Water balance investigation using Equilibrium Water Balance Model

The Equilibrium Water Balance Model (EWBM) was developed in NWRI in frame of the contract KW405-000223 as a tool for estimation of groundwater and climate interaction over area of Southern Ontario (August 2000 – March 2001). But for some reason the results of this contract could not be published. Thus, several new applications for this model were done using other sources of the same information to be published.

INTRODUCTION

The idea of EWBM was formulated by Dooge as a hypothesis of equilibrium between the climate factors, the pedological factors and vegetative factors (Dooge et all, 1999). It means that climate zonality complicated by geo-morphological condition results in water table and corresponding vegetation variability, which results in its tern in evapotranspiration. The depth to water table (WT) is the reflection and the same time the reason for corresponding evapotranspiration. It can be illustrated by hydrogeological map of European Territory of former USSR. Tundra zone is characterized by very close water table position to surface with often transmission into wetlands and surface water. In the zone of high north water the depth to WT on the watershed edges is equal to 2-6 m, zone of not-deep valleys - to 20-25, zone of deep valleys - 25-30, zone of the by-Black Sea-valleys - 100 m and more (Bogoslovsky et all, 1984). There is no mechanism to put it together, but water balance. Dooge uses simple soil moisture accounting accepting ground water as one-way water transmission: recharge from root zone, seepage into river. There are no deeper than riverbed groundwater and its backward moving. My interpretation of the equilibrium hypothesis is that depth to groundwater table characterizes availability of backward moving of water from groundwater table for evapotranspiration in dry periods and recharging of deeper waters in high wet periods (falls, springs, etc.). The results obtained by applying the EWBM to 5 different watersheds of southern Ontario confirmed this interpretation of the equilibrium hypothesis.

DATA USED

Five watersheds were available for this application: upper subwatershed of Spencer Cr. (daily flow from 02HB015 station and air temperature and precipitation from Hamilton airport station), Spencer Cr. watershed at HWY5 (daily flow from 02HB023 and the same temperature and precipitation), upper subwatershed of Etobicoke Cr. (daily flow from 02HC017 and air temperature and precipitation from Pirson airport and Toronto island stations), Etobicoke watershed at QEW (daily flow from 02HC030 and the same source of climate data), and Mimico Cr. watershed at QEW (daily flow from 02HC033 station and the same source of climate data

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Comparative basic information about watersheds is given in table 1.

Table 1. Basic geo-physical information of examined watershed

Creek name	Station name	Drainage area, km2	Effective saturation of wshd deposits Y	Station ID
Spencer Cr.	Westover	63.5	0.11	02hb015
Spencer Cr.	HWY 5	132	0.16	02hb023
Etobicoke Cr.	Brampton	63.2	0.035	02hc017
Etobicoke Cr.	QEW	204	0.033	02hc030
Mimico Cr.	QEW	70.6	0.023	02hc033

To estimate the permeability and water conductivity coefficients for examined watersheds the map of Quaternary geology of Ontario was used, from which the weight of each deposit was obtained and water yield (effective saturation) was estimated according to Hydrological Glossary (Chebotarev, 1978) and Hydrogeological Manual (Nedra, 1987) for each deposit as well as for whole watershed.

EWBM MODEL DESCRIPTION

The model equation for this application was taken as the following:

$$P - R + dG + dM = E \qquad (1)$$

where (in our particular case)
P - month amount of precipitation, mm
R - river runoff, mm
dG - changing in ground water storage, mm
dM - changing in soil moisture storage, mm
E - evapotranspiration as a residual, mm

Precipitation (P) for the first two examined watersheds (Spencer creek) were taken the same, for Etobicoke and Mimico Creeks they were weighted.

River runoff was measured.

Changing in groundwater storage dG was estimated using the following:

$$dG = dH*Y*1000 \qquad (2)$$

where
dH - changing of groundwater level within examined period, m (dH was accepted as a difference between average levels for previous and current months: H previous - H current).

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Y - average water yield of watershed deposits (effective saturation), dimensionless.
1000 - transformation coefficient from meters to mm.

For different deposits on examined watersheds Y was taken as following (according to Hydrological Glossary and Hydrogeological Manual):

Till	Clay	Silt	Fine sand	Medium sand	Gravel
0.02	0.005	0.035	0.12	0.2	0.3

Average water table level for each month was estimated as the following:

$$H = 1000*I \text{ if } H = Hmin, \quad (3)$$

Where

Hmin - head of water table above the creek bed within the creek valley (lowest “uniform area-sink” according to Etcheverry & Perrochet [2000], initial rise of water table according to Daniel [1976], and the head of primary drainage system according to Vermulst and Lange [1999]), where relation between H and I remains to be linear.

