Proceedings of the Nineteenth Annual American Geophysical Union Hydrology Days, August 16 – 20, 1999, Fort Collins, Colorado, USA: 11 – 22.

OPEN INTEGRATION OF A SPATIAL WATER BALANCE MODEL AND GIS TO STUDY THE RESPONSE OF A CATCHMENT

Tirusew Asefa[1], Z. Wang[1], O.Batelaan[1] and F. De Smedt[1]

ABSTRACT

There is an increasing interest in the hydrology community in integrating Geographic Information System (GIS) technology and hydrological models. The spatial dimensionality of most hydrological and environmental problems is addressed by spatially distributed models. One such model is WetSpass (stands for Water and Energy Transfer between Soil Plant and Atmosphere under Steady State). When integrated, spatial models benefit from GIS, as the GIS handle the pre- and post- processing (preparing inputs, spatial analysis, displaying, etc.).

Until now the only way to integrate an application with ARC/INFO was to use ARC Macro Language (AML) scripts and associated menu. Now, ARC/INFO comes with Open Development Environment (ODE) C Application Programming Interface (API) functions to access ARC/INFO functionality from any development environment.

In this research ODE was used to integrate WetSpass with ARC/INFO. In addition, a graphical user interface has been developed using OSF/Motif and C.

The integrated WetSpass and ARC/INFO has been applied to a catchment of 525.55 km^2 in the Grote-Nete catchment, Belgium, to model catchment response for different uses and the result shows a clear picture of the actual evapotranspiration, recharge and surface runoff of the area. The interface developed facilitates input data preparation and output visualization, as well as simulations of effects of different land use changes. The merit and disadvantages of an open integration is also discussed.

INTRODUCTION

Like other environmental and natural resources, there is an increasing and widespread interest in integrating Geographic Information System (GIS) technology with mathematical models within the hydrology community (Batelaan et al., 1993; Engel et al., 1996; Olivera, 1996). Since 1960s when

---

[1] Laboratory of Hydrology, Free University Brussels, Belgium. Pleinlaan 2, 1050 Brussels. tirusew@vub.ac.be Tel.: +32 26293021 Fax: +32 26293022

computer technology became available, hydrologic modeling has been used widely and proved to be successful in dealing with dynamic simulation problems, which have time variation from seconds to years scale. However, most of the frequently used models are lumped, assuming uniform spatial properties in the modeling domain. Available distributed models, which discritize heterogeneous catchment with different properties into small uniform areas, are often hampered by input data preparation and output interpretation due to the large amounts of complex data. GIS with their powerful capability of data capture, manipulation, and display, offer excellent tools to remedy these problems in hydrological modeling. In the past, GIS were not only geo-processor but also graphical user interfaces builder through their interpreted languages (AML in ARC/INFO, Avenue in Arc/View). Now, the changes in GIS even go further to enable one to communicate with it from any development environment or build his own application through C Application Programming Interface (API) functions, as given by the Open Development Environment (ODE) of ARC/INFO (ESRI, 1997).

WetSpass MODEL

Model Description

WetSpass stands for Water and Energy Transfer between Soil, Plants and Atmosphere under Steady State. It uses long-term average precipitation, potential evaporation from free water surface and wind speed as inputs, to simulate average spatial patterns of surface runoff, actual evapotranspiration and groundwater recharge in a basin or a region. It is a simplified version of the time dependent spatial distributed water balance model 'WetSpa' (Batelaan et al., 1996, Wang et al., 1997). The model treats a basin or region as a regular pattern of grid cells. Every grid cell can be subdivided in a vegetated and a non-vegetated part. For every grid cell a water balance will be maintained.

Water balance for vegetated surfaces

The water balance for vegetated surfaces is given by:

$$P = I_v + E_v + S_v + R_v \tag{1}$$

where P is the precipitation, I_v is the interception by vegetation, E_v is the actual evapotranspiration of vegetated surfaces, S_v is the surface runoff and R_v is the groundwater recharge (Fig. 1).

The interception by vegetation is taken as 15 % of the precipitation and evaporates potentially. Due to the limited availability of interception values and the steady state character of the model, an equal interception value for the different vegetation types is assumed.

