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Dynamic emergy accounting for assessing the environmental benefits of subtropical wetland stormwater management systems

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Abstract

An eco-hydrological model of a subtropical urbanizing watershed in south Florida, USA was developed to simulate solar emergy using H.T. Odum's energy systems language as programmed in an iconographic simulation software (i.e., Extend®) to provide dynamic valuation of a wetland stormwater management system (WSMS). The solar emergy (i.e., ultimate amount of solar energy required to produce another form of energy) and emdollar (EM$, value an energy flow contributes to an economy based on its proportion of total emergy flow) values of watershed transpiration (a measure of productivity), surface discharge and change in landscape water storage were quantified for various ratios of wetland to upland areas, valuing wetlands in EM$ ha^{-1} y^{-1}. Simulation results indicated that integrating a WSMS into the watershed increased landscape productivity, decreased surface discharge and increased surface water storage. The eco-hydrological value of watershed productivity was 367 EM$ ha^{-1} y^{-1} when 10% of the watershed was wetland, which was an increase of 65 EM$ ha^{-1} y^{-1} (based on Florida's emergy-to-dollar ratio in 1985, 2×10^{12} sej $\$^{-1}$). The annual contribution of this extra ecological productivity to public welfare was 12 million EM$, which was estimated from the product of eco-hydrological value and local emergy investment ratio of south Dade County (18:1). Average emdollar value of water saved per unit of wetland was 343 EM$ ha^{-1} y^{-1}. Dynamic emergy accounting provided distributions of solar transformities of hydrologic variables as opposed to more commonly used point estimates. Our work advances the temporal dynamic principles of emergy accounting by demonstrating how solar emergy may be continuously tracked through an ecosystem to estimate the value of nature's life-support services.

Keywords: Emergy; Wetland value; Florida Everglades; Ecosystem services; Stormwater wetlands

1. Introduction

Integrating the ecological and hydrologic systems of urban centers into the developed landscape to serve as water quality filters, wildlife habitat and water reservoirs are important goals for achieving economic and

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environmental sustainability. Restoring and creating wetlands in metropolitan areas for stormwater management is one ecological engineering approach that fosters sustainability. Tools for measuring the ecological and hydrological benefits that urban stormwater wetlands provide are needed, so society can more fully assess their multiple benefits and economic costs.

Emergy (with an 'm') evaluation has been evolving over the past four decades as an environmental accounting tool for measuring the contribution of nature's services to economic activities (Odum, 1996; Brown et al., 2000, 2003, in press; Kangas, 2003). Following H.T. Odum's publication of *Environmental Accounting* in 1996, which formalized the emergy accounting approach, publication of emergy evaluations of environmental, energy and ecological-economic systems has accelerated (Brown and Ulgiati, 2004a,b). A review of the most recent examples of applications of emergy evaluation follows. Beck et al. (2001) compared the emergy inputs required to develop and operate four types of urban food production systems (e.g., organic home gardening and edible landscape) to discover that the systems were unsustainable due to miniscule emergy yield ratios (0.0003–0.17) and high environmental loading ratios, which were dominated by the massive economic inputs (e.g., labor and plant materials). Brown and Vivas (2005) created a Landscape Development Intensity (LDI) index that is based on non-renewable emergy use of land uses (e.g., recreational open space and industrial) of a watershed to quantify potential impacts to wetlands. Brown and Ulgiati (2001) found that coastal eco-tourism projects in Papua New Guinea and Mexico had environmental loads 150 and 24 times as intense as the local economy based on emergy flows, respectively, which lead them to conclude the projects were unsustainable. Similarly, Campbell (1998) employed emergy evaluation to assess the human carrying capacity of the U.S. state of Maine, concluding human populations must adjust their environmental load in the context of global-scale pattern of economic pulsing cycles. Higgins (2003) and Tilley and Swank (2003) explored the nuances of conducting emergy evaluations of ecological systems that supported unique human cultural and scientific endeavors with multiple public benefits. Carraretto et al. (2004) confirmed that biodiesel required on the order of three times as much solar emergy per unit of exergy produced as fossils fuels like petroleum and natural gas, which was comparable to estimates made by Ulgiati (2001). Their study estimated the emergy yield ratio of biodiesel fuel to be 1.2, indicating there was a large investment in the process for the yield given. Comar et al. (2005) found a slightly better emergy yield ratio for Brazilian castorbean production. Lou et al. (2004) built upon three traditional emergy indices (Emergy Yield Ratio, Environmental Loading Ratio and Emergy Sustainability Index) to offer three new indices (Index of Economic Performance, Index of Environmental Performance and Index of Sustainable Performance) that explicitly account for the emergy required to manage waste flows in industrial systems. Concerns for properly modeling information flow in service industries to be able to conduct emergy evaluations were discussed by Tilley (2003). Historical emergy accounting of the U.S. during its first 210 years as a republic (1790–2000) was presented by Tilley (in press) showing that the country's total emergy consumption (i.e., renewable plus non-renewable) grew exponentially, its emergy-to-dollar ratio declined exponentially and the annual rate of increase in emergy consumption was highest during the 1960s.

Comparison of emergy evaluation with other energy/environmental accounting methodologies, such as ecological cumulative exergy accounting, embodied energy analysis and extended exergy accounting were recently offered by Hau and Bakshi (2004), Herendeen (2004) and Sciubba and Ulgiati (2005), respectively.

Historically, nearly all emergy evaluations assumed system steady state and constant solar transformities (solar emergy per available energy), which transform available energy (exergy) to solar emergy. However, H.T. Odum lead the way in developing temporally dynamic emergy accounting as a modeling framework for defining mathematical equations and simulation models that incorporate temporal dynamics for emergy and transformities (Odum and Peterson, 1996; Odum, 1996; Odum and Odum, 2000).

Urban stormwater wetland hydrology is highly dynamic with wetlands exposed to extremes of drought or complete inundation for months. Depending on the regional hydrogeology and geomorphology, stormwater wetlands can play important roles in storing rainwaters, controlling groundwater levels and altering surface discharge. Accounting for the daily changes in the solar emergy of these flows and stock changes can be accomplished by employing temporally dynamic emergy accounting.

Whereas steady state emergy accounting, which integrates multiple system forcing factors (e.g., rain, soil genesis and fuel use) into one metric (i.e., solar emergy), has been evolving for several decades, the task of accounting for how system stocks accumulate solar emergy across time was initially investigated by H.T. Odum (Odum and Peterson, 1996; Odum, 1996; Odum and Odum, 2000) and is now a research frontier in emergy evaluation.

Our goals for this paper were to (1) demonstrate how dynamic emergy accounting principles could be used in an eco-hydrological simulation model to track the daily changes in the solar emergy of the water flows and storages in an urbanizing coastal watershed retrofitted with a wetland stormwater management system, (2) assess the eco-hydrological benefits of a WSMS based on dynamic emergy accounting and (3) demonstrate the temporal variability of solar transformities of water in various ecological processes and storages.

H.T. Odum's energy systems language was used to develop a spatially aggregated, eco-hydrologic watershed/wetland simulation model. The model combined hydrological and ecological processes to track surface discharge, groundwater exchange, evaporation, transpiration and changes in surface water storage to estimate the solar emergy and solar transformities of the hydrologic flows given the implementation of a WSMS into the watershed. The energy systems model was simulated with Extend® energy systems blocks (Odum and Peterson, 1996; Odum and Odum, 2000). The iconographic blocks represent sub-routines and possess mathematical properties for simulating mass, energy, emergy and transformity. Daily changes in variables, including emergy and transformity, were tracked to explore their temporal variability. Annual average changes in watershed emergy flows and storages were converted to equivalent emergy-dollars (emdollars) to gain perspective on the ecosystem service value of these public goods.

Emdollars are the equivalent amount of money that circulates in an economy due to the use of emergy (Odum, 1996). Conversion of emergy flows to emdollars redistributes total money flow in proportion to system emergy flow (Campbell et al., 2004). Emdollar value is calculated by dividing an emergy flow by the mean emergy-to-dollar ratio of the economy that encompasses the system investigated for a particular time period (i.e., typically a year). Because emdollars include measures of both environmental work and economic activity, a direct comparison of emdollars to dollars indicates the additional value contributed by nature. For example, if a wetland were found to have an emdollar value of 400 EM$, but its market price was only US$ 75, then emergy evaluation reveals that nature contributed 325 EM$ to the value of the wetland. An emergy evaluation of the U.S. state of West Virginia, which is a major supplier of coal to the nation, by Campbell et al. (2004) offered evidence that the emdollar value of the exported coal was 122×10^9 EM$ per year, but only had a dollar value of US$ 20×10^9, thus revealing that nature's work to produce coal was six times greater than the financial market's value. In our study, emdollars were compared to the taxable value of land, assumed to be a conservative and traditional measure of land's public value. We used Lopez-Barba's (1995) 1985 emergy-to-dollar ratio of Florida, USA (the demonstration location of the WSMS) for our study because this was the year nearest to the time period of the model validation data (1986–1988).

The effects of WSMS on the daily, simulated variability of the solar transformities of watershed hydrologic outputs (i.e., transpiration, surface discharge and sub-surface discharge) were investigated with time series and frequency distribution plots.

2. Dynamic emergy accounting

Emergy is defined as the available energy of one kind required directly and indirectly to make a product or provide a service (Odum, 1988). Emergy is used as an environmental accounting tool that can compare the work of the environment with the work of the human economy on a common basis. Emergy accounting is a biophysical approach to estimating the contribution of nature to economic activity as opposed to other methods that rely on a populations' perceived value of nature's contribution. Emergy would, for example, estimate the natural value of the water of the Floridan Aquifer based on the work of the environment to create and maintain the storage, whereas an approach based on a human's perspective might value it according to the market price of the water withdrawn. After estimating its natural value, emergy accounting would estimate the water's value to the public by considering the human-controlled energies used for its extraction and the potential economic amplification the water could produce in the economy (Buenfil, 2001). Inexpensive, clean, plentiful water from the Floridan Aquifer provides a significant amount of the free-energetic base to the Florida economy and its use has a multiplier effect on economic activity.

Emergy accounts for all natural and human energies by expressing energies of different types as energy of one type (commonly solar radiant power), measuring all energy used directly and indirectly to generate the energy of a product or service (Odum, 1996). Different types of energy are compared using the transformity, which is emergy per unit available energy of one form (e.g., chemical potential of freshwater). For example, electricity has a solar transformity of about 160,000 solar emjoules per joule (sej J^{-1}), while coal has a solar transformity of approximately 40,000 sej J^{-1} (Odum, 1996). Emergy evaluations use solar transformities of input energies to determine their solar emergy. Odum and Odum (2000) gave a new estimate for the global emergy input basis, which increased global solar emergy flow by a factor of 1.68. Solar transformities used in the simulation models we present were based on the older global emergy baseline of 9.44×10^{24} sej y^{-1}. Any reported solar emergy value or solar transformity could be updated by simply multiplying by 1.68. Emdollars were not affected by the change in baseline, thus they do not need any adjustment.

The empower (emergy per time) of an input that contributes to the economy of a nation, state, city, etc. can be expressed as emdollars by dividing the solar empower by the solar emergy-to-money ratio, which places solar empower in a human informational framework (i.e., money) that is hopefully easier to contextualize. Quantitatively, Em$ indicate how much an ecosystem service or product contributes to the economy. This allows environmental contributions, which are free to an economy, to be compared to more traditional macroeconomic measures.

The algorithm for simulating emergy and transformity of production and storage processes was given by H.T. Odum (Odum and Odum, 2000; Odum and Peterson, 1996; Odum, 1996). Emergy change of storage is defined to be dependent upon whether a state variable is increasing or decreasing. A coupled storage and production function, which is building storage in spite of depreciation, accumulates emergy from its individual inputs (being sure to avoid double counting) and loses emergy in outflow pathways that carry an intact part of the storage. For example, a forest receives emergy inputs via solar radiation, wind and precipitation, but may lose emergy when woody debris is carried away by streamflow. On the other hand, if storage is decreasing in energy content, then the emergy value of storage decreases at the same rate of storage decrease.

3. Description of study site

The Black Creek (C-1) drainage basin, which was the site used to develop, calibrate and simulate the emergy-based, eco-hydrology model, is located in the center of south Dade County, Florida, south of Miami, where it is a small part of the human-engineered drainage system of south Florida (Fig. 1). Two-thirds of the Black Creek basin's land use is non-urban and only 15% is impervious surface (Fig. 2). The L-30 canal transfers water from the Miami River southward to the Black Creek canal. Prior to European settlement of south Dade County, Black Creek was one of the 'Transverse Glades' (tidal channels formed during the Pleistocene that cut through the Coastal Ridge), that conveyed flood waters eastward from the Everglades to Biscayne Bay. Presently, the Transverse Glades contain many of the major urban drainage canals (USGS, 1973).

The climate of south Dade County is subtropical with a mean July temperature of 28 °C and a mean January temperature of 19 °C. Average annual rainfall is 1473 mm y^{-1}, with the average annual 10 year return period rainfall ranging between 1864 and 1179 mm y^{-1} (Sculley, 1986). The annual rainfall pattern is distinctly seasonal (Tilley, 1996) with two-thirds (982 mm) of rain falling during the wet season from May to October, and the remaining one-third (491 mm) falling during the dry season from November to April (Sculley, 1986).

Dade County is flat topographically with the highest points only 7.6 m above sea level and the majority of land less than 3.0 m above sea level. The study area is underlain by the unconfined Biscayne Aquifer, which is made up of hard limestone at its top and sandy limestone beneath. The base of the Biscayne Aquifer varies from about 3 m thick in western Dade to approximately

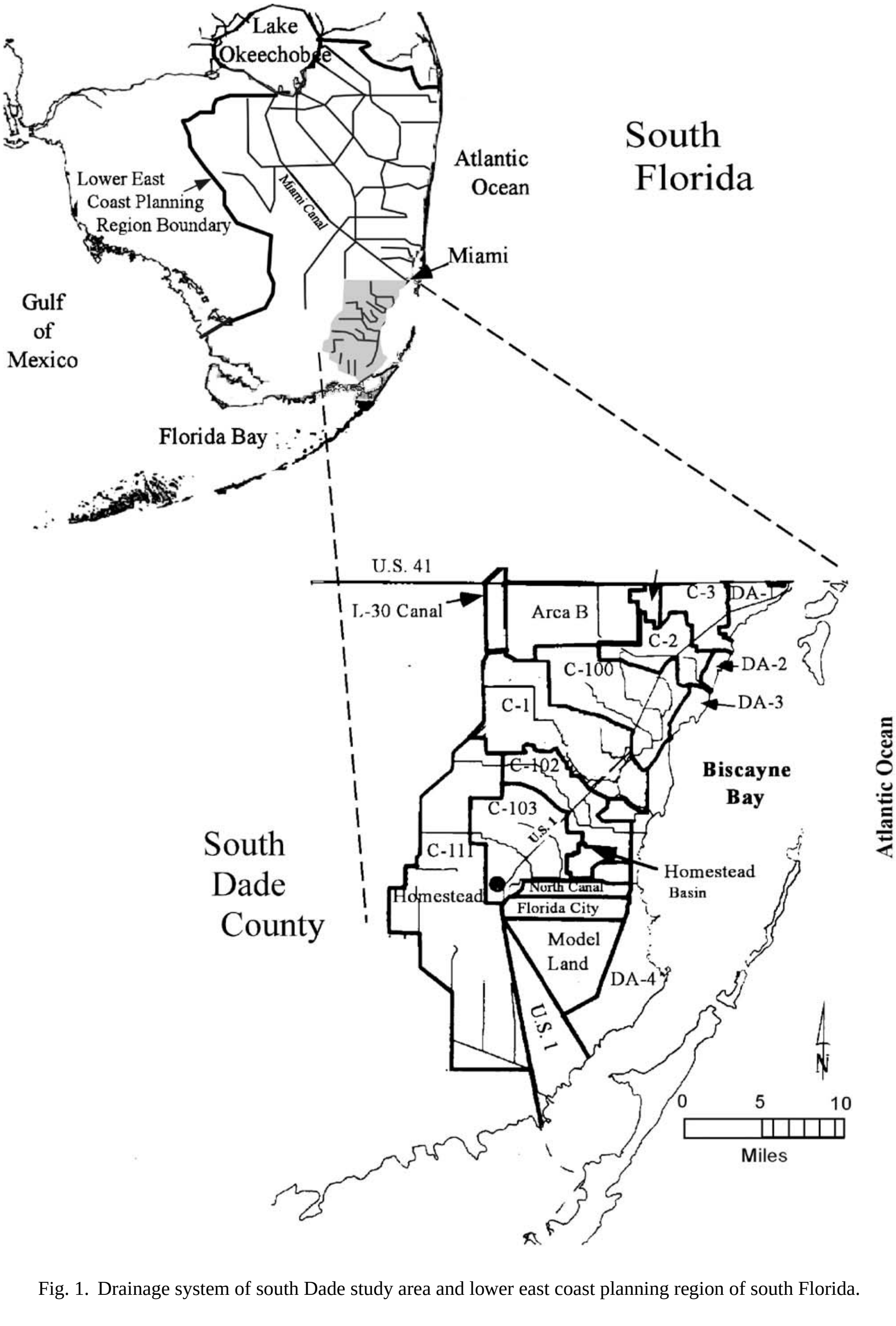


Fig. 1. Drainage system of south Dade study area and lower east coast planning region of south Florida.