I - average gradient of water table, dimensionless, was estimated from simplified equation of Darcy’s law (Freeze & Cherry, 1979)

$$I = B/(F*K*0.0864) \quad (4)$$

B - monthly baseflow, m3/s – genetic component of streamflow, which comes from groundwater storage (daily data obtained by SimpleBase© and summarized monthly)
F - watershed area, km2
0.0864 - summarized adjusting coefficient between day and second, km and m
K - hydraulic transmissivity of deposits above river bed, m/day

$$K = Y*EXP(0.8/(1 - 2.5*Y)) \quad (5)$$

If actual H is higher than H min,

$$H = Hmin + LN(1 + I*r/K) \quad (6)$$

where

r - radius of cones, half of which surface area is equal to the area of watershed (Daniel, 1976)

$$r = SQRT(2*F/3.14) \quad (7)$$

To estimate Hmin the F for river valley was accepted as mach as 3 km2 (1-5 km2 according to Vermulst and Lange, is an average “uniform area-sink”) that was estimated for European experimental watersheds that tend to be small (less than 10 km2) and heavily instrumented”. And there is the room for further improvements: the “uniform area-sink” is nothing else as river valley and can be estimated proportionally to watershed area.

Changing in soil moisture storage dM was estimated on the following statements (simplifications):

1. the unsaturated layer has one capacity within the depth (WMO N168, 1994), that means the moisture storage is proportional to the depth of the unsaturated layer (Bouten 1995, Munro 1984b, Vedom 1996) and changing of water table level

2. residual saturation Sr depends on effective saturation Y (Brooks & Corey, 1964) and approximately can be estimated as following:

$$Sr = 2.5Y/(1 + Y*20) \qquad (8)$$

3. soil moisture conditions in unsaturated layer are the same for any month: no influence of soil temperature or permafrosting.

Finally, soil moisture storage changing was taken as following:

$$dM = dH*2.5Y/(1+Y*20) \qquad (9)$$

RUNNING THE MODEL

The model runs looking a Hmin over the highest correlation between monthly evapotranspiration and air temperature for long-term period (the longer a homogenative period, the better). As a result, the following set of parameters was obtained: the individual Hmin for each watershed, corresponding monthly evapotranspiration for examined period, and correlation coefficients with air temperature and precipitation. Base flow numbers are obtained during preliminary running of SimpleBase© separation model, which is an independent module of the EWBM and can be used separately.

OBTAINED RESULTS

There are monthly evapotranspiration and groundwater head for examined watersheds in table 2.

Table 2. Monthly evapotranspiration (mm) and groundwater head (m) for examined watersheds

Station ID	Period	Parameter	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Year
02hb015	1985-97	Evap.	27.4	38.3	53.9	114	105	69.4	24.9	54.9	618
		Head	1.46	1.46	1.43	1.01	0.66	0.76	1.29	1.44	1.27
02hb023	1987-97	Evap.	12.9	28.3	40.7	128	102	74.4	50.6	1.3	513
		Head	1.03	1.03	1.02	0.67	0.42	0.38	0.52	0.95	0.82
02hc017	1985-93	Evap.	28.7	61.8	62.3	82.6	83.1	67.1	64.1	58.8	590
		Head	1.16	0.93	0.89	0.87	0.87	0.93	0.96	1.02	0.98
02hc030	1985-97	Evap.	28.1	42.6	46.7	65.6	62.2	55.2	48.3	46.7	465
		Head	2.03	1.77	1.67	1.63	1.63	1.68	1.71	1.82	1.78
02hc033	1985-97	Evap.	32.7	42.1	45.9	56.5	57.0	50.5	43.8	44.4	460
		Head	0.83	0.64	0.53	0.47	0.47	0.52	0.54	0.64	0.61

There is the noticeable difference between Spencer and the others watersheds in spite of their relatively close location: Etobicoke and Mimico Creeks are located within Toronto, and Spencer Creek – around Hamilton. And this can be explained by difference between geo-morphological conditions of these watersheds such as large paved area within highly urbanized watershed (evapotranspiration decreasing factor) and large swamped area on the Spencer watershed (also evapotranspiration increasing factor). What is more interesting that there is difference between upper part and total watersheds in each case. There is almost no difference between Etobicoke and Mimiko watersheds (465 and 460 mm). But upper part of Etobicoke is significantly different from total watershed (590 and 465 mm). The difference, 125 mm, cannot be real within such a small watershed like Etobicoke Creek (204 km^2). The same situation can be seen for Spencer Creek (618 and 513 mm). There is 105-mm difference within area of 132 km^2. This can indicate amount of water going to recharge the deeper groundwater in upper part of watershed not drained by upper stream and inclined into creek downstream. This component is simply not present in our water balance equation. Real evapotranspiration is equal to 465 mm for Etobicoke watershed and 513 mm for Spencer. Even those might be overestimated due to complete drainage of watershed is happened at creek mouths. The closer the outlet of examined watershed to ‘the final collector of drainage waters’ (there is Lake Ontario in our case), the closer obtained evapotranspiration to reality.