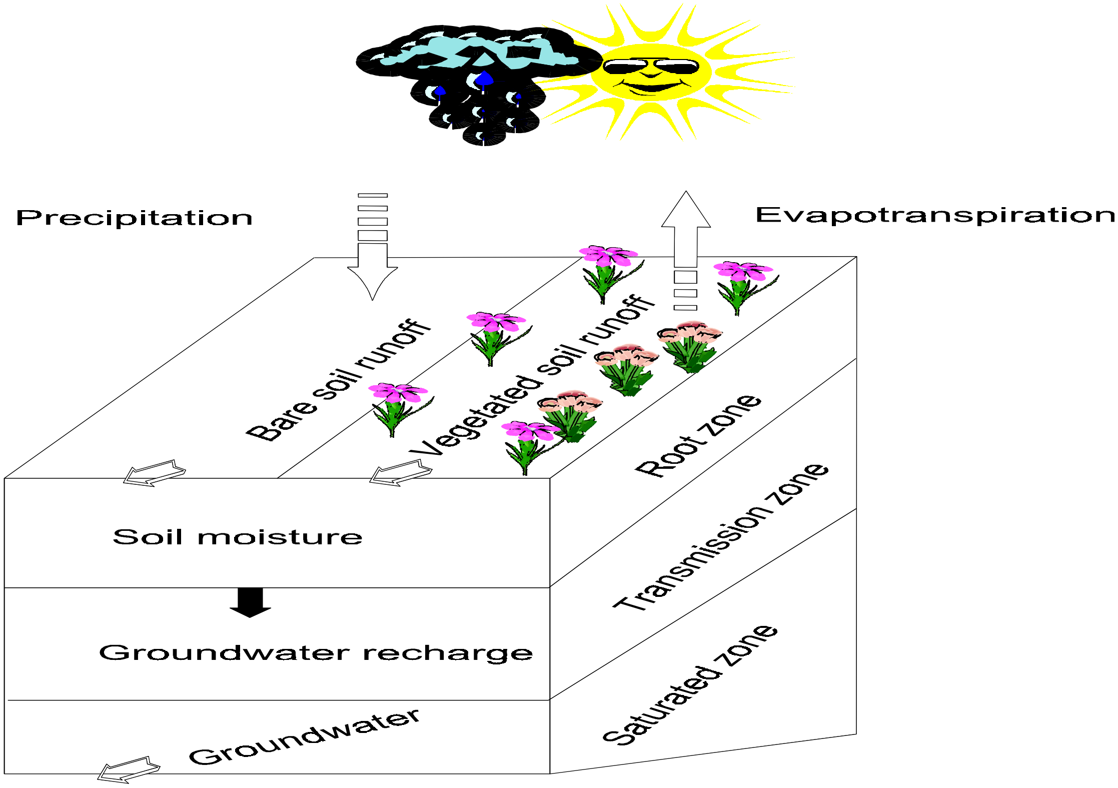

Figure1. Schematic water balance in a typical grid cell.

The actual evapotranspiration is calculated in two steps:

1. The potential evapotranspiration, E_{pv} of a vegetated surface is determined from the potential evaporation of open water, E_o, by means of a vegetation coefficient, c:

$$E_{pv} = c * E_0 \tag{2}$$

The coefficient c is a function of the vegetation type. Hereby, it is assumed that the change in heat storage and capillary rise over a longer period is negligible. The ratio between the potential evapotranspiration and the potential open water evaporation, both given by the Penman-Monteith formula, is the vegetation coefficient (Stewart, 1988):

$$c = \frac{1+\frac{\gamma}{\Delta}}{1+(1+\frac{r_s}{r_a})\frac{\gamma}{\Delta}} \tag{3}$$

where r_s is the surface resistance, γ is a psychometric constant and r_a is the aerodynamic resistance of water, calculated as:

$$r_a = \frac{1}{k^2 u_a z_a} \left(\ln \left(\frac{z_{a-d}}{z_0} \right) \right)^2 \tag{4}$$

where k is the Von Kármán constant, u_a is the wind speed on the measurement level z_a, d is the zero-plane displacement length and z_0 is the roughness length for the vegetation or soil, Δ is the slope of the saturation vapor pressure at the prevailing air temperature. The value of γ/Δ indicates the Penman coefficient, and can be obtained according to the following table:

Table1. γ/Δ variation with temperature.

Ta (°C)	-20	-10	0	5	10	15	20	25	30	35	40
γ/Δ	5.864	2.829	1.456	1.067	0.793	0.597	0.445	0.351	0.273	0.215	0.171

2. In vegetated groundwater discharge areas, the actual evapotranspiration is equal to the potential evapotranspiration, since there is enough soil water available.

$$E_v = E_{pv} \tag{5}$$

The actual evapotranspiration for vegetated infiltration areas, is calculated according the methodology developed by Xu (1992) and Vandewiele et al. (1993):

$$E_v = f * E_{pv} \tag{6}$$

where f is a factor determined by:

$$f = 1 - a_1 e^{\frac{w}{E_{pv}}} \tag{7}$$

where E_{pv} is the potential evapotranspiration calculated according to Equation 2 and a_1 is a factor determined by the sand content of a soil type (Van der Beken and Huybrechts, 1990), and w is the available water for evaporation, coming from the precipitation and the water in the soil.