Fig. 2. Landuse map of the Black Creek (C-1) watershed in 1988.

37 m along the coast (USGS, 1973). Water tables range from 1.5 to 0.3 m above sea level throughout the region (Fish and Stewart, 1991). The Biscayne Aquifer has porosity in the range of 20% (Parker, 1955) and transmissivities on the order of $1.0 \times 10^6\,m^2\,d^{-1}$ (Fish and Stewart, 1991). The surface geology consists of soft limestone (marl) (USGS, 1973).

4. Model development

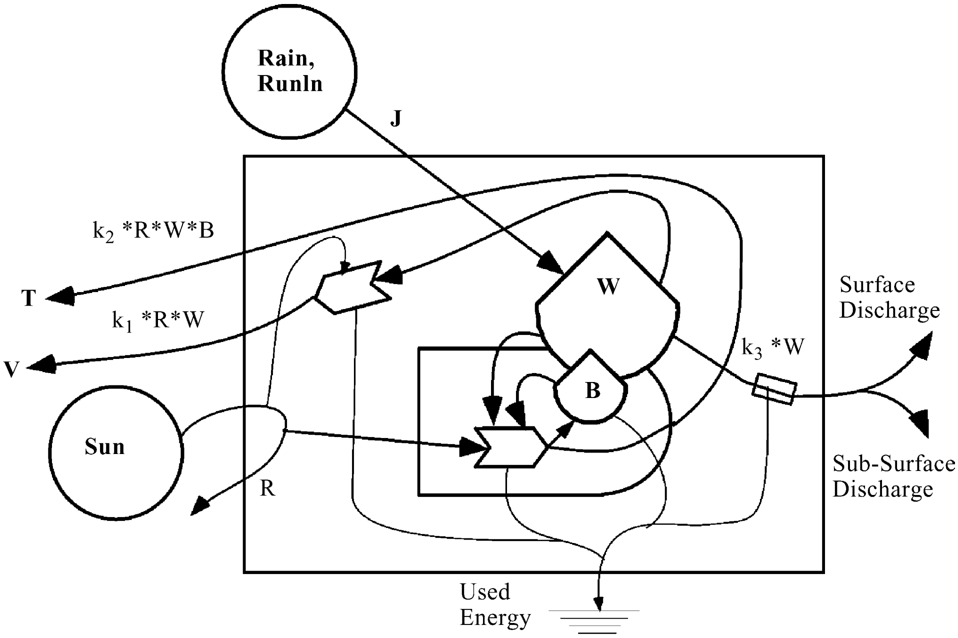
To evaluate configurations of wetland stormwater management systems and to test theories of temporal changes in empower resulting from the interplay of water and landscapes, a computer simulation model was developed using the energy systems symbol language devised by H.T. Odum (Odum, 1983, 1994, 1996; Odum and Odum, 2000). The process of developing the eco-hydrological, emergy accounting simulation went as follows:

1. Complex diagrams of the system were drawn arranging all relevant driving energies, internal components and pathways according to their solar transformity.
2. Diagrams were aggregated to reduce complexity by selecting the forcing functions, components, flows and processes that contributed or processed the most solar emergy.
3. Computer simulation models were constructed from the systems diagram using H.T. Odum's (Odum and Odum, 2000) energy systems blocks in Extend® iconographic simulation software.
4. Energy sources, pathway coefficients and storages were calibrated from literature-derived values.
5. The model was validated against historic hydrological data.

4.1. Energy systems blocks in Extend®

Extend® blocks representing energy systems symbols were previously created and incorporated into icon libraries (see Odum and Odum, 2000). To create an energy systems model in Extend®, the energy system blocks were arranged as in the energy systems diagram. Pathways were then added to the Extend® model by connecting the energy systems blocks via the block connectors. Programming computer code was unnecessary in Extend® since the energy systems blocks had the appropriate code for their mathematical representation (Odum and Odum, 2000). Once connected with flow pathways, the Extend® model was a mathematical representation of the systems diagram.[1]

[1] Extend by Imagine That, Inc., 6830 Via Del Oro. Suite 230, San Jose, CA 95119, USA.



Water Stored (W): $dW/dt = J - K_1 * R * W - k_2 * R * W * B - k_3 * W$

Emergy Stored (E): If $dW/dt > 0$ then

$dE/dt = Tr_j * J - Tr_w * k_3 * W$

if $dW/dt < 0$ then

$dE/dt = Tr_w * dW/dt$

if $dW/dt = 0$ then

$dE/dt = 0$

Transformity of $W = Tr_w = E/W$

Fig. 3. Energy systems diagram with equations for simulating emergy changes in watershed storages. Evaporation and transpiration did not remove emergy from the storage, whereas surface and sub-surface discharge did. (B, biomass; W, water; T, transpiration; V, evaporation; R, available insolation; J, water inflow; t, time; Tr, transformity and E, emergy.)

4.1.1. Simulating emergy

Equations for simulating solar emergy were coded in the Extend energy systems blocks (Odum and Peterson, 1996). Solar transformities of forcing functions (e.g., rainfall and solar radiation) and initial storage values were chosen based on literature values (Odum, 1996). Fig. 3 shows an energy systems diagram defining how the emergy value of water flows and storages were simulated in the watershed model. The time rate of change of water stored was a balance of inputs and outputs. The change in emergy of water stored was described by three equations. The equation applied was contingent upon the sign of the change in water stored. If water stored increased, the change in emergy stored was the sum of total empower input minus empower output. If amount stored did not change, then emergy did not change. When water stored decreased, the emergy stored was reduced by the product of water output and its transformity.

Water evaporated or transpired did not reduce the emergy value of water stored because this was dispersed material being recycled at the larger scale and had lost its ability to do work in the watershed system. This rule assumed that evapotranspiration was a necessary loss in the process of producing surface discharge and groundwater recharge. Water leaving as surface discharge or sub-surface recharge carried the transformity of water stored, thus outflowing water removed emergy from the stored water.

4.1.2. Calibration of eco-hydrological model

The eco-hydrological model was calibrated with rate constants previously determined for the south Dade region. Calibration and validation were conducted assuming that there was no WSMS in the Black Creek (C-1) basin since there was little wetland area during the period simulated. The model was then modified to include a WSMS, which meant including state variables for wetland water, wetland soil moisture and wetland biomass and flows for surface runoff, wetland evapotranspiration (ET) and canal input to the wetland.

4.1.3. Model validation

Validation of the model was accomplished by comparing simulated values of canal discharge and surficial aquifer levels to actual time series data for the Black Creek basin. In addition, other model parameters (i.e., infiltration, surface runoff, evaporation, transpiration and recharge) were compared to values typical for south Florida. Validation consisted of running the model with 3 years of actual rainfall and canal inflow data for the period 1986–1988. Daily rainfall and canal inflow data were from measurements taken at the Miami International Airport and at the S-338 control structure located at the upstream end of the Black Creek canal, respectively. The simulated canal discharge was compared to flow measurements taken at the S-21 control structure on the Black Creek The simulated average watershed water table level was compared to measurements taken at the G1362 observation well located near the center of the watershed.

4.1.4. Emdollar evaluation of wetland hydrologic properties

Values for the WSMS include an eco-hydrological value (i.e., landscape water conservation and water used for ecological life-support) and a public value (i.e., direct human use, such as irrigation, consumption and industrial process). Eco-hydrological values were estimated from (1) the emdollar flow associated with surface discharge and transpiration and (2) the emdollar value of the extra water storage capacity in the basin. Simulated empower and emergy were converted to emdollars by dividing by the 1985 emergy-to-dollar ratio of Florida (2.0×10^{12} sej $\$^{-1}$, Lopez-Barba, 1995). The mean daily emdollar value of surface water discharge to Biscayne Bay was plotted against the size of the WSMS and the slope of a least-squares fit was taken to represent the annual value of water saved per area of WSMS (EM\$ ha^{-1} y^{-1}). An estimate of average public value was found by multiplying the solar emergy of the water saved by the average regional (i.e., south Dade County) solar emergy investment ratio (7:1 in 1988; Lopez-Barba, 1995). This assumed that the water, as a basic material for economic activity, had the ability to attract more economic investment to the region. In other words, the public value estimate considered the economic multiplier effect of the water.

4.2. Model description

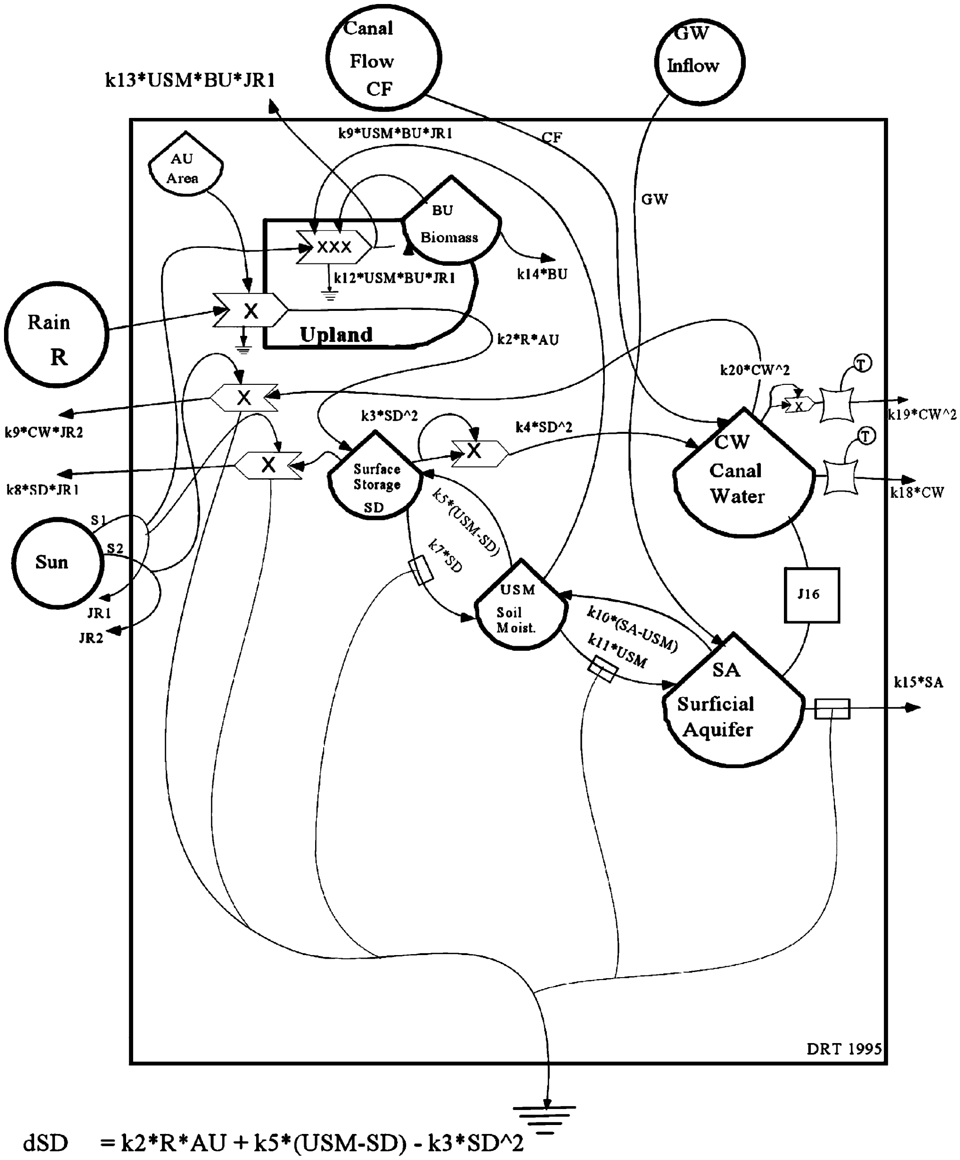
The simulation model (Figs. 4 and 5) was developed for low-relief watersheds that may or may not have wetland areas for surface water storage. In Fig. 4, the diagram has the pathways labeled with algebraic expressions and the difference equations provided at the bottom. Fig. 5 gives the value of inputs, storages and flows used in model calibration.

4.2.1. System boundary conditions

The system was a volume defined by the watershed divide, the base of the surficial aquifer and a plane parallel to the treeline. It has sunlight (S), rain (R), canal inflow (CF) and groundwater (GW) as forcing functions (Fig. 4). Sunlight was standardized to a sine function with a mean amplitude and period. Rainfall ($m\,d^{-1}$) was multiplied by upland area to obtain volume of rainfall ($m^3\,d^{-1}$) flowing into surface storage (SD). To simulate the existing conditions actual rainfall data measured at the Miami International Airport for the period 1986–1988 and actual canal inflow measured by SFWMD at the upstream S-338 control structure on the Black Creek (C-1) canal was used. Groundwater inflow to the surficial aquifer storage was assumed constant at 34,000 $m^3\,d^{-1}$ (or 0.33 $mm\,d^{-1}$) during simulations. Fig. 6 is a graph of the daily rainfall, daily canal inflow and daily sub-surface inflow used as input to the model.

4.2.2. State variables

The system state variables were upland area (AU), upland biomass (BU), surface storage, soil moisture



$$dSD = k2*R*AU + k5*(USM-SD) - k3*SD^{\wedge}2 - k7*SD - k8*SD*JR1$$

$$dUSM = k7*SD + k10*(SA-USM) - k5*(USM-SD) - k9*USM*BU*JR1 - k11*USM$$

$$dSA = k11*USM + GW + J16 - k10*(SA-USM) - k15*SA$$

$$dCW = CF + k4*SD^{\wedge}2 - k20*CW^{\wedge}2 - k18*CW - J16 - k9*CW*JR2$$

$$J16 = k16*[(\text{elevation of SA} - \text{elevation of CW}) *\text{Canal Perimeter}]$$

$$dBU = k12*USM*BU*JR1 - k14*BU$$

$$JR1 = S1 / (1 + ks1a*USM*BU + ks1b*SD)$$

$$JR2 = S2 / (1 + ks2*CW)$$

R = Rainfall Data File
CF = Canal Flow Data File
GW = Constant Flow
S1,S2 = Sine Wave

Fig. 4. Energy systems diagram of watershed model containing no significant amount of wetland storage. Algebraic expressions are written on pathways and rate of change equations for state variables are given below.