Behavior of water table is strongly divided by Y numbers. Let say watersheds with Y>0.1 has one picture, with Y<0.1 – another. And this is very understandable. Etobicoke and Mimico watersheds have much more broken topography, and groundwater head of 1-2 m is far from evaporating surface (more than 3 m, Robert Klimas, private talk). If to take paved impermeable surfaces of heavy urbanized areas into account, it is easy to realize that there is no connection between groundwater head and evapotranspiration in warmest months, or it is very weak.

Another deal is Spencer creek. Its valley is heavily forested, watershed areas are mostly agricultural fields (Crook, 1999). Dropping of water table in July and August, even in September is not surprise. But what is really strange, it is stable position of level in May and June, when huge amount of water is used for transpiration that should be large in heavy forested and agricultivated watershed. But it can be explained by transmission of water from an adjoin watershed under high position of groundwater in spring and beginning of summer. And it is very possible if take into account very next location of escarpment to Spencer watershed. So to answer this question the adjoin watersheds should be investigated as well.

Calibration results are presented in table 3. There are highest correlation coefficients between estimated evapotranspiration, air temperature and precipitation.

Table 3. EWBM calibration results

Station ID	H min, m	R air temper.	R precipitation	Y	BFI
02hb015	1.4	0.72	0.51	0.11	0.74
02hb023	1	0.72	0.23	0.16	0.62
02hc017	0.74	0.35	0.69	0.035	0.34
02hc030	1.25	0.32	0.79	0.033	0.30
02hc033	0	0.27	0.83	0.0225	0.33

So far it is not very easy to interpret Hmin numbers. But it is possible to guess that for Mimico creek Hmin is equal to 0 because of highly canalized creek's valley (area of Greater Toronto) in spite of the original deposits have very fine texture (Y = 0.0225): the higher drainage capacity of watershed, the lower Hmin. Generally, presence of the coarse material that is flashed out from all over the watershed and concentrated in river valley provides lower Hmin for higher number of Y. Unfortunately, such a small number of examined watersheds is not enough to make this conclusion for sure. Furthermore, if compare Hmin from table 3 with H from table 2, the interpretation Hmin as a water head within river valley becomes doubtful for watersheds with high Y (sand, gravel). For those watersheds the relationship between baseflow and groundwater gradient is linear within almost whole magnitude of water table fluctuation.

The base flow index stands for BFI - the volume of baseflow divided by the volume of total flow (Smakhtin, 2001). Obtained high correlation coefficients of evapotranspiration with air temperature for both of Spencer creek watersheds (0.72 and 0.72) harmonize with BFI numbers that indicate large share of groundwater in the creek flow (0.74 and 0.62). What is more interesting for Spencer creek there is the identification of a large swamp, Beverly Swamp, in the lower part of watershed. There is higher evapotranspiration on whole watershed than on the upper its part in July (the warmest month), due to which the share of base flow (highest in summer) becomes noticeably lower for total watershed.

For Etobicoke and Mimico watersheds availability of water, precipitation is mach more important in evapotranspiration process than air temperature. Correlation with precipitation indicates this (0.69, 0.79 and 0.83).

CONCLUSIONS

Investigation of water balance using EWBM was a good approbation of this model as a tool for groundwater and climate interaction. This gave the following results:

1. Long-term monthly evapotranspiration and the water table head above the creek beds for five watersheds were obtained and analysed.
2. The difference between year evapotranspiration of upper and whole watershed may be identified as losses of flow due to recharging of deeper groundwater and not drained by flow at the upper outlet.
3. The differences between monthly evapotranspiration of Spencer creek in upper and lower reaches in combination with BFI numbers clearly indicate presence of water body: wetland or lake, which increases evapotranspiration in the wormiest month.
4. Water table behaviour at Spencer watershed indicates possible transmission of groundwater from outside of watershed in months with high water table (spring). This needs to be checked.
5. Geo-morphometrical feature of river valley can be characterised by Hmin – the model parameter, which in different models has different interpretations, - only for watersheds with very low Y (<0.05). This parameter is a key one providing close connection between groundwater and climate and also should be investigated for bigger amount of watersheds.

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