Equation 2 and the factors a_1 can be obtained from calibration of a water balance model on monthly scale for different basins (Van der Beken and Huybrechts, 1990). If this equation with corresponding factors is used, then the available water for evapotranspiration has to be calculated on monthly time basis as:

$$w = P_m + (\theta_{vc} - \theta_{vw})L_w \tag{8}$$

where P_m is the average monthly precipitation, θ_{vc} the water content in the soil at field capacity, θ_{vw} the water content in the soil at permanent wilting point, and L_w is the rooting depth.

The surface runoff, S_v, is calculated as a coefficient times the net-precipitation:

$$S_v = C_{Sv} * (P - E_v - I_v) \tag{9}$$

where C_{Sv} is a surface runoff coefficient for vegetated surfaces, adjusted from Mallants and Feyen (1990).

The groundwater recharge can be calculated, as a rest term, from the water balance:

$$R_v = P - S_v - E_v - I_v \tag{10}$$

Water balance for non-vegetated surfaces

The same procedure as for the vegetated surfaces can be applied for the non-vegetated surfaces. The water balance for non-vegetated surfaces is given by:

$$P = E_s + S_s + R_s \tag{11}$$

where P is the precipitation, E_s is the actual evpotranspiration of the non-vegetated surfaces, S_s is the surface runoff and R_s is the groundwater recharge.

The potential evapotranspiration is given by:

$$E_{ps} = c * E_0 \tag{12}$$

In the model the coefficient c is 1, because it is assumed that the surface resistance of water and non-vegetated soils are equal. The actual evapotranspiration is calculated as (Xu, 1992 and Vandewiele et al., 1993):

$$E_s = f * E_{ps} \tag{13}$$

where f is a factor determined by:

$$f = 1 - a_1 e^{-\frac{w}{E_{ps}}} \tag{14}$$

where E_{ps} is the potential evapotranspiration calculated according to Equation12, a_1 is a factor which is determined by the sand content in a soil type (Van der Beken and Huybrechts , 1990), and w is the available water for evapotranspiration, coming from the precipitation and the water in the soil. The available water for evapotranspiration is calculated, on monthly basis, as:

$$w = P_m + (\theta_{vc} - \theta_{vw})L_w \tag{15}$$

where P_m is the average monthly precipitation, θ_{vc} the water content in the soil at field capacity, θ_{vw} the water content in the soil at permanent wilting point, and L_w the extinction depth of the evaporation in the soil, here taken as 1 m.

For groundwater discharge areas f in Equation 13 is 1 because on the saturated non-vegetated soil the evapotranspiration is potential.

S_s, the surface runoff is calculated as a coefficient times the net-precipitation

$$S_s = C_{Ss} * (P - E_s) \tag{16}$$

where C_{Ss} is a surface runoff coefficient for non-vegetated surfaces, adjusted after Mallants and Feyen (1990).

The groundwater recharge can now be calculated from the water balance:

$$R_s = P - S_s - E_v \tag{17}$$

Water balance per grid cell

The total water balance per grid cell can now be calculated with the previous described water balance components for vegetated and non-vegetated parts of a grid cell:

$$P = a_v(I_v + E_v + S_v + R_v) + a_s(E_s + S_s + R_s) \tag{18}$$

where a_v and a_s are respectively the vegetated and non-vegetated area fractions of a grid cell.

Model input and Output

The WetSpass model requires basically five categories of input data: climatic, catchment configuration, vegetation, soil properties and boundary conditions. The climatic data include precipitation, potential evapotranspiration, wind speed and penman coefficient. The catchment configuration includes the land use types, slope and groundwater depth. The soil parameters include hydraulic properties and empirical coefficients for modeling evapotranspiration and surface runoff. Boundary condition includes the extension of the area to be modeled. The outputs from the WetSpass model include the actual evapotranspiration, surface runoff and groundwater recharge distribution over a region. The results from different scenarios of land management practices can then be used by decision-makers to help prepare intelligent land management plans.