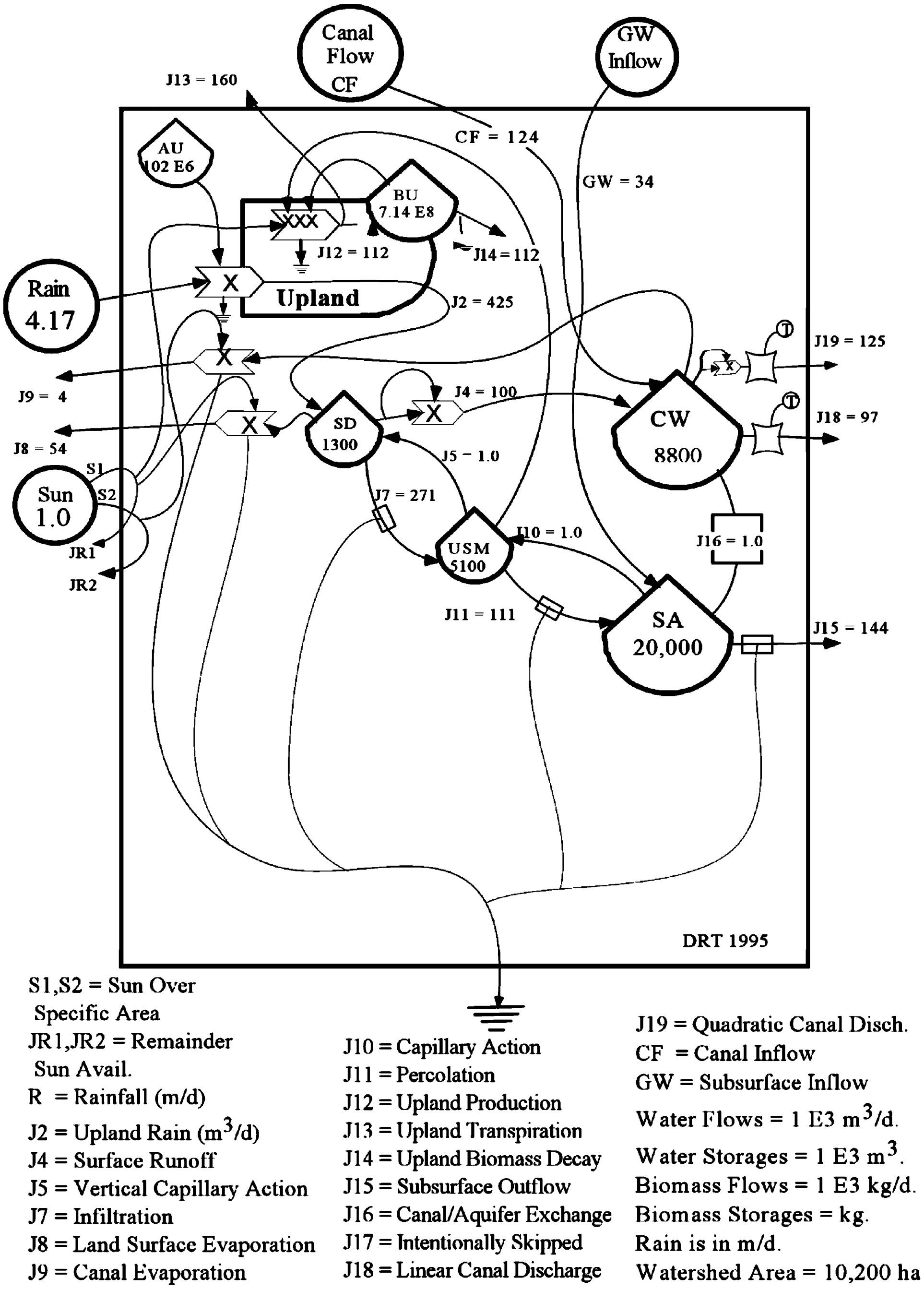


Fig. 5. Energy systems diagram of watershed model with no wetland storage with definitions and calibration values of flows and storages (AU, area; BU, biomass; SD, surface storage; USM, upland soil moisture; CW, canal water; SA, surficial aquifer).

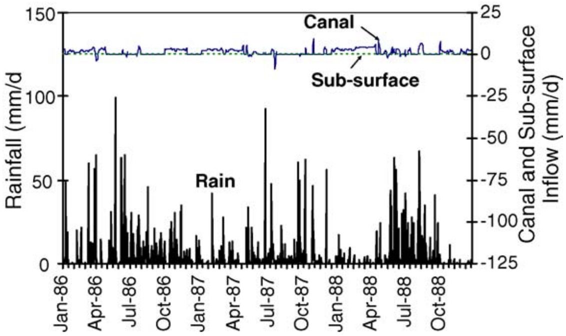


Fig. 6. Rainfall, canal inflow and sub-surface inflow used as input for simulating Black Creek (C-1) watershed.

(USM), surficial aquifer water (SA) and canal water (CW). The upland area was the entire Black Creek watershed (10,200 ha). The upland biomass represented total ecosystem biomass on non-paved areas, and was assumed to have characteristics typical of urban open-land or a south Florida grassy scrub ecosystem. Rainwater that accumulated on the land surface, temporarily retained, was represented by surface storage. The soil moisture storage represented the subsurface water between the ground surface and the surficial aquifer that was available for upland transpiration and capillary rise to surface storage. The thickness of the surficial aquifer was assumed to average one meter (1.0 m) with a porosity of 0.20 (Parker, 1955). The size of the canal storage (8.8 million m^3) was derived based on a total canal length of 44,000 m, a mean width of 20 m and a mean depth of 10 m, which represented the water of the entire watershed canal system.

4.2.3. Interactions and pathways

Upland gross ecosystem production (J12) was a function of sunlight, soil moisture and upland biomass (Fig. 5). Sunlight was a flow limited forcing function, i.e., only the unused portion of the sunlight flow (JR) was available for producing more biomass. Ecosystem respiration (J14) was a linear function of the upland biomass storage. Net ecosystem production was the difference between the two.

The volume of rainfall, calculated as the product of daily rainfall ($m\,d^{-1}$) and watershed area (m^2), was directed to surface storage (Fig. 5). The surface storage also received capillary rise (J5) from the soil moisture zone. Water exited the surface storage either as evaporation (J8), infiltration (J7) or surface runoff (J4). Sunlight interacted with surface storage to produce evaporation. Infiltration entered the soil moisture zone as a linear function of the surface storage value. Surface runoff was directed to the canal in proportion to the square of surface storage. This mathematical relationship forced surface runoff to become a larger percentage of rainfall as rainfall intensity increased with significant surface runoff not occurring until rainfall intensity was greater than $6.0\,mm\,d^{-1}$.

In addition to receiving surface runoff, the canal storage received input from the surficial aquifer (J16) and canal inflow. Surface discharge from the canal was the sum of a linear (J18) and a quadratic (J19) function of canal water storage. Each of these pathways was controlled by a switch representing human operation of the control structure located at the mouth of the canal. Discharge could be completely stopped (i.e., J18 = J19 = 0) with the switch. The pathway between the canal and surficial aquifer could have flow in either direction, i.e., groundwater recharge and discharge. The direction and magnitude of flow (J16) was determined by the equation given at the bottom of Fig. 4, which was represented symbolically by a miscellaneous box.

Infiltration from surface storage (J7) provided the majority of input to the soil moisture zone. Soil moisture also received capillary rise from the surficial aquifer (J10). The rate of capillary rise was proportional to the difference between surficial aquifer volume and soil moisture volume. Upland biomass transpired water from the soil moisture storage (J13). Water also percolated to the surficial aquifer (J11) as a linear function of soil moisture.

Groundwater inflow was directed to the surficial aquifer. The surficial storage received water from soil moisture (J11) and sub-surface discharge from the canal (J16). Sub-surface outflow from the surficial aquifer (J15) and capillary rise to the soil moisture storage (J10) were pathways for water leaving the groundwater. Groundwater outflow (J15) was a linear function of surficial aquifer volume. The rate of capillary rise was proportional to the difference between soil moisture volume and surficial aquifer volume.

4.3. Model calibration

Values used to calibrate the watershed model are displayed on pathways and storages in Fig. 5. A description of flow pathways appears along with the difference

Table 1
Description of driving energies, storages, and flow data used to calibrate Black Creek (C-1) watershed model given in Fig. 12

Note	Description	Variable	Equation	Calibration				Reference
				Value	Unit	*k*-Value		
Inputs								
1	Rainfall	R		1524	$mm\ y^{-1}$			Sculley (1986)
2	Insolation	S		1	n.a.			
3	Canal inflow	CF		124,000	$m^3\ d^{-1}$			SFWMD (1993)
4	Groundwater inflow	GW		34,000	$m^3\ d^{-1}$			SFWMD (1993)
Flows								
5	Upland rainfall volume	J2	k2 × R × AU	425	$10^3\ m^3\ d^{-1}$	1.00	Rainfall rate × watershed area	
6	Surface runoff	J4	$k4 \times SD^2$	100	$10^3\ m^3\ d^{-1}$	5.69E − 08	Estimated as 24% of rainfall	
7	Vertical capillary action	J5	k5 × (USM–SD)	1	$10^3\ m^3\ d^{-1}$	2.65E − 04	Assumed	
8	Soil infiltration	J7	k7 × SD	271	$10^3\ m^3\ d^{-1}$	2.04E − 01	By difference, J2–J4–J8	
9	Upland surface evaporation	J8	k8 × SD × JR1	54	$10^3\ m^3\ d^{-1}$	6.27E − 02	Estimated as 0.5 $mm\ d^{-1}$	
10	Canal evaporation	J9	k9 × SD × JR2	4	$10^3\ m^3\ d^{-1}$	4.64E − 03 estimated as 4.5 $mm\ d^{-1}$		
11	Vertical capillary action	J10	k10 × (SA–USM)	1	$10^3\ m^3\ d^{-1}$	6.54E − 05	Assumed	
12	Remainder of upland insolation	JR1	S1/(1 + ks1a × USM × BU + ks1b × SD)	0.65	n.a.		Assumed	
13	Remainder of canal insolation	JR2	S2/(1 + ks2 × CW)	0.65	n.a.		Assumed	
14	Percolation to surficial aquifer	J11	k11 × USM	111	$10^3\ m^3\ d^{-1}$	2.18E − 02	By difference, J7–J13	
15	Gross upland production	J12	k12 × USM × JR1 × BU	112	$10^3\ kg\ d^{-1}$	4.73E − 11	Assumed	
16	Upland transpiration	J13	k13 × USM × JR1 × BU	160	$10^3\ m^3\ d^{-1}$	6.76E − 11	Estimated as 1.6 $mm\ d^{-1}$	Carter et al. (1973)
17	Upland biomass decay	J14	k14 × BU	112	$10^3\ kg\ d^{-1}$	1.57E − 04	Equal to J12	
18	Surficial aquifer system outflow	J15	k15 × SA	144	$10^3\ m^3\ d^{-1}$	7.06E − 03	For balance, outflow = inflow	
19	Canal/aquifer exchange	J16	k16 × [(elevation of SA − elevation of CW) × canal perimeter]	1	$10^3\ m^3\ d^{-1}$	−1.14E − 03		Heimburg (1976)
20	Canal discharge, linear	J18	k18 × CW	97	$10^3\ m^3\ d^{-1}$	1.10E − 02	Assumed 45% of discharge	SFWMD (1993)
21	Canal discharge, quadratic	J19	$k19 \times CW^2$	125	$10^3\ m^3\ d^{-1}$	1.61E − 09	Assumed 55% of discharge	SFWMD (1993)
Storages								
22	Upland biomass	BU		714,000,000	kg			
	per m^2			7	$kg\ m^2$		Estimated as 50% of forested upland	
23	Surface detention	SD	Area × mean depth	1,326,000	m^3			
	Mean depth			13	mm		Assumed 3 day residence time	
24	Upland soil moisture	USM	Area × depth × porosity	5,100,000	m^3			
	Mean depth			0.25	m		Assumed	
	Mean porosity			20%			Assumed	
25	Surficial aquifer volume	SA	Area × depth × porosity	20,400,000	m^3			
26	Surficial aquifer depth			1	m			USGS (1973)
27	Surficial aquifer porosity			20%				Parker (1955)
28	Canal water	CW	Length × width × depth	8,800,000	m^3			

29	Length		44,000	m	
30	Mean depth		10	m	USGS (1973)
31	Mean Width		20	m	USGS (1973)
32	Upland area	AU	102,000,000	m^2	
33	Black Creek watershed area		102,000,000	m^2	SFWMD (1993)

Note: 1, simulated with daily data from 1986 to 1988 (Sculley, 1986); 2, sine wave with mean of 1.0, range of ±0.25 and annual period; 3, simulated with daily data from 1986 to 1988 (SFWMD, 1993); 4, simulated with constant rate (SFWMD, 1993); 5, rainfall rate × watershed area; 6, estimated as 24% of rainfall; 7, assumed; 8, by difference, J2–J4–J8; 9, estimated as 0.5 mm d^{-1}; 10, estimated as 4.5 mm d^{-1}; 11, assumed; 12, assumed; 13, assumed; 14, by difference, J7–J13; 15, assumed; 16, estimated as 1.6 mm d^{-1} (Carter et al., 1973); 17, equal to J12; 18, for balance, outflow = inflow; 19, elevation difference integrated over perimeter (Heimburg, 1976); 20, assumed 45% of discharge (SFWMD, 1993); 21, assumed 55% of discharge (SFWMD, 1993); 22, estimated as 50% of forested upland; 23, assumed 3 day residence time; 24, assumed; 25, area × depth × porosity; 26, assumed 1 m thick; 27, reported average (Parker, 1955); 28, L × W × D; 29, estimated from map; 30, assumed average; 31, assumed average; 32, (SFWMD, 1994).

equations, calibration values, units of measurement and values of pathway coefficients (*k*'s) in Table 1. Assumptions and literature references for the derived calibration values are explained there as well.

4.3.1. Sources

Sunlight was standardized to a sine function with a mean of 1.0 unit per day, amplitude of 0.50 units, and a period of 1 year. Maximum intensity occurred in July and minimum in January. Rainfall was taken as a constant daily value of 4.17 mm d^{-1} during calibration, but actual, measured daily rainfall was used during validation and simulations. This was the mean annual rainfall (1522 mm y^{-1}) reported by Sculley (1986) divided by 365 days. A constant value of 124,000 $m^3\,d^{-1}$ (1.22 mm d^{-1}) derived from SFWMD (1993) water budgets was used for canal inflow. Groundwater input (34,000 $m^3\,d^{-1}$ or 0.33 mm d^{-1}) was derived from SFWMD (1993) water budgets completed for the District's Lower East Coast Region.

4.3.2. State variables

Total upland biomass used in calibration was 7 kg m^{-2} or 714×10^6 kg for the watershed. A value of 1.3 million m^3 (13 mm depth) for surface storage calibration was derived by assuming an average residence time of 3 days for rainfall. The soil moisture storage was assumed to average 0.25 m deep with a porosity of 0.20, giving a volume of $5.1 \times 10^6\,m^3$. A value of $20.0 \times 10^6\,m^3$ was used for the surficial aquifer, assuming a thickness of 1.0 m and a porosity of 0.20 given by Parker (1955). Canal water was assumed to equal $8.8 \times 10^6\,m^3$.

4.4. Model validation

Model validation was accomplished by comparing the simulated height of the water table and canal discharge to actual groundwater levels and actual canal discharge for the Black Creek watershed and by comparing other model parameters (i.e., infiltration, surface runoff, evaporation, transpiration and recharge) to values typical for south Florida.

Fig. 7a compares measured and simulated mean daily discharge for the 3-year period (1986–1988). The simulated average daily discharge (239,000 $m^3\,d^{-1}$) was about 4% less than that measured (249,000 $m^3\,d^{-1}$). Measured discharge was

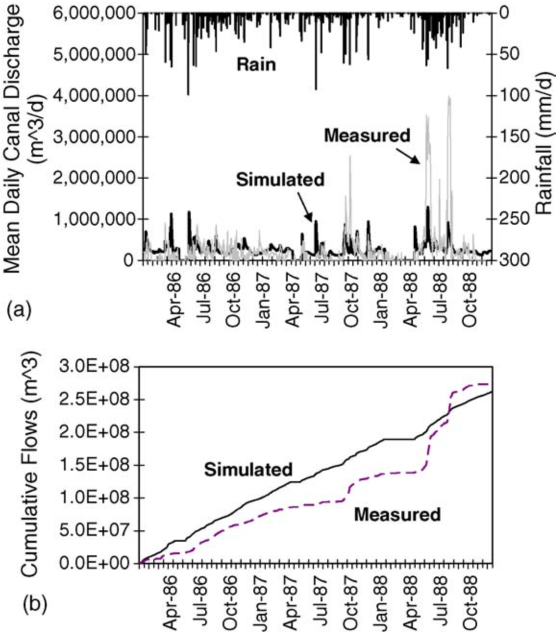


Fig. 7. Comparison of measured and simulated daily (a) and cumulative (b) canal flow hydrographs for Black Creek (C-1) canal with no wetland storage.

more variable (standard deviation, $s = 519{,}000\ m^3\ d^{-1}$) than simulated discharge ($s = 172{,}000\ m^3\ d^{-1}$). Simulated discharge was less sensitive to rainfall events than measured discharge as can be seen during the four summer months shown in Fig. 8.

Fig. 7b shows the measured and simulated cumulative canal discharge. The 3 year simulated cumulative discharge ($260 \times 10^6\ m^3$) was 5% less than the measured value ($275 \times 10^6\ m^3$). The simulated discharge was 62% of basin rainfall ($417 \times 10^6\ m^3$) and 42% of total water input (canal + sub-surface + rainfall = $612 \times 10^6\ m^3$). Although the simulated and measured cumulative discharge differ by only 5%, the majority of the difference could be attributed to the summer period of 1988 when extremely large discharge rates occurred but were not matched by the model (Fig. 7b).

