, and λ. However, it can be noticed that the yearly rate of increase in c_T is higher in D2 compared to D1. D2 is the thinnest soil cover with 15 cm of peat/mineral mix overlying 20 cm of glacial till. The increase in c_T reflects the fact that actual evapotranspiration from the till layer increases over years because the roots need to uptake water from this layer to substitute for any possible shortage in the upper thin layer of peat.

The annual rates of increase of the normalized till infiltration and shale percolation parameter values (I_{cT} and I_{cS}) are significantly higher in D2 (Fig. 8) than in D1. This could be interpreted as a higher percentage of the soil moisture in D2 moving downward from the peat to the till and from the till to the shale layers, compared to D1.

Evolution of sub-watershed D3 (100 cm)

The set of the optimum model parameter values of the developed SDW model for sub-watershed D3 is given in Table 3. Similar process and analysis to those followed with sub-watersheds D1 and D2 were conducted for sub-watershed D3. The increasing trend in c_P, c_T, and λ over the years (Figure 9) is significantly higher than those experienced in sub-watersheds D1 and D2. This can be attributed to more solid establishment of the vegetation on D3, which has the thickest cover. Site visits even confirm that vegetation is healthier and more uniform in D3 compared to D1 and D2. Even though the thickness of the peat/mineral layer is 20 cm, similar to D1, the thickness of D3 (100 cm) allows for more capacity to store and release water and keep the salt diffusion from the underlying shale layer far from the roots. This helps the roots to penetrate and develop within the till layer, increasing the evapotranspiration from the till layer and thus, increasing c_T coefficient.

Apparently, the thickness of the cover D3 in such a sub-humid region reduces the portion of soil moisture percolating below the root zone to the underlying shale layer (Figure 10b). This portion is represented by the normalized shale percolation parameter value (I_{cS}). The portion of soil moisture moving downward from the peat/mineral layer to the till layer (represented by the normalized parameter I_{cT}) is still monotonically increasing over time. The thickness of the cover causes the time period needed for the cover to settle and reach final soil aggregate structure to increase (Figure 10a).

Discussion

Tracing the watershed evolution through the temporal trends of the model parameters is strongly related to the concept of "equifinality" (Beven, 2005). The realistic concept of equifinality, started by Beven (1993), is based on the finding that a set of multiple models and even multiple sets of parameters within one model could provide acceptable fits to observational data. Thus, searching for a single correct description of reality or an optimum solution should be avoided if possible. One can argue that the "problem" of equifinality is intuitively aggravated by the fact that the majority of watershed models are treated as functional rainfall-runoff models; i.e., the only model performance indicator is the acceptable fit to observational runoff data. When using multiple performance indicators (e.g., runoff, evapotranspiration, and soil moisture content) and attempting to obtain acceptable fits to observational data of multiple hydrologic variables, the number of acceptable models and parameter sets should decrease significantly or be limited to one "optimum." This may or may not be the case all the time.

The SDW model was calibrated and validated using multiple performance indicators (volumetric soil moisture content, actual evapotranspiration using the eddy covariance-measured evapotranspiration, and runoff) (Elshorbagy et al., 2005; Jutla, 2006). Interestingly, multiple sets of parameter values from different regions of the parameter space were found acceptable, which indicates that even with multiple performance indicators, there is equifinality of parameter sets (at least a few) in providing acceptable fits to observational data.

The argument raised in this paper is that the concept of equifinality of models and parameter sets in providing acceptable fits to observational data is valid from a numerical and computational viewpoint. Multiple mathematical representations of a real hydrologic system (e.g., a watershed) are possible and logical due to the adoption of the system analysis approach. A conceptual and physically correct formulation, such as Darcy equation, is valid at the soil column scale, but it may not be representative at the watershed scale without a calibration parameter. The system of interconnected physically based equations results in a "conceptual" model that relies heavily on an interconnected set of system parameters for its performance. The system parameters encapsulate what is unknown about the system rather than what is known, and thus, allow for multiple sets of possible combinations of parameter values that provide acceptable fits to observational data. This should not be surprising because the observational data (even though based on a split sample) is what was used to generate the parameter sets. The modeller may fail to exclude any of the parameter sets because of the lack of criteria that can be used to evaluate each parameter set. In this paper, the research hypothesis presented earlier can serve as a criterion so that any parameter set that leads to rejecting the hypothesis is rejected.

The analysis presented in the previous section shows that even though the saturated hydraulic conductivity of the soil covers (Figure 2) started to stabilize, the equivalent system parameters (I_{cT}, I_{cS}) are still monotonically increasing because they not only represent the portion of downward movement of water, but they are also linked to the fact that roots are developing, taking more water from lower soil layers, and encouraging redistribution of soil moisture. An opposite temporal trend of infiltration and percolation parameters would be counter-intuitive, and therefore parameter values that led to a counter-intuitive behaviour (rejecting the hypothesis) were rejected regardless of their numerical optimality in terms of reducing the model functional error (e.g., difference between observed and simulated variable). The paper also presents another useful benefit of simulation models; that is to test hypotheses and not just predict future values (Silberstein, 2006).