The simulated surficial aquifer level was near the measured level (Fig. 9a). The measured level is from the G1362 observation well located near the center of the basin. The U.S. Geological Survey (1986–1989) only reported a value for every 5th day; therefore, the daily plot assumed that the reported value was the level for 5 consecutive days. The simulated level was spatially integrated for the entire basin. The measured level exhibited some large changes from week to week, whereas the simulated level changed less abruptly. Two obvious periods of discrepancy occurred during the last half of 1986 and from February 1988 to September 1988. The latter period corresponded with the period in which the canal discharge was switched off in the model in an attempt to account for the human decision to close the canal gate. The simulated level more often overestimated rather than underestimated the measured level. Peaks in the measured level most often corresponded to rainfall events. Some rainfall events did not have proportionate increases in measured water table levels; for example, the water table continued to drop after a 42 mm rainfall event in January 1987. The

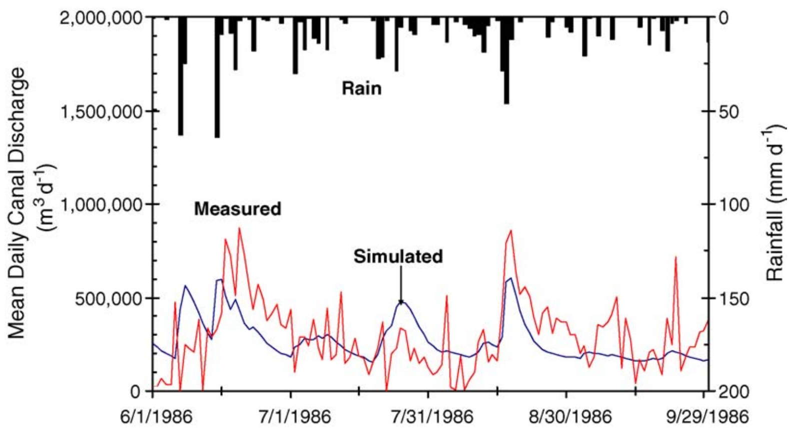


Fig. 8. Comparison of measured and simulated canal discharge for Black Creek for summer of 1986 with no wetland storage.

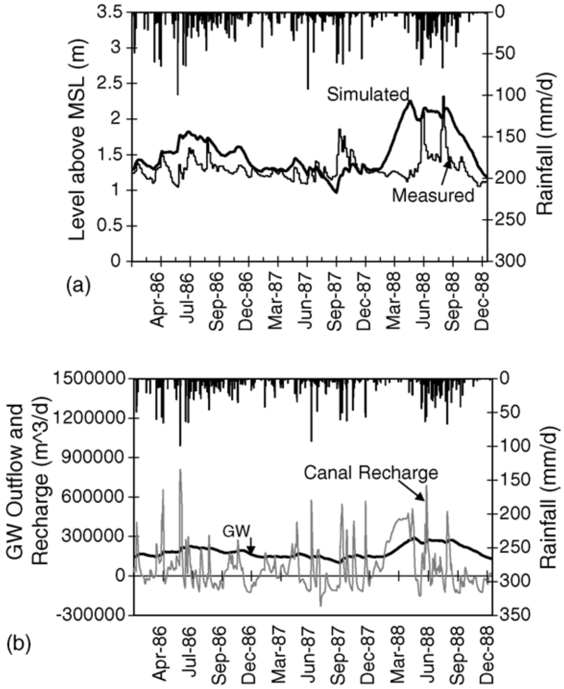


Fig. 9. Comparison of measured and simulated surficial aquifer level (a) and simulated groundwater outflow and recharge (b) for the Black Creek (C-1) basin with no wetland storage.

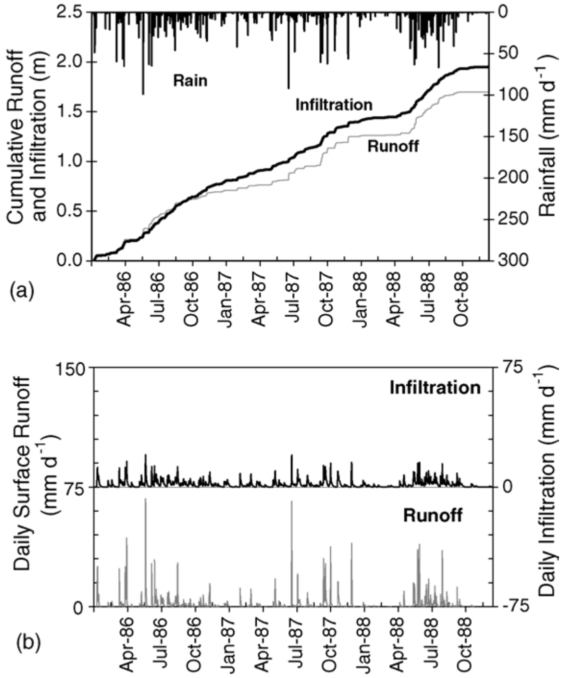


Fig. 10. Cumulative (a) and daily (b) simulated surface runoff and infiltration for Black Creek (C-1) watershed with no wetland storage.

simulated level did not respond as abruptly to rainfall events.

The simulated canal recharge of the surficial aquifer and groundwater outflow are shown in Fig. 9b. For the 3-year simulation $75 \times 10^6\,m^3$ recharged the surficial aquifer from the canal. This was 29% of simulated canal discharge, 18% of basin rainfall and 12% of total water inflow. Negative values of recharge were periods of aquifer discharge to the canal. The 3-year total simulated surficial aquifer outflow was $200 \times 10^6\,m^3$. This was about 77% of simulated canal discharge, 48% of basin rainfall and 33% of total water input.

Fig. 10a shows cumulative simulated surface runoff and infiltration for the 3-year simulation period. Cumulative infiltration and surface runoff equaled 2.0 and 1.7 m for the 3 years, respectively. Infiltration represented 48% of rainfall while runoff was 42%. Daily surface runoff exhibited greater variation than infiltration ($s = 5.2\,mm\,d^{-1}$ versus $s = 2.5\,mm\,d^{-1}$). Infiltration varied between 0 and 20 (0–20) $mm\,d^{-1}$ while surface runoff ranged from 0 to 68 (0–68) $mm\,d^{-1}$. When rainfall intensity was small infiltration rates were larger than surface runoff rates, but as rainfall events increased in intensity runoff rates exceeded infiltration rates. The largest rainfall event during the 3 years (100 mm in June 1986) resulted in a peak daily infiltration of $20\,mm\,d^{-1}$ and runoff of $68\,mm\,d^{-1}$ (Fig. 10b).

Fig. 11a features the simulated daily surface evaporation and transpiration for the Black Creek watershed. Although daily surface evaporation displayed a broader range (0–5.8 $mm\,d^{-1}$) than transpiration (0.1–2.3 $mm\,d^{-1}$), daily variation was similar [$\sigma_{evap} = 0.58$ and $\sigma_{transp} = 0.54\,mm\,d^{-1}$]. Surface evaporation responded instantly to rainfall, whereas peaks in transpiration lagged rainfall events (Fig. 11a).

Three year simulated cumulative surface evaporation and upland transpiration are presented in Fig. 11b. Total transpiration ($113 \times 10^6\,m^3$) and surface evaporation ($45 \times 10^6\,m^3$), when combined, accounted for 38% of rainfall. Canal evaporation ($2 \times 10^6\,m^3$) was not included in the graph since it was less than 1% of rainfall.

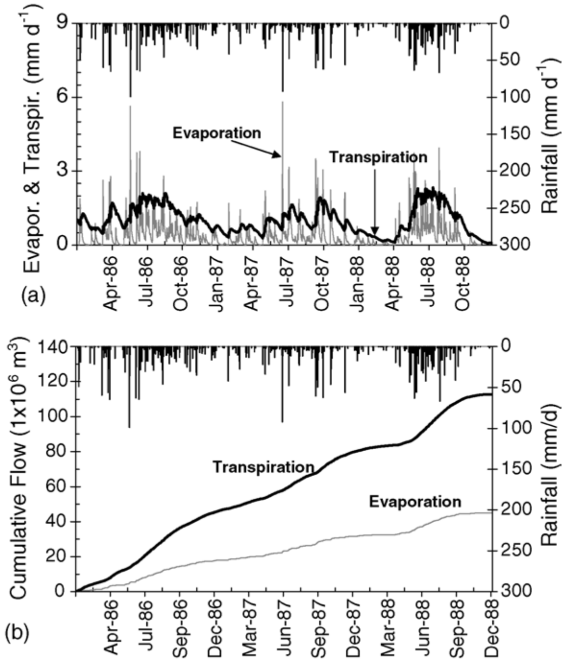


Fig. 11. Simulated daily (a) and cumulative (b) surface evaporation and transpiration for Black Creek (C-1) watershed with no wetland storage.

4.4.1. Description of watershed model with wetland system

Figs. 12 and 13 are systems diagrams of the simulation model with the proposed WSMS included. In Fig. 12, the diagram has the pathways labeled with algebraic expressions and the difference equations provided at the bottom.

4.4.2. System boundary and driving energies

When the watershed model was modified by including WSMS, the same system boundaries and inputs were used as previously described. Although input values were the same, all canal inflow and some rainfall (J29) was routed through the wetland water storage. The sunlight source was split between upland and wetland areas, since the areas cover different parts of the watershed.

4.4.3. Storages, pathways and interactions

Storages for wetland water (WW), wetland soil moisture (WSM) and wetland vegetation (BW) and pathway connections were added to the model to represent the wetland system. The major change in internal flow pathways was the re-routing of surface runoff (J4) to wetland storage instead of to canal storage. Wetland discharge to the canal (J21) was added and occurred in proportion to the amount present in the wetland. Surficial aquifer recharge was provided by wetland water (J17). Evaporation of wetland water (J23) was proportional to sunlight available (JR3). Wetland water infiltrated to wetland soil moisture based on the difference between the two (J24). Wetland transpiration (J28) of wetland soil moisture was proportional to available sunlight (JR3) and vegetation present (BW).

4.4.4. Calibration of model with wetland system

Table 2 provides a description of the data used to calibrate the watershed model when a WSMS was included. Calibration values were derived by combining data from several types of literature, including water budgets published by SFWMD (1993), transpiration data from Brown (1978), evaporation reported by Carter et al. (1973) and wetland water budgets and productivity estimates summarized in Mitsch and Gosselink (1993).

5. Results

5.1. Simulation of wetland stormwater management system

The following gives results from simulations of the model when a WSMS was included. Table 3 summarizes changes made in model parameters and initial conditions for sensitivity analysis.

Including a WSMS equal to 1% of total watershed area significantly lowered peaks in canal discharge (Fig. 14a). Fig. 14a shows the simulated canal surface discharge from the Black Creek (C-1) watershed with and without a WSMS. The WSMS ensured a base flow of 180,000 $m^3\,d^{-1}$.

Variation in canal discharge was lowered as WSMS size was increased from 1 to 25% of basin area (Fig. 14b). When WSMS was 1% of basin area, the canal discharge was maximum at 630,000 $m^3\,d^{-1}$, whereas when WSMS was 25% of basin area, the peak canal discharge was only 320,000 $m^3\,d^{-1}$. Increasing the size of the WSMS resulted in more steady canal discharge, lowered the peaks and raised the base flow.

Table 2
Description of driving energies, storages and flow data used to calibrate Black Creek (C-1) watershed model when a wetland stormwater management system was included (see Fig. 12 for diagram)

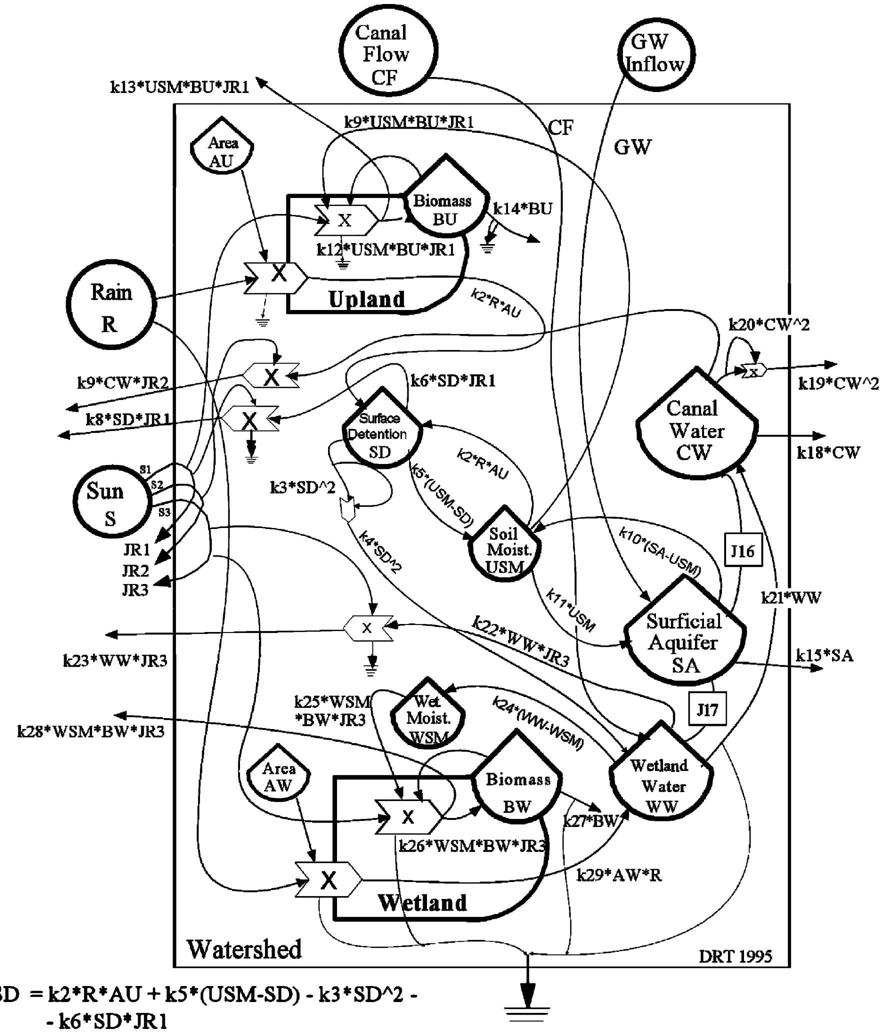
Note	Description	Variable	Equation	Calibration Value	Unit	k-Value		Reference
Inputs								
1	Rainfall	R		1524	mm y^{-1}			Sculley (1986)
2	Insolation	S		1	Standardized			
3	Canal inflow	CF		124,000	$m^3\ d^{-1}$			SFWMD (1993)
4	Groundwater inflow	GW		34,000	$m^3\ d^{-1}$			SFWMD (1993)
Flows								
5	Upland rainfall volume	J2	k2 × R × AU	405	$10^3\ m^3\ d^{-1}$	1.00	Rainfall rate × watershed area	
6	Surface runoff	J4	k4 × SD^2	93	$10^3\ m^3\ d^{-1}$	5.86E − 08	Estimated as 24% of rainfall	
7	Vertical capillary action	J5	k5 × (USM–SD)	1	$10^3\ m^3\ d^{-1}$	2.6E − 07	Assumed	
8	Soil infiltration	J7	k7 × SD	259	$10^3\ m^3\ d^{-1}$	0.205605	By difference, J2–J4–J8	
9	Upland surface evaporation	J8	k8 × SD × JR1	53	$10^3\ m^3\ d^{-1}$	0.064728	Estimated as 0.5 mm d^{-1}	
10	Canal evaporation	J9	k9 × SD × JR2	3	$10^3\ m^3\ d^{-1}$	0.003664	Estimated as 4.5 mm d^{-1}	
11	Vertical capillary action	J10	k10 × (SA–USM)	1	$10^3\ m^3\ d^{-1}$	6.54E − 05	Assumed	
12	Remainder of upland insolation	JR1	S1/(1 + ks1a × USM × BU + ks1b × SD)	0.65	Standardized		Assumed	
13	Remainder of canal insolation	JR2	S2/(1 + ks2 × CW)	0.65	Standardized		Assumed	
14	Percolation to surficial aquifer	J11	k11 × USM	106	$10^3\ m^3\ d^{-1}$	0.020784	By difference, J7 – J13	
15	Gross upland production	J12	k12 × USM × JR1 × BU	107	10^3 kg d^{-1}	4.76E − 11	Assumed, 1.1 g $m^2\ d^{-1}$	
16	Upland transpiration	J13	k13 × USM × JR1 × BU	153	$10^3\ m^3\ d^{-1}$	6.8E − 11	Estimated as 1.6 mm d^{-1}	Carter et al. (1973)
17	Upland biomass decay	J14	k14 × BU	107	10^3 kg d^{-1}	0.000158	Equal to J12	
18	Surficial aquifer system outflow	J15	k15 × SA	140	$10^3\ m^3\ d^{-1}$	0.006863	For balance, Outflow = Inflow	
19	Canal/aquifer exchange	J16	k16 × [(elevation of SA − elevation of CW) × canal perimeter]	1	$10^3\ m^3\ d^{-1}$	−0.00114		Heimburg (1976)
20	Wetland/aquifer exchange	J17	k17 × (ht. of WW)^2 − (ht. of SA)^2]/	1	$10^3\ m^3\ d^{-1}$	411.3628		Heimburg (1976)
21	Canal discharge, linear	J18	k18 × CW	22	$10^3\ m^3\ d^{-1}$	0.0025	Assumed 45% of discharge	SFWMD (1993)
22	Canal discharge, quadratic	J19	k19 × CW^2	125	$10^3\ m^3\ d^{-1}$	1.61E − 09	Assumed 55% of discharge	SFWMD (1993)
23	Wetland discharge to canal	J21	k21 × WW	222	$10^3\ m^3\ d^{-1}$	0.174118		
24	Wetland evaporation	J23	k23 × WW × JR3	5	$10^3\ m^3\ d^{-1}$	0.001508		
25	Wetland soil infiltration	J24	k24 × (WW − WSM)	10	$10^3\ m^3\ d^{-1}$	0.009804		
26	Wetland production	J26	k26 × WSM × BW × JR3	12	10^3 kg d^{-1}	7.1E − 10	2.4 g $m^2\ d^{-1}$	
27	Wetland biomass decay	J27	k27 × BW	12	10^3 kg d^{-1}	0.000118		
28	Wetland transpiration	J28	k28 × WSM × BW × JR3	10	$10^3\ m^3\ d^{-1}$	5.91E − 10		
29	Wetland rainfall	J29	k29 × AW × R	20	$10^3\ m^3\ d^{-1}$	1		
30	Remainder of wetland sunlight	JR3	S3/(1 + ks3 WW + ks4WSMBW)	0.65	Standardized			
Storages								
31	Upland biomass	BU		6.78E + 08	kg			
	per m^2			7	kg m^2		Estimated as 50% of forested upland	
32	Surface detention	SD	Area × mean depth	1,259,700	m^3			
	Mean depth			13	mm		Assumed 3 day residence time	

Table 2 (*Continued*)

Note	Description	Variable	Equation	Calibration				Reference
				Value	Unit	*k*-Value		
33	Upland soil moisture	USM	Area × depth × porosity	5,100,000	m^3			
	Mean depth			0.25	m		Assumed	
	Mean porosity			20%			Assumed	
34	Surficial aquifer volume	SA	Area × depth × porosity	2.04E + 07	m^3			
35	Surficial aquifer depth			1	m			USGS (1973)
36	Surficial aquifer porosity			20%				Parker (1955)
37	Canal water	CW	Length × width × depth	8,800,000	m^3			
38	Length			44,000	m			
39	Mean depth			10	m			USGS (1973)
40	Mean width			20	m			USGS (1973)
41	Upland area	AU		9.69E + 07	m^2			
42	Wetland area	AW		5,100,000	m^2	5%		
43	Wetland water volume	WW		1,275,000	m^3			
44	Wetland depth			0.25	m			
45	Wetland soil moisture	WSM		255,000	m^3			
46	Mean depth			0.05				
47	Wetland biomass	BW		1.02E + 08	kg			
48	per m^2			20	kg m^2			
49	Black Creek watershed area			1.02E + 08	m^2			SFWMD (1993)

Note: 1, simulated with daily data from 1986 to 1988 (Sculley, 1986); 2, sine wave, mean = 1.00, range = ±0.25, period = annual; 3, simulated with daily data from 1986 to 1988 (SFWMD, 1993); 4, simulated with constant rate (SFWMD, 1993); 5, rainfall rate × watershed area; 6, estimated as 23% of rainfall (SFWMD, 1993); 7, assumed; 8, by difference, J2–J4–J8; 9, estimated as 0.5 mm d^{-1}; 10, estimated as 4.5 mm d^{-1}; 11, assumed; 12, assumed; 13, assumed; 14, by difference, J7–J13; 15, assumed; 16, estimated as 1.6 mm d^{-1} (Carter et al., 1973); 17, equal to J12; 18, for balance, outflow = inflow; 19, elevation difference integrated over perimeter (Heimburg, 1976); 20, equation developed for Cypress Dome (Heimburg, 1976); 21, assumed 45% of discharge (SFWMD, 1993); 22, assumed 55% of discharge (SFWMD, 1993); 23, for balance, outflow = inflow; 24, estimated 1.0 mm (Carter et al., 1973); 25, for balance, infiltration = transpiration; 26, low value summarized by Mitsch and Gosselink (1993) for Florida; 27, for balance, equals production; 28, estimated 2.0 mm d^{-1} (Brown, 1978); 29, rainfall over wetland; 30, assumed; 31, estimated as 50% of forested upland; 32, assumed 3 day residence time; 33, assumed; 34, area × depth × porosity; 35, assumed one meter thick; 36, reported average (Parker, 1955); 37L × W × D; 38, estimated from map SFWMD Information Resources Division; 39, assumed average; 40, assumed average; 4195% of watershed; 425% of watershed; 43, mean depth × area; 44, assumed; 45, assumed; 46, assumed; 47, area × density; 48, average value summarized by Mitsch and Gosselink (1993) for Florida; 49, reported.

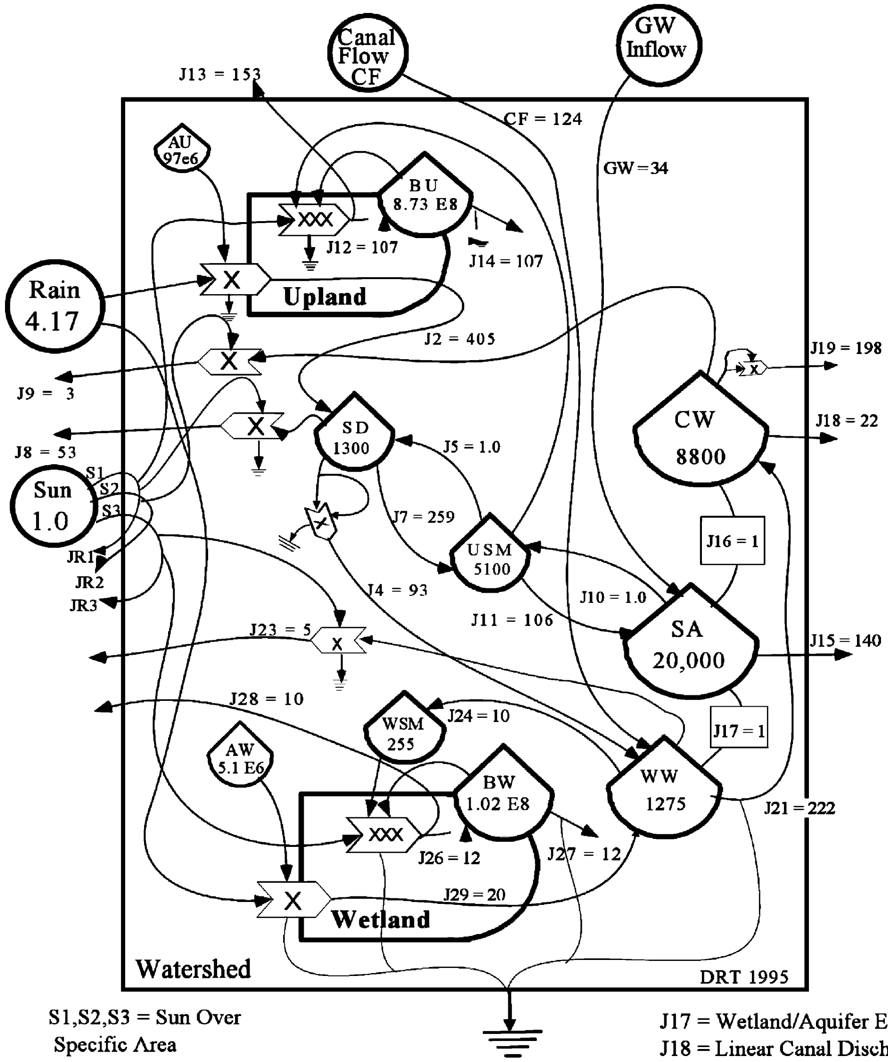
Maximum (peak) daily discharge and percent decrease in maximum discharge decreased as WSMS increased (Fig. 15a). Increasing the WSMS from 1 to 5% decreased maximum discharge by 180,000 $m^3 d^{-1}$ from 630,000 to 450,000 $m^3 d^{-1}$, whereas increasing the WSMS from 20 to 25% of basin area decreased maximum discharge by only 10,000 $m^3 d^{-1}$ from 330,000 to 320,000 $m^3 d^{-1}$.



dSD = k2*R*AU + k5*(USM-SD) - k3*SD^2 - k6*SD*JR1
dUSM = k10*(SA-USM) + k5*(USM-SD) - k9*USM*BU*JR1 - k11*USM
dSA = k11*USM + GW + J16 + J17 - k10*(SA-USM) - k15*SA
dWW = k4*SD^2 + CF + k29*AW*R - k24*(WW-WSM) - J17 - k21*WW - k22*WW*JR3
dWSM= k24*(WW-WSM) - k25*WSM*BW*JR3
J16 = k16*[(elevation of SA - elevation of CW)*Canal Perimeter]
J17 = k17*[(ht. of WW)^2 - (ht. of SA)^2]/ ln(radius to measurment/wetland radius) (Heimburg, 1976).

dCW = k21*WW - k20*CW^2 - k18*CW - J16 - k9*CW*JR2
dBU = k12*USM*BU*JR1 - k14*BU
dBW = k26*WSM*BW*JR3 - k27*BW
JR1 = S1 / (1 + ks1a*USM*BU + ks1b*SD)
JR2 = S2 / (1 + ks2*CW)
JR3 = S3 / (1 + ks3*WW + ks4*WSM*BW)

Fig. 12. Energy systems diagram of watershed model containing wetland stormwater management system (WSMS). Algebraic expressions are written on pathways and rate of change equations for state variables are given below. (R from actual data, CF was constant, GW was constant.)



S1,S2,S3 = Sun Over Specific Area
JR1,JR2,JR3 = Remainder Sun Avail.
R = Rainfall (m/d)
J2 = Upland Rain (m^3/d)
J4 = Surface Runoff
J5 = Vertical Capillary Action
J7 = Infiltration
J8 = Land Surface Evaporation
J9 = Canal Evaporation
J10 = Capillary Action
J11 = Percolation
J12 = Upland Production
J13 = Upland Transpiration
J14 = Upland Biomass Decay
J15 = Subsurface Outflow
J16 = Canal/Aquifer Exchange
J17 = Wetland/Aquifer Exchange
J18 = Linear Canal Discharge
J19 = Quadratic Canal Disch.
J21 = Wetland Discharge to Canal
J23 = Wetland Evaporation
J24 = Wetland Soil Infiltration
J28 = Wetland Transpiration
J26 = Wetland Production
J27 = Wetland Biomas Decay

Fig. 13. Energy systems diagram of watershed model containing WSMS with definitions and calibration values of flows and storages (AU, upland area; BU, upland biomass; SD, surface storage; USM, upland soil moisture; CW, canal water, SA, surficial aquifer; AW, wetland area; WSM, wetland soil moisture; BW, wetland biomass; WW, wetland water).

Table 3
Summary of parameter settings used for testing sensitivity of Black Creek canal watershed model to wetland area

Upland area (ha)	Wetland area (ha)	Upland biomass (1×10^6 kg)	Wetland biomass (1×10^6 kg)	Wetland soil moisture (1×10^3 m^3)	Wetland water (1×10^3 m^3)	Wetland sunlight (standardized units)
10200	0	714	0	0	0	0
10098	102	707	20	51	255	0.2
9690	510	678	102	255	1275	1
9180	1020	643	204	510	2550	2
7650	2550	536	510	1275	6375	5

Average and minimum daily canal discharge values varied little when a WSMS was present (Fig. 15a). The standard deviation of daily canal discharge decreased from 172,000 m^3 d^{-1} when WSMS size equaled 0% of basin area to 40,000 m^3 d^{-1} for WSMS size of 25% of basin area.

WSMS size had a small effect on average surficial aquifer level (Fig. 15b). The mean surficial aquifer level was close to 1.5 m above mean sea level (MSL) for each WSMS size (0–25% of basin area) tested. Larger WSMS decreased the difference between maximum and minimum groundwater levels (Fig. 15b).

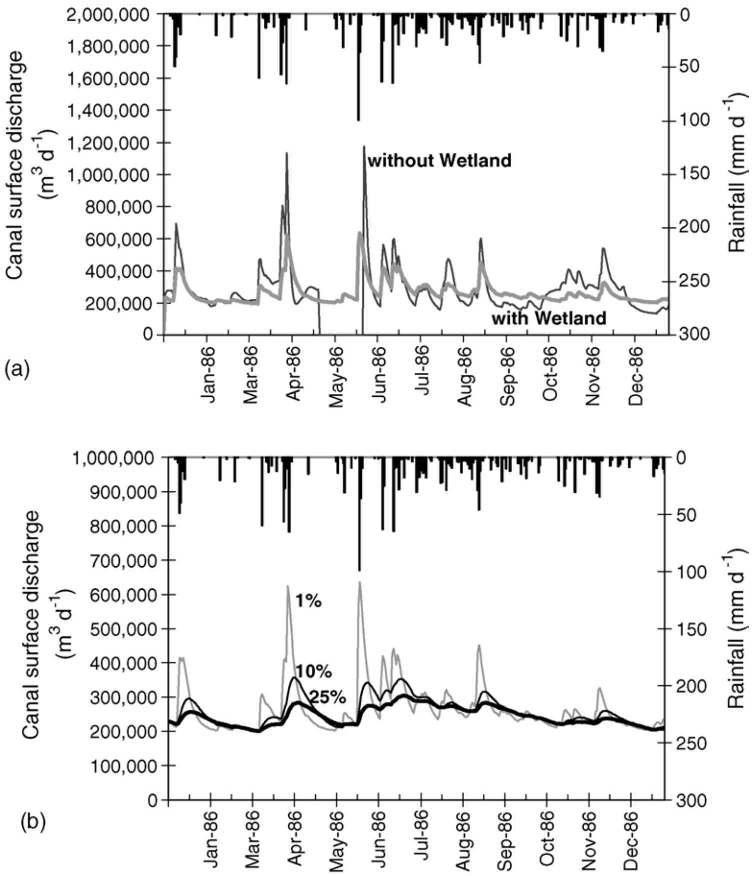


Fig. 14. Comparison of simulated canal discharge for Black Creek (C-1) basin without a WSMS and with one equal to 1% of basin area (a) and comparison of canal discharge when wetland size was 1, 10 and 25% of basin area (b).

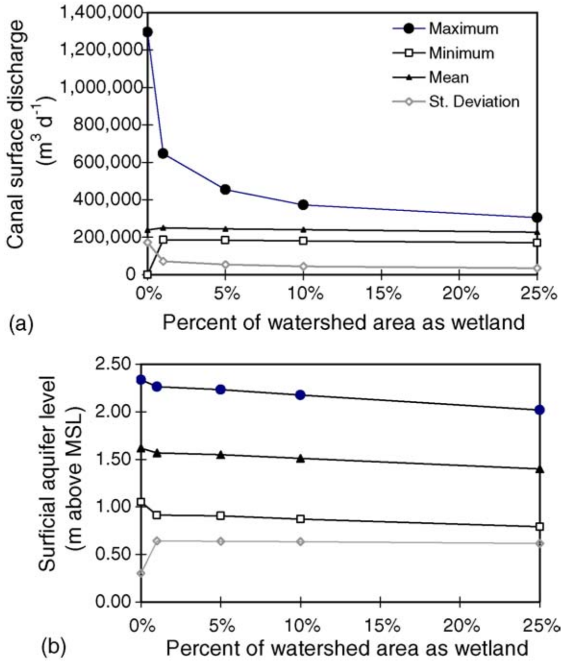


Fig. 15. Summary statistics of daily flows for 3 year simulation for (a) canal discharge and (b) ground water level for Black Creek basin with wetland area ranging from 0 to 25% of watershed area.