It is acknowledged here that the evolution hypothesis does not exist in stable watersheds, which makes replicating the approach presented in this paper impossible. However, this approach of tracing the watershed evolution is valuable since it provides useful insights into the issues of equifinality and non-uniqueness. Its replication using other restored watersheds is feasible and possible. The approach could also encourage researchers to seek hydrologic criteria to evaluate the calibration parameter sets and to be able to eliminate some of the sets. Reducing the number of acceptable parameter sets will play a role in decreasing the predictive uncertainty of watershed models. Any further improvement of the SDW model (model structure, reduced dimensionality, or predictive accuracy) should be evaluated using the evolution hypothesis. Within a few years, the reconstructed watershed under consideration is expected to stabilize, and thus retain a parameter set that is not varying over time.

Conclusions

Watersheds that are reconstructed in northern Alberta, Canada, by placing soil caps over mined-out excavation piles go through a process of hydrologic evolution over a few years until they eventually stabilize. The thaw-freeze cycles are the major known cause for such evolution. The measured in-situ hydraulic conductivity verifies the evolution concept through an apparent increase in the values of saturated hydraulic conductivity over the first few years. The evolution of a reconstructed watershed in northern Alberta was traced using the inter-annual trend of calibration parameters of the system dynamics watershed model developed earlier. Relying on the hypothesis of the watershed evolution allowed the number of parameter sets that fit the observational data to be narrowed down.

In the case study under consideration, one set of calibration parameters was found to fit the observational data and verify the evolution hypothesis. The search for parameter sets is not claimed to be exhaustive but was extensive enough to cover wide range of possibilities. Further work and research can be conducted to use the approach presented in this paper to provide a more insightful critique on the effect of such an approach on concepts such as equifinality and the predictive uncertainty of watershed models.

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Table 1. The calibration parameter values of the SDW model over the simulation period (sub-watershed D1).

Year	c_P	c_T	λ	T_{Imax}	m_F	c_i	I_{cT}	I_{cS}
2000	6	2.4	10	45	0.90	5	0.35	30
2001	5.9	2.55	29	45	0.90	5	0.75	33
2002	7.5	2.55	25.5	45	0.90	5	1.1	33
2003	7.5	2.2	32.5	45	0.90	5	1.1	34
2004	11	2.7	31	50	0.90	5	1.55	35

Table 2. The calibration parameter values of the SDW model over the simulation period (sub-watershed D2).

Year	c_P	c_T	λ	T_{Imax}	m_F	c_i	I_{cT}	I_{cS}
2000	7	5.6	30	45	0.9	5	0.2	0.6
2001	8	5.9	31	45	0.9	5	0.3	1.6
2002	10.5	5.9	32.5	45	0.9	5	0.8	1.6
2003	9	6.2	33.5	45	0.9	5	1.7	2.7
2004	15.5	6.9	35	45	0.9	5	4.2	4

Table 3. The calibration parameter values of the SDW model over the simulation period (sub-watershed D3).

Year	c_P	c_T	λ	T_{Imax}	m_F	c_i	I_{cT}	I_{cS}
2000	7.5	2.5	30	50	0.9	5	0.65	20
2001	11	4.5	43	50	0.9	5	1.45	21.5
2002	13.5	7.5	62	50	0.9	5	2.2	22
2003	21.5	8.3	58	50	09	5	2.8	22.5
2004	23	17.5	73	50	0.9	5	3.9	23.5

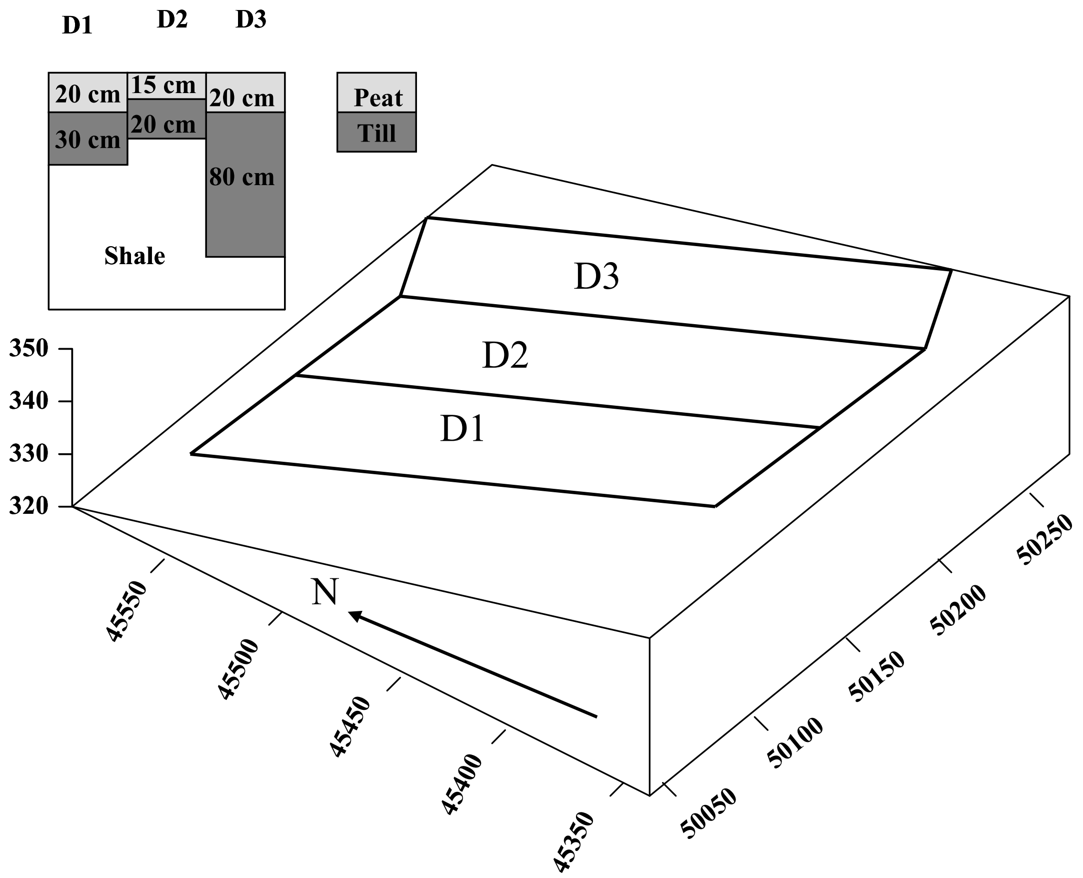


Figure 1. The reconstructed sub-watersheds: D1, D2, and D3 (scale in meters).

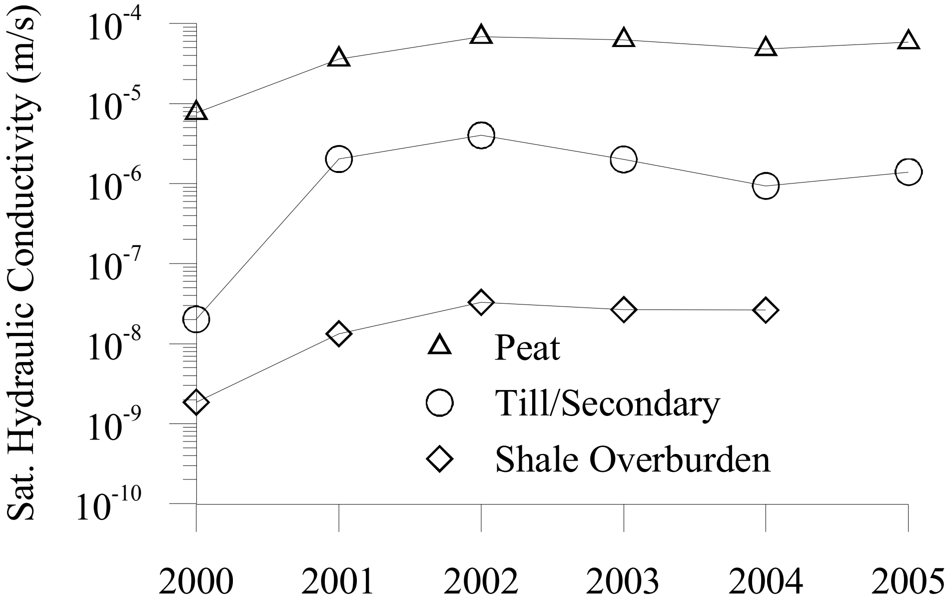


Figure 2. In-situ saturated hydraulic conductivity; after Kelln et al. (2006).