The rate of wetland transpiration increased logarithmically as wetland area became a larger portion of the basin (Fig. 16). Table 4 and Fig. 16 shows the rates of evaporation and transpiration from both the upland and wetland areas as well as transpiration for the entire watershed. For the smallest wetland area tested (102 ha), transpiration was about 1 mm d^{-1}, while the largest wetland area (2550 ha) had a rate of 2.3 mm d^{-1}. Upland evaporation and transpiration, and wetland evaporation were basically constant. The

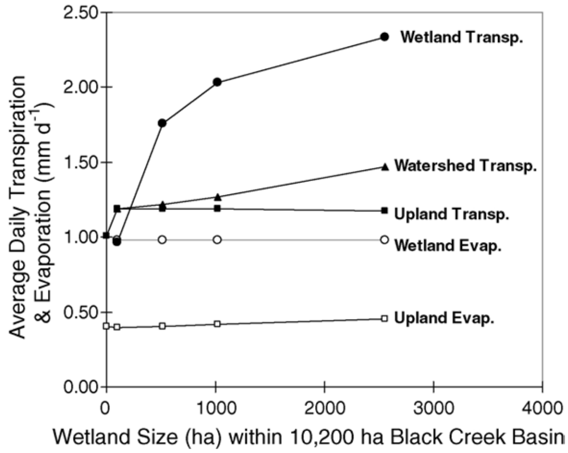


Fig. 16. Average simulated upland and wetland evaporation and transpiration rates for period (1986–1988) in Black Creek basin. Upland rates per unit of upland area, wetland rates per unit of wetland area and watershed rate per watershed area.

hydroperiod, the amount of time the WSMS had water, is demonstrated in Fig. 17 for variously sized WSMS. Most notable was how the larger wetland had a longer hydroperiod.

5.2. Emergy properties and values

Emergy flows were simulated in the model to investigate the effect of wetland size on total watershed empower. The flow of emergy and resulting changes in transformity of various storages and processes in a watershed receiving discrete step-wise input (i.e., rainfall and canal input) adds significantly to understanding the role of wetlands in stormwater management and may provide perspective on optimum configurations of uplands and wetlands.

Table 4
Average simulated upland and wetland evaporation and transpiration rates for period 1986–1988 in Black Creek basin

Upland area (ha)	Wetland area (ha)	Evaporation and transpiration (mm d^{-1})				
		Upland evaporation	Wetland evaporation	Upland transpiration	Wetland transpiration	Watershed transpiration
10200	0	0.40	n.a.	1.01	n.a.	1.01
10098	102	0.40	0.98	1.19	0.96	1.19
9690	510	0.41	0.98	1.19	1.75	1.21
9180	1020	0.42	0.98	1.19	2.03	1.27
7650	2550	0.45	0.98	1.18	2.34	1.47

n.a., not applicable.

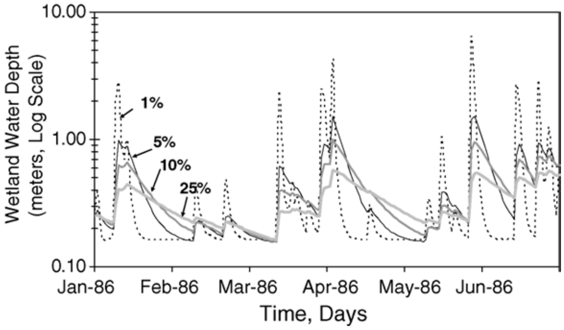


Fig. 17. Simulated wetland water depth (volume/area) predicted by model in Fig. 12 for different percentages of basin occupied by wetlands.

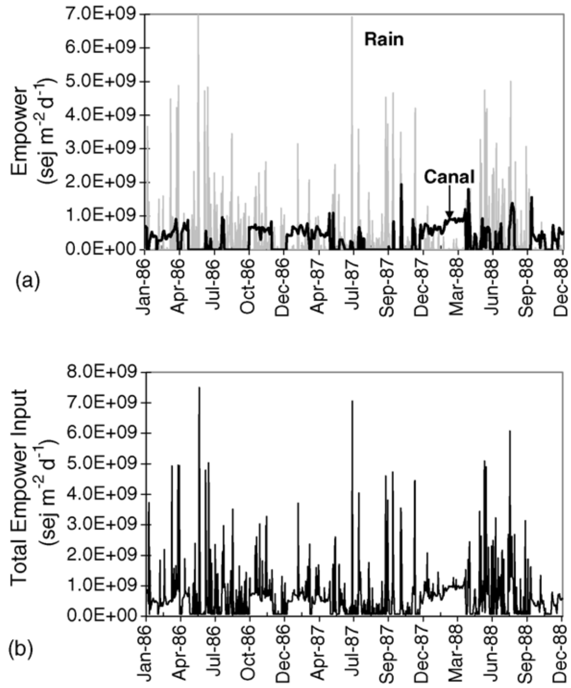


Fig. 18. Empower of rainfall and canal inflow (a) and total empower input (b) used in simulation model of Black Creek watershed.

5.2.1. Empower of driving energies

Transformities used for rainfall, canal inflow, and sub-surface inflow were 15,000, 40,000 and 40,000 sej J^{-1}, respectively, which were based on global averages previously reported by Odum (1996), but rounded to the nearest 5000 increment for convenience and improved clarity. Empower density (sej m^{-2} d^{-1}) of rainfall, canal inflow and sub-surface inflow is shown in Fig. 18a and their sum in Fig. 18b. The 3-year mean daily empower density of inputs for rain (2.8×10^8 sej m^{-2} d^{-1}) and canal flows (3.0×10^8 sej m^{-2} d^{-1}) made up 43 and 46%, respectively, of total empower input. Groundwater empower input accounted for the remaining 11%. Variation in rainfall empower density ($\sigma = 7.7 \times 10^8$ sej m^{-2} d^{-1}) was more than twice that for canal inflow ($\sigma = 3.4 \times 10^8$ sej m^{-2} d^{-1}). Sub-surface empower input was constant. The maximum empower density for rainfall, canal and sub-surface inputs was 74×10^8, 19×10^8 and 0.007×10^8 sej m^{-2} d^{-1}, respectively.

5.2.2. Empower of transpiration

Daily empower of water transpired by the Black Creek basin's upland vegetation when wetland area was zero varied from 0.2×10^8 to 3.5×10^8 sej m^{-2} d^{-1} (Fig. 19). The left scale in Fig. 19 is empower density of transpiration (sej m^{-2} d^{-1}) and the right scale is total empower density input in the same units.

5.2.3. Emdollar value of wetland storage

The average value of water saved (i.e., not discharged to sea) per year per unit of wetland area was determined to be 343 EM\$ ha^{-1} y^{-1} (Fig. 20). A refinement to this average value was made based on valuing the first 100 ha separately from other wetland area, since the first 100 ha, reduced the emdollar value of watershed discharge by the greatest amount (Fig. 20). This approach gave values of 6800 EM\$ ha^{-1} y^{-1} for the first 100 ha of wetland and 219 EM\$ ha^{-1} y^{-1} for wetland area beyond this. Fig. 21 shows the incremental value of water saved per wetland area added. Converting the emdollar values to potential investment dollars assuming the average investment ratio of Florida (7:1; Lopez-Barba, 1995) yielded wetland values of US\$ 47,600 ha^{-1} y^{-1} for the first 100 ha added and US\$ 1533 ha^{-1} y^{-1} for wetlands added beyond this. If the investment ratio of Dade County (18:1; Lopez-Barba, 1995) was assumed the wetland values were much higher (US\$ 122,300 ha^{-1} y^{-1} for initial 100 ha and US\$ 3942 ha^{-1} y^{-1} for other area, see Table 5).

The second method used to value wetland storage was based on water transpired. Annual EM\$ value of watershed transpiration per hectare of watershed varied

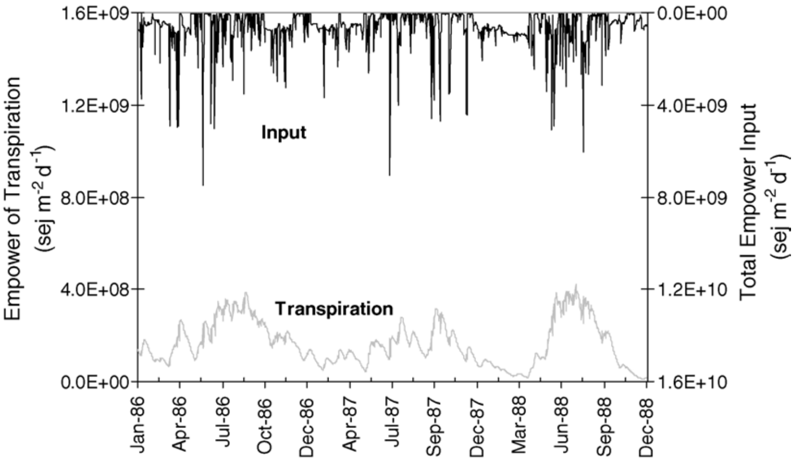


Fig. 19. Simulated empower of transpiration for Black Creek watershed with no wetland area. (*Note*: differences in scales.)

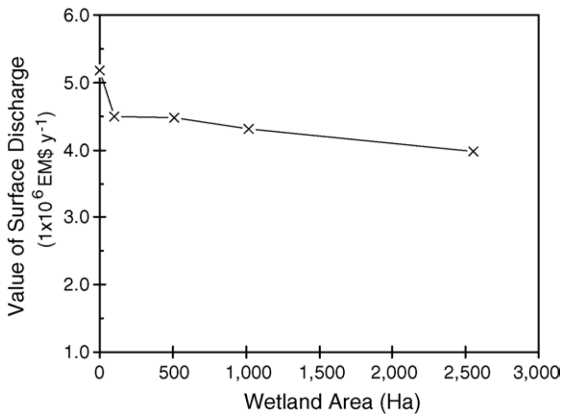


Fig. 20. Emdollar value of surface discharge from Black Creek watershed with wetland area varying from 0 to 2550 ha.

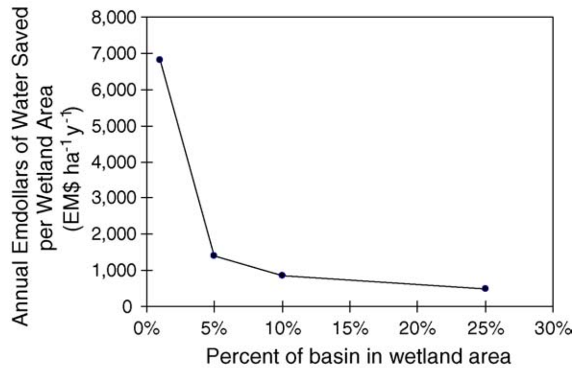


Fig. 21. Emdollar value of water saved (i.e., not discharged) per area of wetland added to watershed.

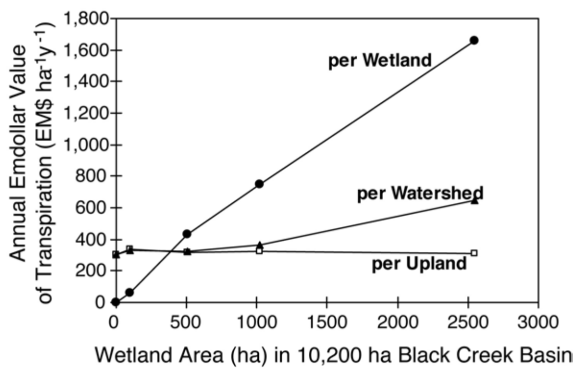


Fig. 22. Annual emdollar value of transpiration of upland, wetland and watershed, per hectare of upland, wetland and watershed, respectively. Black Creek basin (10,200 ha) with wetland area ranging from 0 to 2550 ha (0–25%).

with wetland to upland ratio (Fig. 22). Values ranged from a low of 302 EM$ ha^{-1} y^{-1} when there was no wetland to a high of 648 EM$ ha^{-1} y^{-1} when wetland area totaled 25% of basin area. These values are higher than a Swedish spruce forest (150 EM$ ha^{-1} y^{-1}, Doherty, 1995) and overlap with a mature rain forest (350 EM$ ha^{-1} y^{-1}, Odum et al., 2000). Fig. 22 and Table 6 show separately, the emdollar value of water transpired per hectare of upland area and wetland area. The wetland value consistently increased from 59 to 1660 EM$ ha^{-1} y^{-1} as wetland area increased over the range simulated (1–25% of basin). Less variable over the range of upland/wetland ratios tested,

Table 5
Emdollar value and investment potential value of watershed surface discharge, total water saved, and water saved per wetland area added, for wetland areas ranging from 0 to 2550 ha for the 10,200 ha Black Creek basin

Upland area (ha)	Wetland area (ha)	Watershed surface discharge EM\$ y^{-1} (1×10^6)	Total water saved EM\$ y^{-1} (1×10^6)	Total water saved per wetland area added EM\$ ha^{-1} y^{-1}	Marginal water saved per increment of wetland added EM\$ ha^{-1} y^{-1}
Emdollar value					
10200	0	5.18	n.a.	n.a.	n.a.
10098	102	4.49	0.69	6800	6800
9690	510	4.47	0.71	1400	45
9180	1020	4.31	0.88	859	322
7650	2550	3.98	1.20	472	215
		Watershed surface discharge \$ y^{-1} (1×10^6)	Total water saved \$ y^{-1} (1×10^6)	Total water saved per wetland area added \$ ha^{-1} y^{-1}	Marginal water saved per wetland added \$ ha^{-1} y^{-1}
Potential dollar investment assuming Florida investment ratio (7:1)					
10200	0	\$36.3	n.a.	n.a.	n.a.
10098	102	\$31.4	\$4.85	\$47600	\$47600
9690	510	\$31.3	\$4.98	\$9770	\$313
9180	1020	\$30.1	\$6.13	\$6010	\$2250
7650	2550	\$27.8	\$8.43	\$3310	\$1500
Potential dollar investment assuming Dade Co. investment ratio (18:1)					
10200	0	\$93.3	n.a.	n.a.	n.a.
10098	102	\$80.8	\$12.5	\$122000	\$122000
9690	510	\$80.5	\$12.8	\$25100	\$805
9180	1020	\$77.5	\$15.8	\$15500	\$5800
7650	2550	\$71.6	\$21.7	\$8500	\$3870

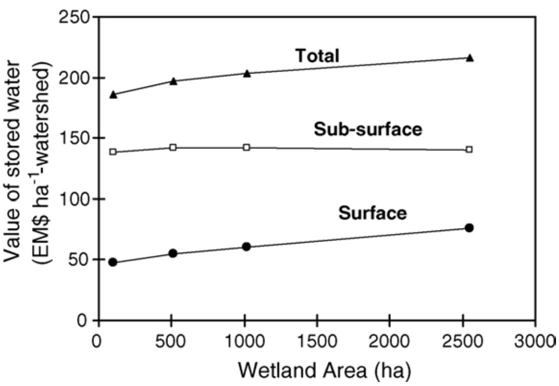


Fig. 23. Emdollar value of water stored per unit of watershed over range of wetland areas for the 10,200 ha Black Creek basin.

the value of upland transpiration was between 302 and 334 EM\$ ha^{-1} y^{-1}.

The amount of surface and sub-surface water retained within the basin due to including a WSMS provided the basis for a third method of valuing hydrologic properties of wetlands. On a per unit basis, Fig. 23 presents the emdollar value of surface water, sub-surface and combined water stored. The value of surface water stored per watershed area ranged from 48 to 76 EM\$ ha^{-1}. The difference (285,000 EM\$) between the value of water stored when wetland area was 1% and when it was 25%, divided by the difference in wetland area (2448 ha) gave a value of 116 EM\$ ha^{-1} of wetland.

To evaluate the effects of reducing the input of canal water on south Dade, the sensitivity of watershed empower (transpiration and outflow) was investigated by simulating with canal input reduced to 75, 50 and 25% of the average value. Table 7 shows the emdollar value of water flows resulting from the sensitivity analysis when the wetland area equaled 10% of basin area. Cutting canal input in half, reduced total emdollar input by 2.7 million EM\$ y^{-1} from 12.4 to 9.7 million EM\$ y^{-1}. The reduced input caused total transpiration to fall by 0.3 million EM\$ y^{-1} from 3.8 to 3.5 million EM\$ y^{-1} and total water outflow to decrease by 1.5 million EM\$ y^{-1}.