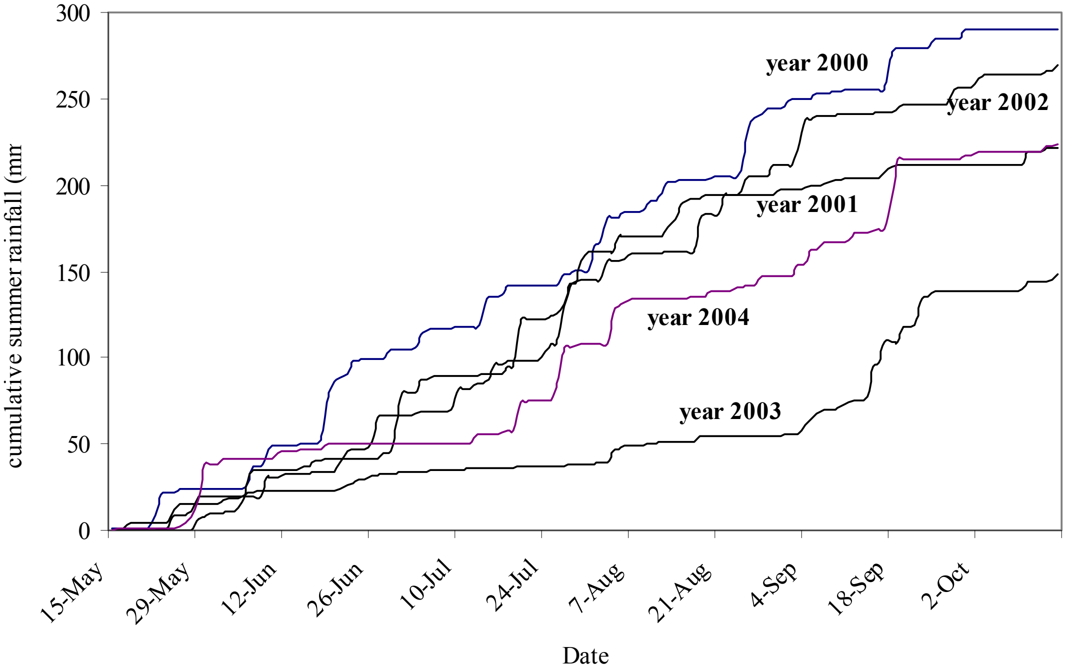


Figure 3. The depth of cumulative summer rainfall over the reconstructed watershed.

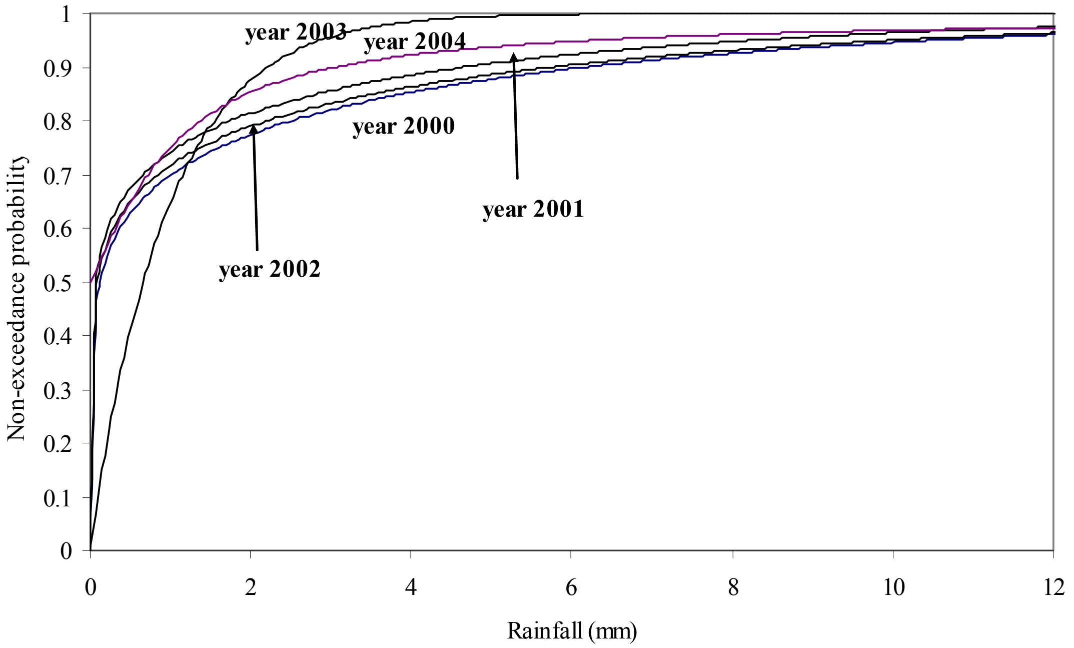


Figure 4. Non-exceedance frequency curves of summer rainfall values over the simulation period. The graphs are truncated after 12 mm.