Table 8 compares the emdollar values of stormwater wetlands (productivity and water conservation) to

Table 6
Total and per unit area emdollar value and investment potential value of upland, wetland, and watershed transpiration for wetland area ranging from 0 to 2550 ha for the10,200 ha Black Creek basin

Wetland area (ha)	Upland EM\$ y^{-1} (1×10^6)	Wetland EM\$ y^{-1} (1×10^6)	Watershed EM\$ y^{-1} (1×10^6)	Per upland area EM\$ $ha^{-1}\,y^{-1}$	Per wetland area EM\$ $ha^{-1}\,y^{-1}$	Per watershed area EM\$ $ha^{-1}\,y^{-1}$
Emdollar flow of transpiration						
0	3.08	n.a.	3.08	302	0	302
102	3.38	0.01	3.38	334	59	332
510	3.10	0.22	3.32	320	429	326
1020	2.98	0.77	3.74	324	751	367
2550	2.37	4.23	6.61	310	1660	648
	Upland \$ y^{-1} (1×10^6)	Wetland \$ y^{-1} (1×10^6)	Watershed \$ y^{-1} (1×10^6)	Per upland area \$ $ha^{-1}\,y^{-1}$	Per wetland area \$ $ha^{-1}\,y^{-1}$	Per watershed area \$ $ha^{-1}\,y^{-1}$
Potential investment value of transpiration assuming Florida average ratio (7:1)						
0	\$21.6	n.a.	\$21.6	\$2110	n.a.	\$2120
102	\$23.6	\$0.04	\$23.7	\$2340	\$413	\$2320
510	\$21.7	\$1.53	\$23.3	\$2240	\$3010	\$2280
1020	\$20.8	\$5.37	\$26.2	\$2270	\$5260	\$2570
2550	\$16.6	\$29.6	\$46.2	\$2170	\$11600	\$4500
Potential investment value of transpiration using Dade Co. average ratio (18:1)						
0	\$55.5	n.a.	\$55.5	\$5440	n.a.	\$5440
102	\$60.8	\$0.11	\$60.9	\$6020	\$1060	\$5970
510	\$55.8	\$3.90	\$59.8	\$5760	\$7730	\$5870
1020	\$53.5	\$13.8	\$67.3	\$5830	\$13500	\$6600
2550	\$42.7	\$76.2	\$118.9	\$5580	\$29900	\$11700

more traditional economic measures of land value. A stormwater wetland occupying 10% of a landscape would annually save 859 EM\$ of stormwater per hectare of wetland and produce vegetation at an annual rate valued at 751 EM\$ ha^{-1}. Property tax revenue generated by an average hectare in Dade County was \$1930 y^{-1} in 1989, while state and local tax revenue was \$2250 $ha^{-1}\,y^{-1}$ (Florida Bureau of Economic and Business Research, 1991). Assuming that a stormwater wetland attracted investment at the average ratio for Dade County (18:1), then the water saved by a hectare of wetland will attract about 15,500 EM\$ y^{-1} and the wetland productivity will attract about 13,500 EM\$ y^{-1}. The average per land area economic activity in Dade County for 1989 as measured by personal income was US\$ 65,200 $ha^{-1}\,y^{-1}$ (Florida Bureau of Economic and Business Research, 1991).

5.2.4. *Dynamics of transformity*

Daily transformity of canal water and groundwater chemical potential energy varied over time (Fig. 24) as a result of emergy inflows and outflows. Daily fluctuation of transformity was less with a larger WSMS. Canal water transformity decreased significantly following

Table 7
Decrease in annual emdollar flow (1×10^6 EM\$ y^{-1}) of upland and wetland transpiration, canal discharge (CD), groundwater discharge (GWD) and total discharge (CD + GWD) assuming fractional inputs of historical average canal input during the 3 year simulation

% Of average canal input	Total input	Wetland transpiration	Upland transpiration	Total transpiration	Canal discharge	Groundwater discharge	Total discharge
100	12.4	0.77	3.0	3.8	4.3	3.0	7.3
75	11.1	0.68	3.0	3.7	3.9	2.7	6.5
50	9.7	0.57	3.0	3.5	3.5	2.3	5.8
25	8.4	0.44	3.0	3.4	3.1	2.0	5.1

Table 8
Emergy-based values of water saved and productivity of a stormwater wetland compared to various economic values of land in Dade County, Florida

Measurement	Value	Attracted value[a]
Stormwater saved[b,c] (EM\$ ha^{-1} y^{-1})	859	15500
Stormwater wetland productivity[b,c,d] (EM\$ ha^{-1} y^{-1})	751	13500
Property tax revenue (1989)[e] (\$ ha^{-1} y^{-1})	1930	
State and local tax revenue (1989)[e] (\$ ha^{-1} y^{-1})	2250	
Dade Co. personal income (1989)[e] (\$ ha^{-1} y^{-1})		65200

[a] Emdollar value based on Dade Co. investment ratio of 18:1.
[b] Emdollar values based on ratio of upland to wetland area of 10:1.
[c] Per unit of stormwater wetland.
[d] As measured by transpiration.
[e] Dade County (Florida Bureau of Economic and Business Research, 1991).

large rainfall events (Fig. 24) due to dilution with lower transformity rainfall. When the watershed had no wetland area the change in groundwater transformity was distinctly different from when wetland area was included (Fig. 24). The rise in transformity occurring in early 1988 coincided with the period in which canal discharge was switched off during the simulation. Comparing the two extreme sizes of wetland simulated (1 and 25%) showed that daily transformity was higher and more stable with larger size. The maximum mean daily transformity of canal water (~26,000 sej J^{-1}) and surficial aquifer water (~25,000 sej J^{-1}) occurred when there was no wetland area (Fig. 25a). Adding wetland area to the watershed decreased the mean

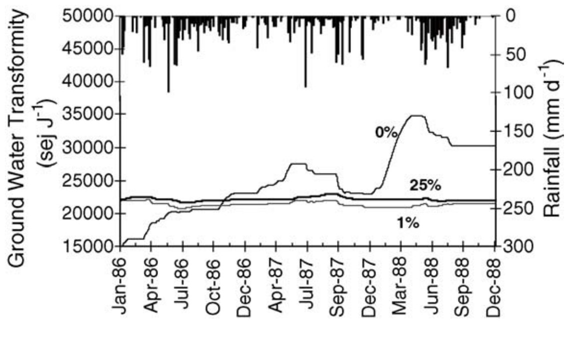


Fig. 24. Simulated daily transformity of groundwater for Black Creek watershed when wetland area was 0, 1 and 25% of basin area.

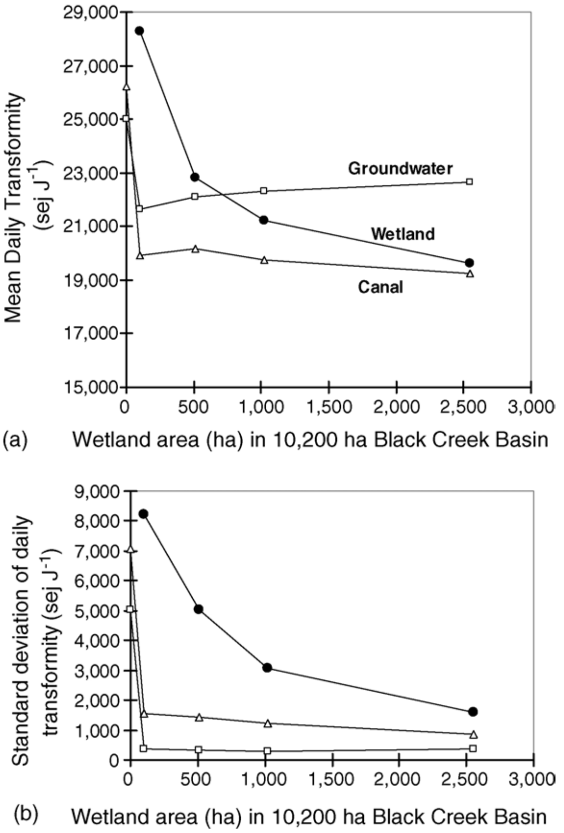


Fig. 25. Mean (a) and standard deviation (b) of daily transformity for canal water, groundwater and wetland water for range of wetland areas from 0 to 2550 ha for the 10,200 ha Black Creek watershed.

daily transformity of both canal and groundwater. The mean daily transformity of wetland water decreased asymptotically to about 19,500 sej J^{-1} as WSMS was increased from 1 to 25% of basin area (Fig. 25a).

The standard deviation of daily transformity of canal water and surficial aquifer water was 4.7 and 13.9 times greater than when wetland area equaled 102 ha (1% of basin) (Fig. 25b). The standard deviation of daily wetland water transformity declined over 5000 sej J^{-1} from 8230 sej J^{-1}, when WSMS was 1% of basin area, to 1595 sej J^{-1}, when WSMS was 25% (Fig. 25b).

The distribution of daily canal water transformity narrowed considerably when wetland area was present and continued to exhibit less spread and skewness as wetland area was enlarged (Fig. 26). When WSMS size was 1% of basin area the number of days in which canal water transformity was less than 18,000 sej J^{-1} was

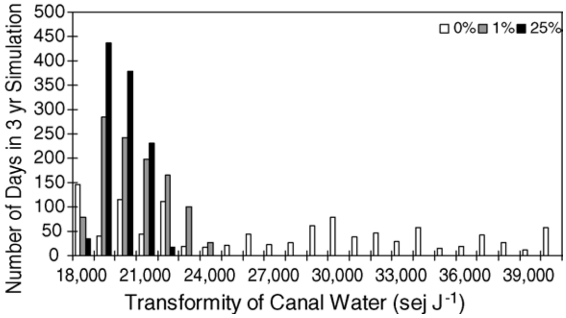


Fig. 26. Frequency distribution of simulated transformity of canal water in Black Creek watershed for three areas of wetland.

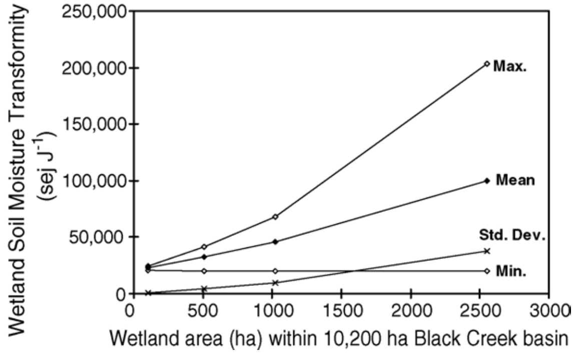


Fig. 27. Simulated average transformity of wetland soil moisture with wetland area ranging from 102 to 2550 ha for the 10,200 ha Black Creek basin.

twice as much as when WSMS size was 25%. There were over 100 days in 3 years in which the transformity was greater than 23,000 sej J^{-1} when WSMS equaled 1%, but no days when WSMS equaled 25%. Seventy-five percent of the time the daily transformity of canal water was between 18,000 and 20,000 sej J^{-1} when WSMS equaled 25%, but only 50% of the days did the transformity fall within this interval when WSMS was 1%.

The transformity of soil moisture within the wetland increased with size (Fig. 27). The soil moisture of the 102 ha (1% of basin) wetland had a transformity of 22,600 sej J^{-1} while that of the 2550 ha (25% of basin) wetland had a transformity of 95,500 sej J^{-1}. A least-squares fit of the average wetland soil moisture transformity for the four sizes (102, 510, 1020 and 2550 ha) of wetland simulated produced a slope of 31.9 sej J^{-1} per ha of wetland, indicating that, at least over this size range, each additional hectare of wetland increased the transformity by 31.9 sej J^{-1}.

Many jumps in the transformity of canal water corresponded to pulsed input with the direction of change a function of pulse size (in empower terms) and preceding transformity of canal water (Fig. 28). For example, if transformity of canal water was high, then small pulses would cause a decrease like seen on day 124 (Fig. 28). If, however, canal water transformity was low, then small inputs could increase the transformity like seen on day 39. Large pulses greater than 3.0×10^{17} sej d^{-1} almost always decreased canal water transformity. The transformity of wetland water and wetland soil water also varied over time. As with canal

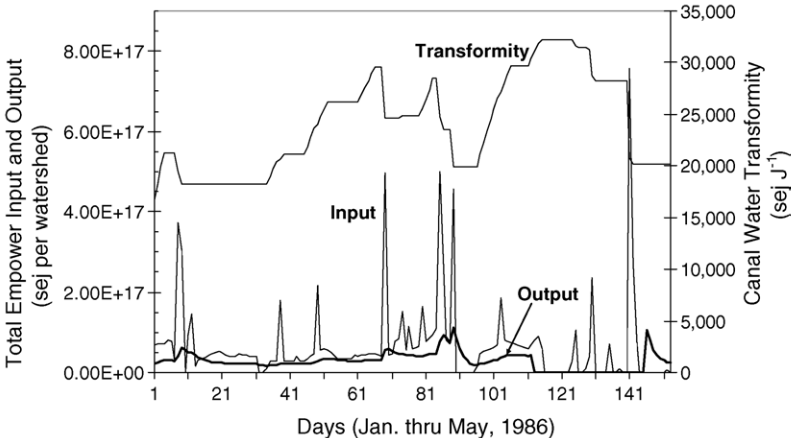


Fig. 28. Comparison of empower input (rain plus canal), empower output of canal discharge and transformity of canal water when there was no wetland area highlighting effect of pulsed inputs on transformity of canal water.

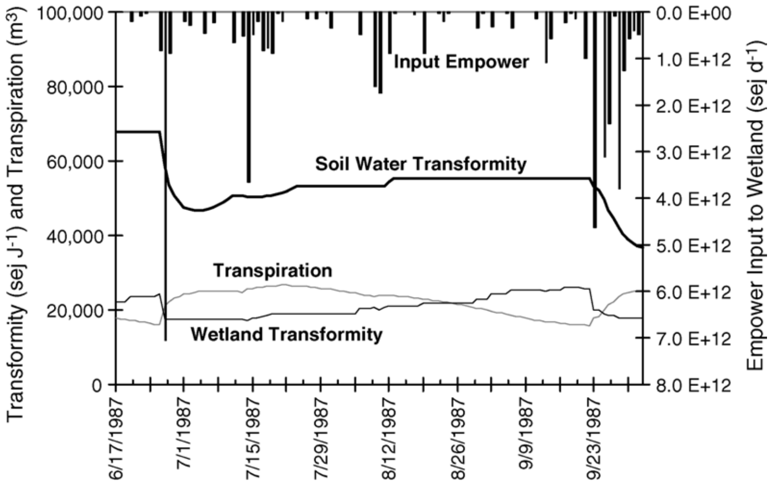


Fig. 29. Simulated transformity of wetland water and wetland soil moisture, wetland transpiration ($m^3\ d^{-1}$ for 1020 ha wetland) and empower input to wetland when wetland area was 10% of basin. Note response of transformities to pulsed rain events.

water, the larger input pulses decreased transformity, while smaller pulses either had no significant effect or slightly increased transformity (Fig. 29).

6. Discussion

6.1. Simulated hydrologic values of wetlands

Values of wetlands were determined based on three different hydrological aspects (productivity from transpiration, water conservation and water storage). All were measured with emdollars to quantify its contribution to public welfare in terms more easily placed into context by people (i.e., the complement to the dollar in emergy-based environmental accounting).

6.1.1. Water conservation

Based on simulation results, a small amount of wetland used in a WSMS had a great ability to conserve water for the landscape. A stormwater wetland equal to just 1% of basin area had a value of 6800 EM\$ $ha^{-1}\ y^{-1}$. As the area of wetland was increased, its per unit value declined, so that when 25% of the basin was in stormwater wetland, its water conservation value was about 500 EM\$ $ha^{-1}\ y^{-1}$ (see Fig. 21). In the 10,200 ha Black Creek basin, this means that if just 102 ha of wetland (1% of basin) were used in a WSMS, intercepting all runoff, the decrease in water not discharged from the land would increase the annual gross economic product by at least US\$ 694,000 or possibly by as much as US\$ 4,800,000 assuming that an EM\$ of renewable environmental energy was matched at a rate comparable to the state mean (see Table 5).

6.1.2. Watershed productivity (transpiration)

The per unit value of wetland productivity increased with wetland size (see Fig. 22). While the value of transpiration for a stormwater wetland equal to 1% of total basin area was only about 60 EM\$ $ha^{-1}\ y^{-1}$, at 25% of basin area the value jumped significantly to 1660 EM\$ $ha^{-1}\ y^{-1}$ (see Table 6). This is due to two factors. The first is that wetland transpiration was higher on a per unit basis for larger stormwater wetlands and the second being that the transformity of the water source for transpiration (wetland soil moisture) increased also.

For the Black Creek basin (10,200 ha), the total contribution of transpiration to the economy was US\$ 22,000,000 y^{-1} when there was no wetland area, assuming the 7 to 1 investment ratio for Florida. Incorporating a 2550 ha stormwater wetland would more than double the value of watershed transpiration to US\$ 48,000,000 y^{-1} (see Table 6).