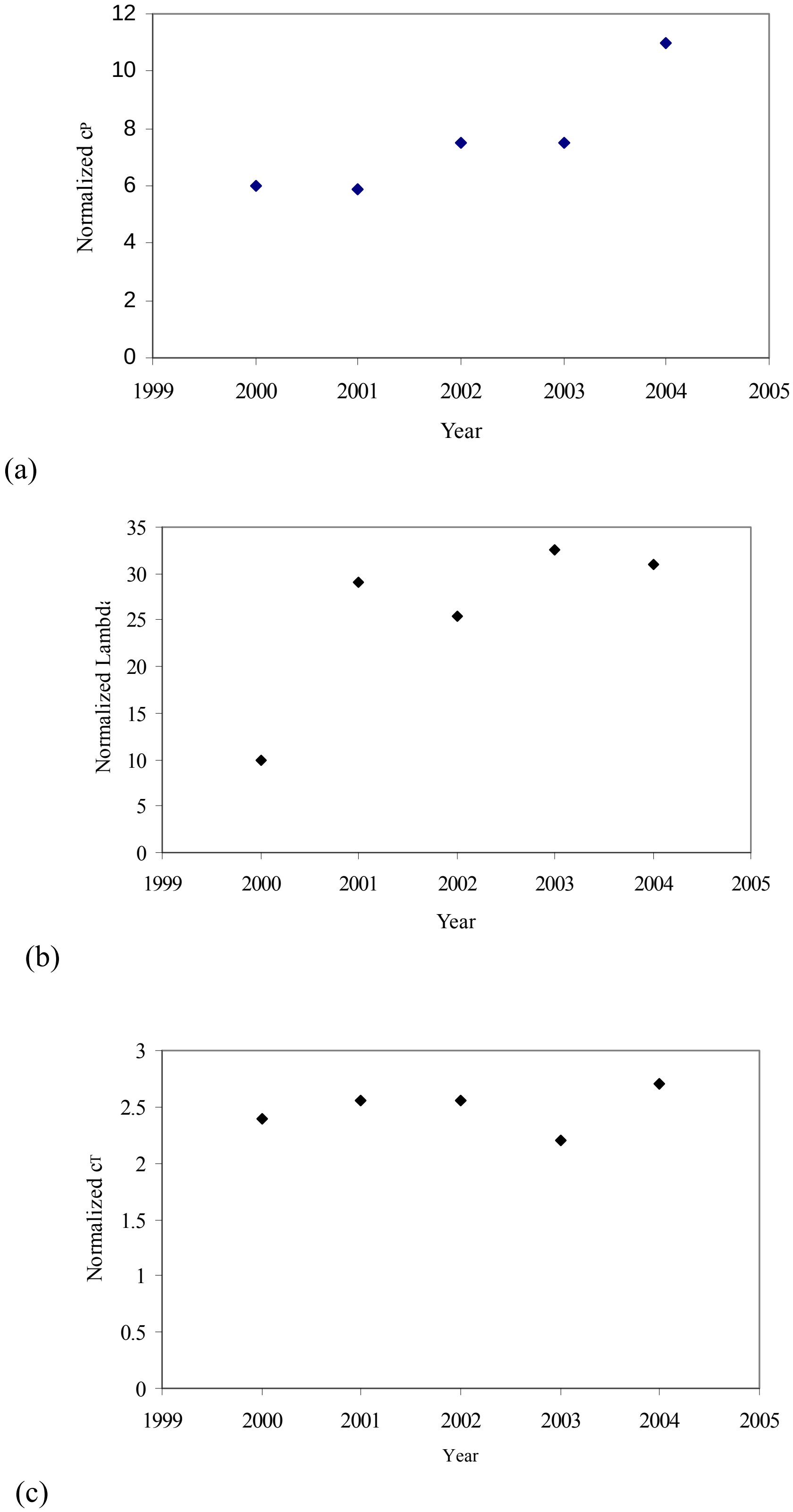
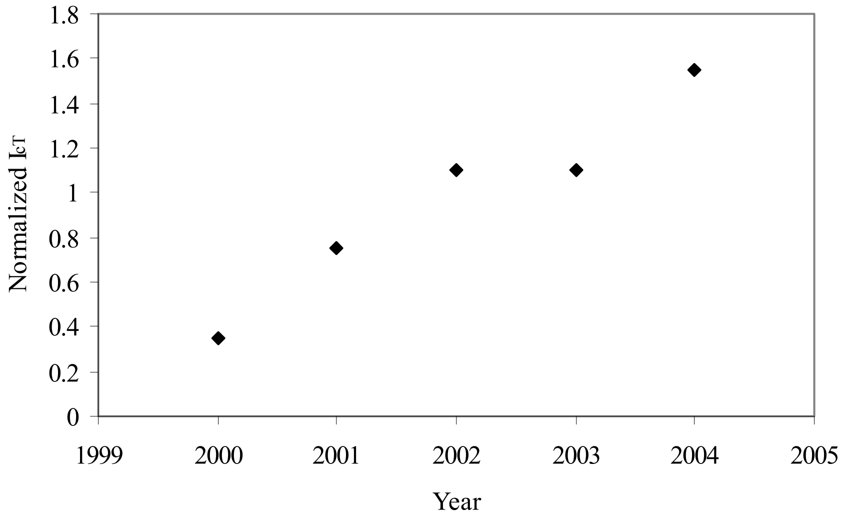
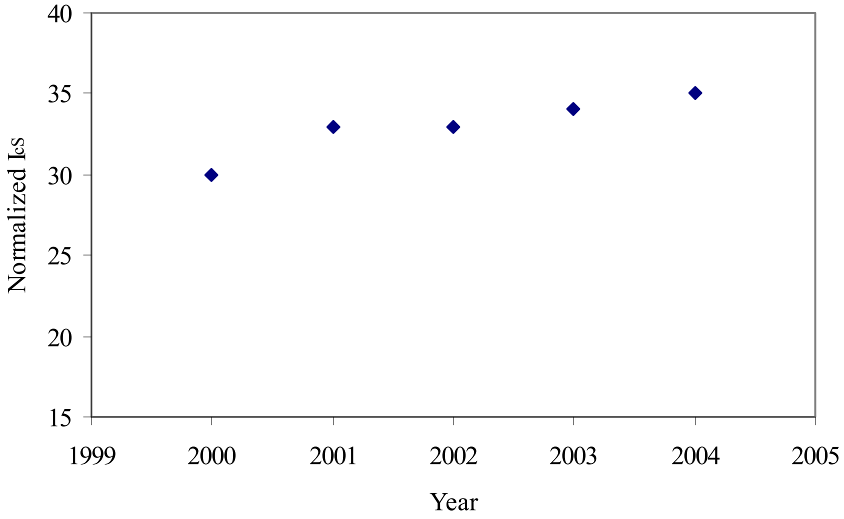


Figure 5. Normalized Evapotranspiration parameters (sub-watershed D1).

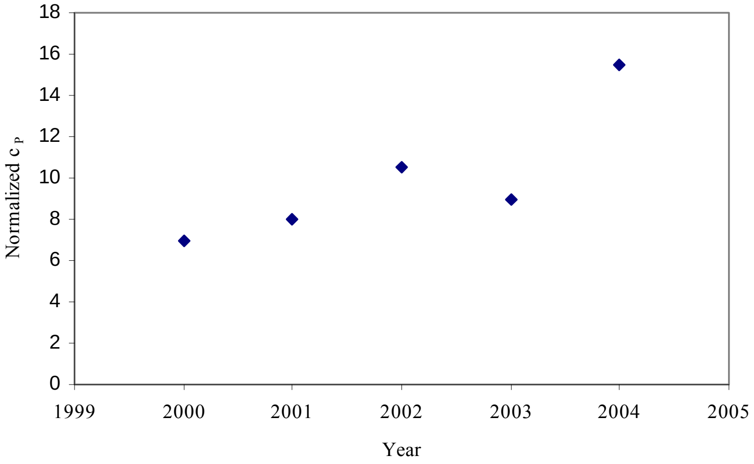


(a)

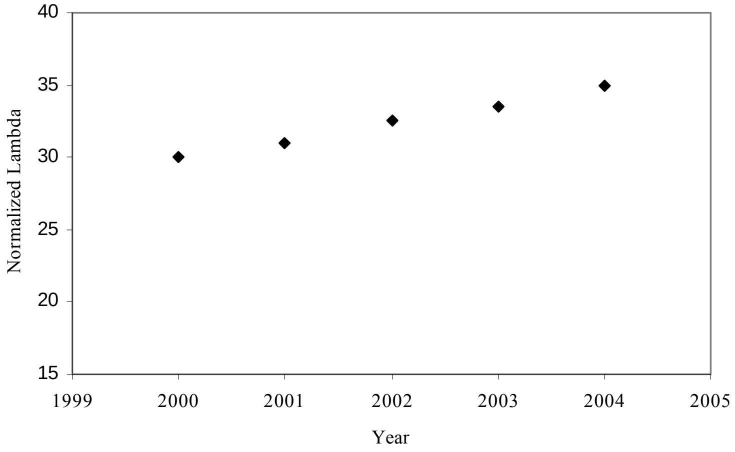


(b)

Figure 6. Normalized infiltration parameters (sub-watershed D1).



(a)