6.1.3. Water storage

Stormwater wetlands increased the amount of water stored on the landscape, i.e., surface water plus surficial aquifer (1 m depth below ground). For the simulated

Table 9
Emdollar values of water stored within watershed in surface and sub-surface for a range of wetland areas

Wetland area (ha)	Surface water EM$ (1×10^6)	Surface water/ watershed EM$ ha^{-1}	Sub-surface water EM$ (1×10^6)	Sub-surface/ watershed EM$ ha^{-1}	Total water EM$ (1×10^6)	Total water/ watershed EM$ ha^{-1}
102	0.488	48	1.41	138	1.90	186
510	0.560	55	1.45	142	2.01	197
1020	0.619	61	1.45	142	2.07	203
2550	0.772	76	1.43	140	2.20	216

Black Creek basin (10,200 ha), the total value of water stored ranged from 1.9×10^6 EM$ when wetland area was 102 ha to 2.2×10^6 EM$ when wetland area was 2550 ha (see Table 9).

6.1.4. Benefits to the everglades ecosystem

The Black Creek basin, for the 1986–1988 period simulated, received almost 50% of its emergy input via the canal system, flowing from the Everglades and Lake Okeechobee in the central part of south Florida. Due to convergence upon the landscape, this water had a higher transformity than rainfall, and consequently a higher capability to do work. It may be beneficial to south Florida, if south Dade County did not rely so heavily on this water supplement, but instead implemented WSMS to conserve and store the rain falling within its boundaries, thus keeping Lake Okeechobee waters in productive processes in the central Everglades. On the other hand, south Dade is receiving a large subsidy of water, which seems to be poorly used, since much of it is allowed to flow through the county into Biscayne Bay. It would be to south Dade's advantage to construct a WSMS so that better use of the water supplement is possible.

Adding wetland area to the south Dade landscape could substitute for the water supplement delivered through the canal system, keeping landscape productivity at the same level. The simulation model showed that if the volume of canal inflow was reduced by 75% (a value of 4.0×10^6 EM$ y^{-1}) and 10% of the basin was reserved as wetland for the WSMS, then the productivity of the natural landscape would be 0.3×10^6 EM$ y^{-1} higher than if the current canal inflows were used with no WSMS. Therefore, the net benefit would be 4.3×10^6 EM$ y^{-1}. Effects on watershed emdollar flows when canal water input was reduced and wetland treatment area was 10% of basin are shown in Table 7.

6.2. Simulation model

6.2.1. Energy systems diagrams, iconographic Extend® and dynamic emergy accounting

The energy systems language, with its mathematical definitions, was programmed into an Extend—Energy Systems Symbol Library, which are iconographic blocks that contain the programming code necessary for simulating emergy flows (Odum and Odum, 2000). Dynamic emergy accounting requires that the energy and mass of inputs, internal flows and storages be tracked, which is possible with the Extend—Energy Systems Symbol Library. Thus, not only do energy systems diagrams offer conceptual holistic views of systems and a mathematical tool for establishing models, it is now integrated with Extend—Energy Systems Library to simulate the temporal dynamics of solar emergy. The Extend—Energy Systems block icons allow models to be set-up and run quickly and easily; it combines energetic principles, such as energy conservation (first law) and entropy (second law), with the holistic systems perspective of Odum's energy systems language (Martin and Tilley, 2000).

6.2.2. Watershed discharge

The simulation results showed that stormwater wetlands could significantly reduce peaks in canal discharge. For instance, under the current drainage system which lacks significant wetland storage, a 70 mm rainfall event resulted in a peak discharge of over 1,000,000 $m^3\,d^{-1}$, but when a stormwater wetland equal to 1% of total basin area was added to intercept runoff, peak flow was reduced to just over 600,000 $m^3\,d^{-1}$ (a 40% reduction, Fig. 14). A stormwater wetland equal to 10% reduced the peak discharge even further to about 350,000 $m^3\,d^{-1}$. Given the need to restore the pattern of natural discharge to bays and estuaries to promote their ecological health, this demonstrates the potential benefits that WSMS provide to coastal ecosystems.

6.2.3. Validity of model

The ability of the model to duplicate measured hydrologic parameters (surface discharge and water tables) could possibly be improved by several factors. Daily-simulated discharge (Fig. 8) and groundwater levels (Fig. 9a) could possibly have been closer to the actual measured values, if rainfall data more precise than daily was used (e.g., hourly or half-hourly rainfall data). Also, rain data from the Black Creek watershed was not available, so rainfall data collected at the Miami International Airport, which was nearby, but outside the basin boundary, were used. Since the spatial distribution of daily rainstorms in south Dade tends to be localized, using the Miami Airport rain data may not be a good approximation to rain falling within the Black Creek basin.

Maybe the largest factor contributing to the discrepancies between the simulated and measured values was that the canal outflow structure was controlled by the south Florida Water Management District (SFWMD). There are several reasons why SFWMD manages the canal discharge, including (i) maintenance of a prespecified water table level for crop production, (ii) prevention and reduction of flood damage and (iii) prevention of saltwater intrusion to the freshwater Biscayne Aquifer. Unfortunately, the only attempt to include any of these management decisions in the model was to use a switch to turn off canal discharge during early autumn to emulate decisions based on agricultural practices. A more detailed human decision component could have improved the ability of the model to reproduce the actual discharge.

Considering the complexities involved in simultaneously simulating surface and sub-surface hydrology in an urbanizing watershed, the model was reasonably accurate in reproducing the general trends in surface discharge and water tables (see Figs. 8, 9 and 30). The simulated discharge increased after rain events larger than about 25 mm, whereas the measured discharge increases after some rain events, but decreases after others (see, for example, early June, mid-July and late September of 1986 in Fig. 8). For the first 2 years of the simulation period, the simulated water table was never more than 40–50 cm away from the measured level, except for a few weeks in October 1987 (Fig. 9). Regardless of an absolute scale, the relative changes in simulated and measured groundwater levels were notably well synchronized (Fig. 30).

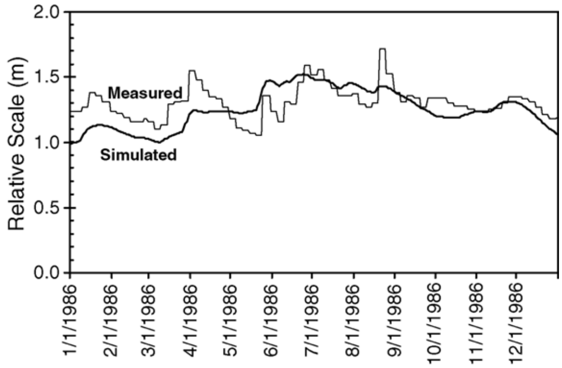


Fig. 30. Comparison of synchronicity of measured and simulated surficial aquifer levels using a relative scale with no wetland storage.

6.3. Dynamic properties of water transformity

6.3.1. Dynamics of transformity

Fig. 25 showed that the transformity of wetland water decreased asymptotically as wetland area increased. One explanation may be that as the wetland area was enlarged, rainfall with a lower transformity (15,000 sej J^{-1}) became a larger percentage of total empower to the wetland while empower from canal input (transformity = 40,000 sej J^{-1}) was constant, but decreasing as a percent of total. Empower input from canal inflow was always 248×10^{14} sej d^{-1}, while empower from rain ranged from 3×10^{14} sej d^{-1} when wetland area was 1% of basin area to 73×10^{14} sej d^{-1} when wetland area was 25%.

The transformity of canal water also tended to decrease as wetland area was enlarged (see Fig. 25); it was 26,200 sej J^{-1} when there was no wetland and 19,300 sej J^{-1} when wetland was 25% of basin area (see Table 10). When the WSMS was included in the model, canal inflow was redirected to wetland water instead of flowing directly to canal water (compare diagrams in Figs. 4 and 12). The transformity of canal inflow was 40,000 sej J^{-1} while that of rain was 15,000 sej J^{-1}. The re-routing of canal inflow significantly reduced the empower reaching canal water, there by reducing its transformity.

Table 10
Mean and standard deviation of daily transformity for canal water, groundwater and wetland water for range of wetland areas from 0 to 2550 ha for the 10,200 ha Black Creek watershed

Mean (sej J^{-1})				Standard deviation (sej J^{-1})		
Wetland area (ha)	Canal water	Groundwater	Wetland water	Canal water	Groundwater	Wetland water
0	26200	25000		7060	5040	
102	19900	21600	28300	1550	362	8230
510	20200	22100	22800	1450	328	5030
1020	19700	22300	21200	1240	303	3060
2550	19300	22600	19600	870	360	1600

6.3.2. Alternative estimates of water transformities

Depending on assumptions made about how to allocate emergy to flow pathways in a system, different transformities may result. We compared three methods for allocating emergy, which can be summarized as: (1) allocating all the inflow empower to the total outflow energy which assumed that all outputs from the system were of similar quality, thus 'splitting' the energy and emergy (Fig. 31), (2) allocating all the inflow empower to the energy of each individual outflow pathway separately which assumed that all the incoming emergy was necessary to create each flow, which assumes energies were 'co-products' (Fig. 32) or (3) tracing the internal flow of emergy along the pathways in the simulation model making allocation decisions at each process interaction. This method, which we call "internal tracking" is a refinement over previous techniques and was used in our watershed simulation model (Fig. 33).

Comparing the transformities that result from each allocation method provides some insight on the ramifications of using each method. As summarized in Table 11, the co-product allocation procedure always produced the highest transformities and was the least conservative energetically (i.e., emergy output greater than emergy input). The 'split' allocation procedure forced the output transformities to be identical and was the most energetically conservative (i.e., emergy output equals emergy input). Whereas 'split' and 'co-product' allocation procedures were conducted based on steady state systems, which historically was standard practice in emergy accounting (Brown and Herendeen, 1996), our internal tracking procedure takes advantage of the ability to continuously track emergy flow throughout a system, making a mixture of allocation decisions at each energy transformation. Thus, the 'internal track-

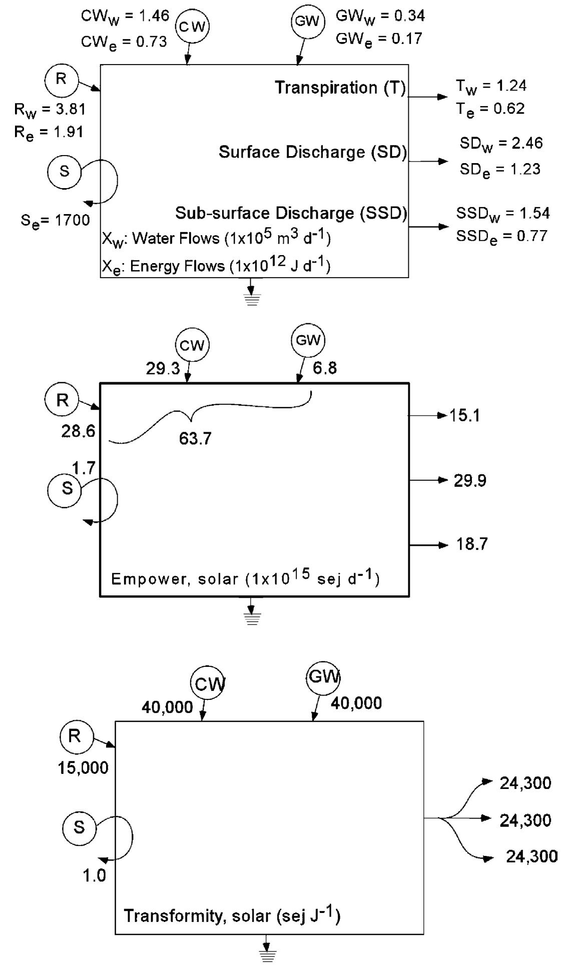


Fig. 31. Summary diagrams of water and energy flows, empower and transformity assuming all three outputs are splits of Black Creek (C-1) watershed system with wetland stormwater management system 5% of basin.

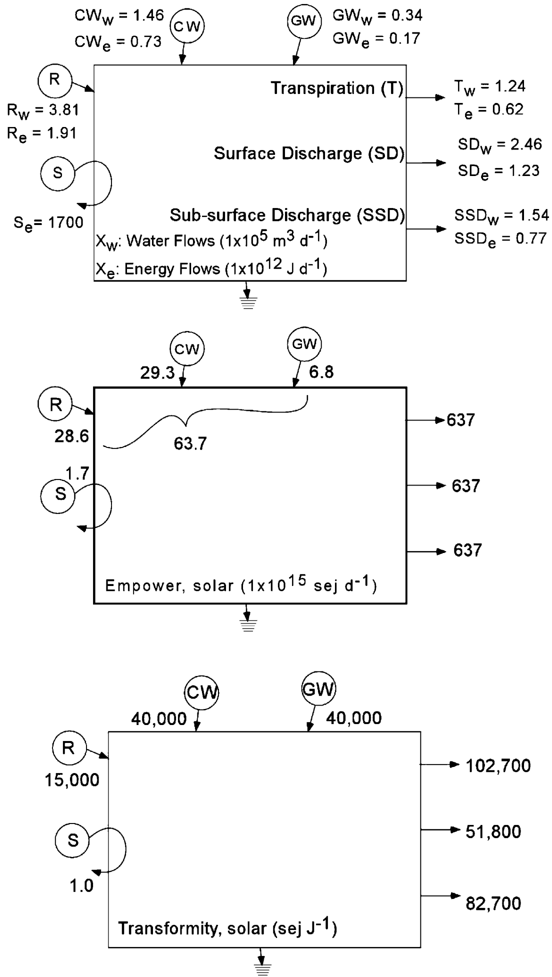


Fig. 32. Summary diagrams of water and energy flows, empower and transformity assuming all three outputs are co-products of Black Creek (C-1) watershed system with wetland stormwater management system 5% of basin.

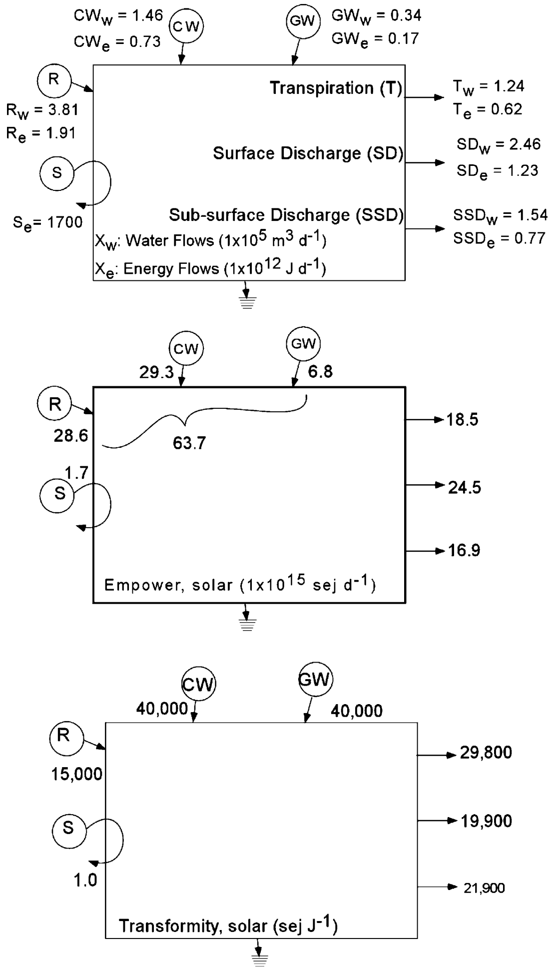


Fig. 33. Summary diagrams of water and energy flows, empower and transformity from model simulations of Black Creek (C-1) watershed system with wetland stormwater management system 5% of basin.

Table 11
Summary of transformity estimates (sej J^{-1}) assuming different allocation rules

Note	Allocation procedure	Transpiration	Canal discharge	Groundwater outflow
1	Co-products	102000	51800	82700
2	Internal tracking (0% wetland)	32800	23700	24500
3	Internal tracking (5% wetland)	29800	19000	21900
4	Splits	24300	24300	24300

Note: 1, energy outflow simulated in model when wetland area was 5% of basin area (see Fig. 32); 2, internal tracking with simulation model when there was no wetland area; 3, internal tracking with simulation model when wetland area was 5% of basin; 4, energy outflow simulated in model when wetland area was 5% of basin area (see Fig. 31).

ing' procedure was a hybrid allocation method, which in our study, produced transformities for transpiration, canal discharge and groundwater outflow that were intermediate between pure 'co-product' and 'split' rules (Table 11). Internal tracking gave a lower transformity for transpiration than co-product allocation, but a higher one than split allocation. On the other hand, internal tracking produced the lowest transformities for surface and sub-surface discharge. Comparison of the three emergy allocation procedures suggested that internal tracking offers a refinement to the aggregated, steady state approaches of co-products and splits, but does so at the expense of requiring an elaborate computer simulation model. Dynamic emergy accounting is in its infancy, and therefore could benefit greatly from more research.

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