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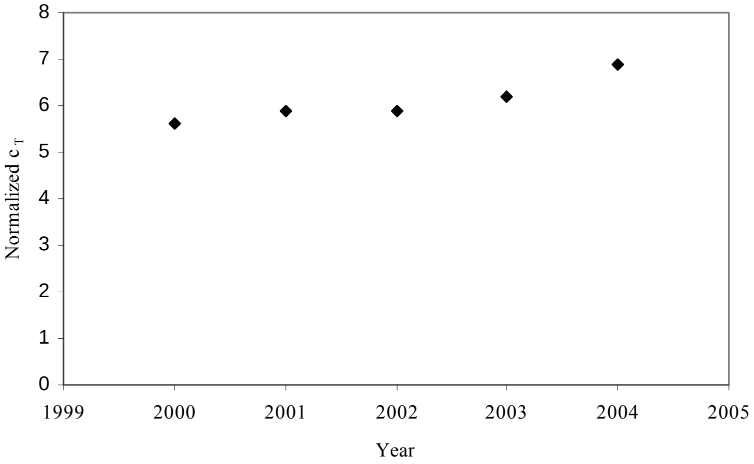
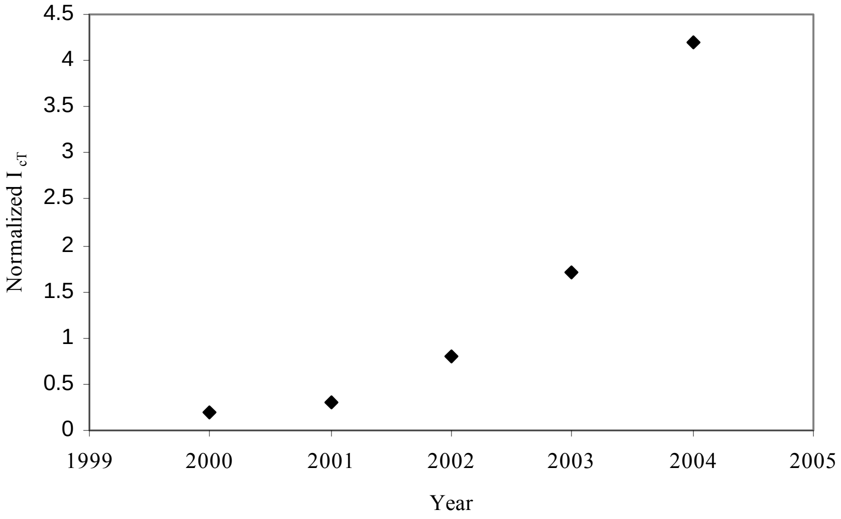
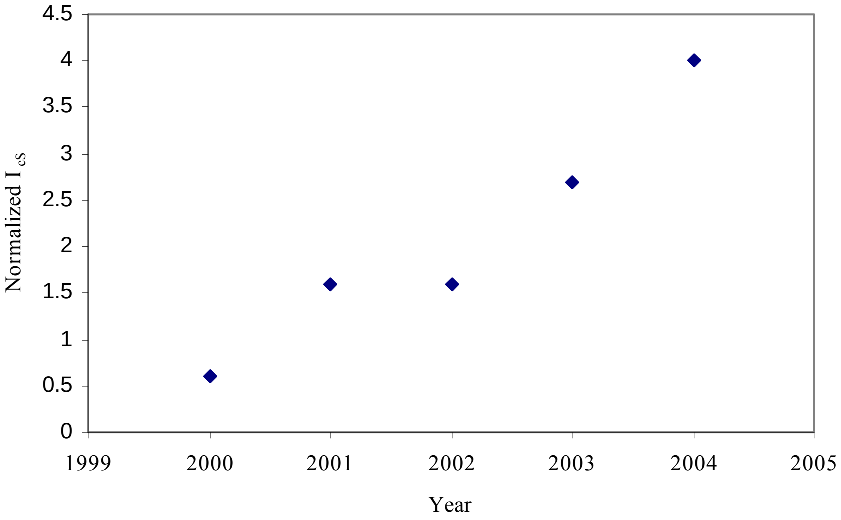


(c)

Figure 7. Normalized Evapotranspiration parameters (sub-watershed D2).

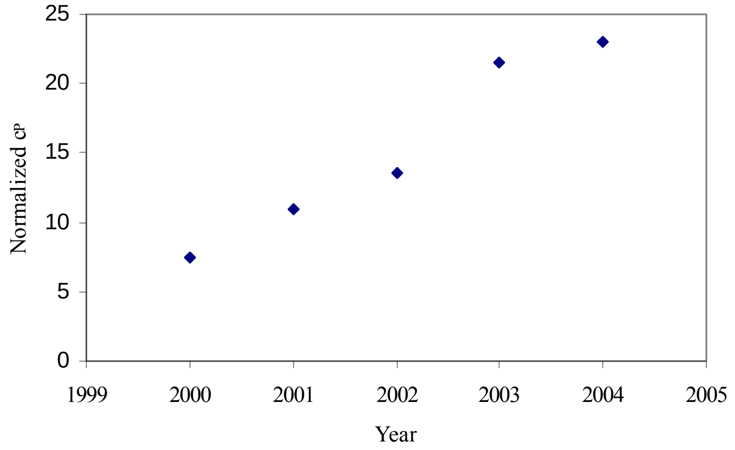


(a)

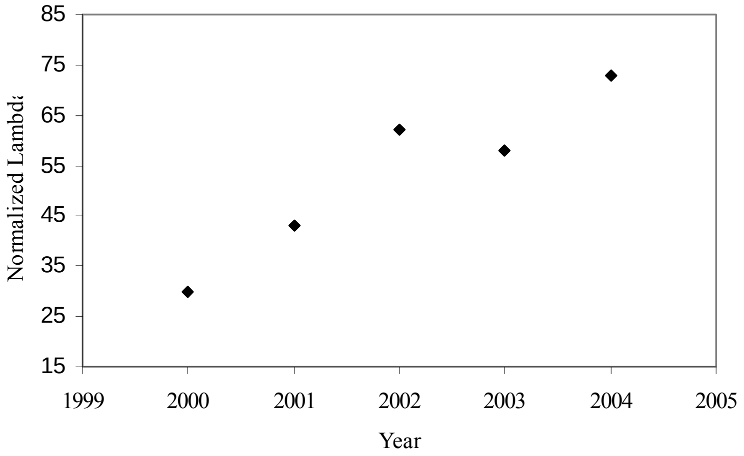


(b)

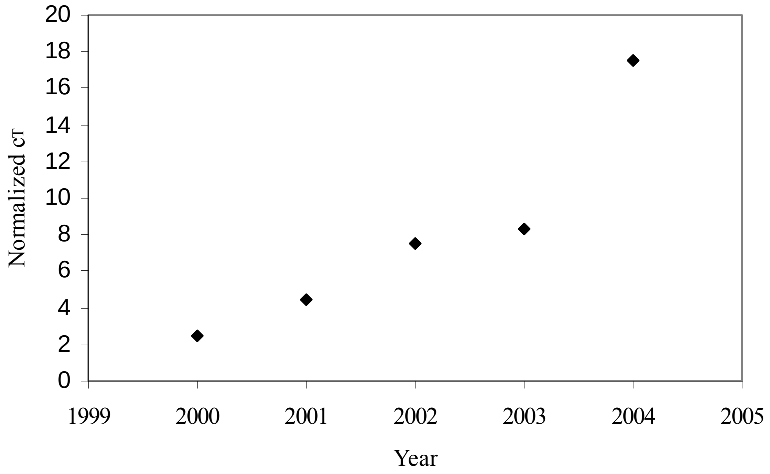
Figure 8. Normalized infiltration parameters (sub-watershed D2).



(a)

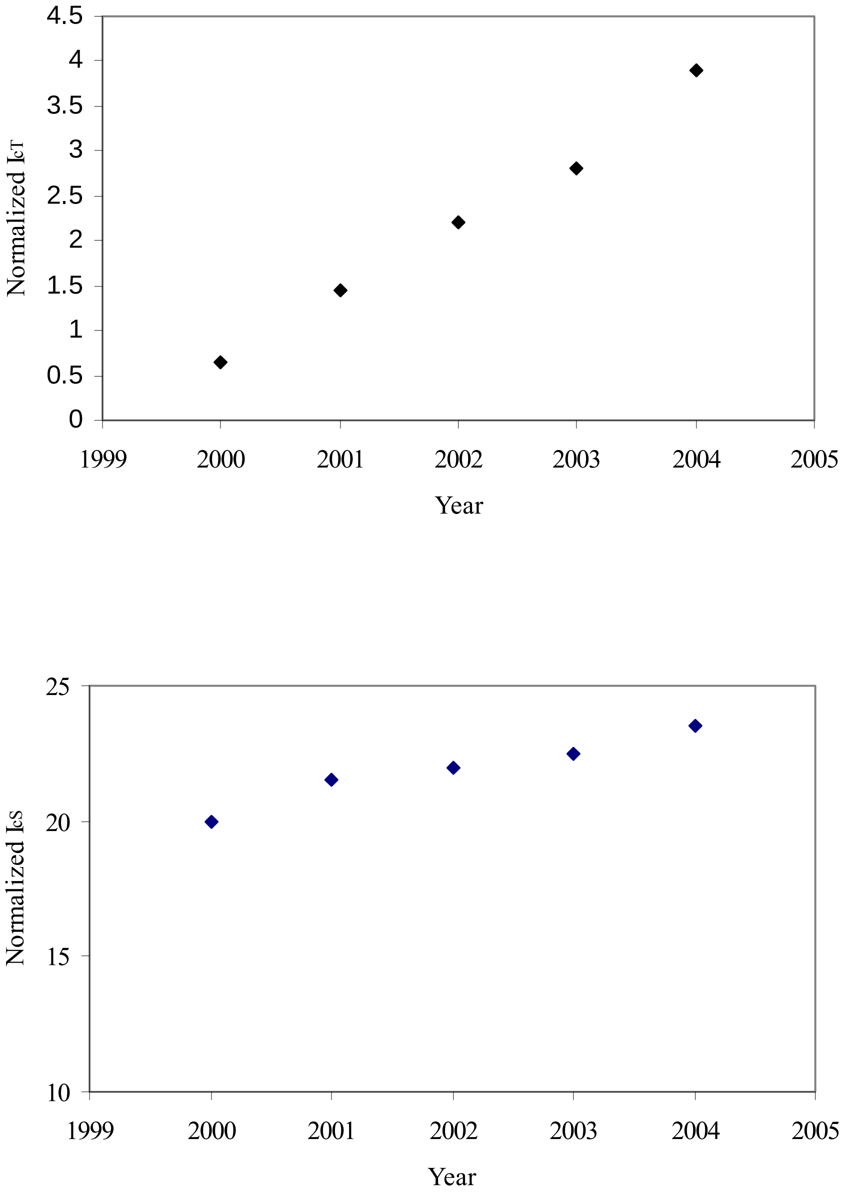


(b)



(c)

Figure 9. Normalized Evapotranspiration parameters (sub-watershed D3).



(a)

(b)

Figure 10. Normalized infiltration parameters (sub-watershed D3).