GIS ODE INTERFACE

A GIS/Model interface can be created in three ways, depending on the integration method: a) GIS based modeling or integrating a model and GIS such that the model becomes one of analytical functions of GIS; b) integrating GIS and a model through data conversion by creating programs to pass spatial data from the GIS to the model, then convert the result back to display and further analyze in GIS; c) by imbedding the input/output routines of the GIS into the model, allowing the model to read and write GIS data in its native format (Kopp 1996). In this research the second approach was followed. Until now the only way to create ARC/INFO application and integration was to use ARC Macro Language (AML) scripts and associated menu which is not as fast as a compiled languages. Now, ARC/INFO comes with Open Development Environment (ODE) C Application Programming Interface (API) functions to access ARC/INFO from any development environment

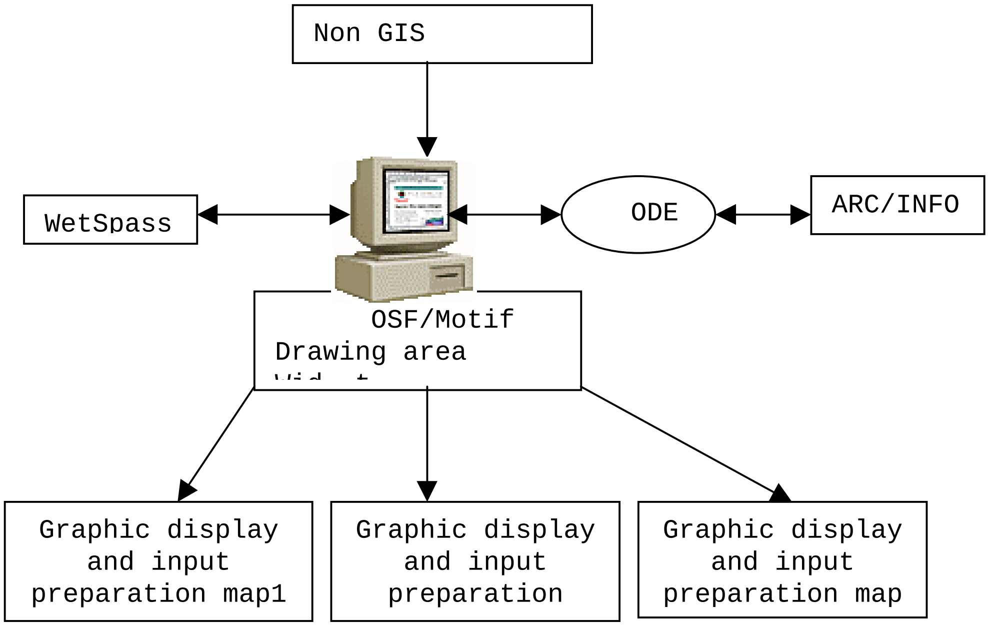

Figure 2. Schematic representation of the ODE integration.

The integration of WetSpass hydrological model with ARC/INFO in the Open Development Environment(ODE) consists of:

- Selecting the development environment;
- Creating a drawing area widget where ARC/INFO and the hydrological model interact with each other as well as with the user.
- Connecting both ARC/INFO and the hydrological model to the widget.

The ODE exposes the ARC/INFO program for editing, mapping, analysis, and geo-processing as a collection of libraries, providing an application programming interface (API) to the functionality available at the ARCEDIT, ARCPLOT, and GRID command lines.

The application is built by creating an X Window drawing area widget (see Fig. 2 above) and connecting ARC/INFO to it. ARC/INFO then uses the widget for all graphical output. Other non-GIS applications can also use the drawing area widget. ARC/INFO is not the sole controller of the drawing area, hence the name ‘Open Development Environment’. In addition, a ‘point and click’ menu-driven user interface have been developed by using OSF/Motif and C, while ODE C API functions were used to send commands to ARC/INFO engines.

APPLICATION

Study area

The integrated WetSpass and ARC/INFO is applied to Grote-Nete area, 525.25 km^2, north of Brussels, Belgium. Elevation values range between 0 m to 73 m above sea level. The area is dominantly flat with mean slope 0.3 % and most of its part has a slope less than 1%. Precipitation values are almost uniform through out the year. The average precipitation value in the area ranges from 743mm to a maximum of 800mm. Based on WetSpass’s soil classification, four types of soil dominate the project area: sand, sandy loam, loamy sand and silty loam. The land uses in the project area have 7 of the 14 Wetspass’s classes. Out of this, 27% crop/mixed farming, 20% deciduous broad leaf forest, 19% grass, 15% non-vegetated, 11% ever green pine forest, 7% deciduous shrubs and 2% open water.

Results

Figure 3, 4 and 5 show the calculated actual evapotranspiration, groundwater recharge and surface runoff distributions over the study area.

The integrated WetSpass model has also made easier to visualize the outputs with respect to one or more inputs as shown in the subsequent tables. As shown in Table 2, about 33% of the evapotranspiration come from crop/mixed farming area, which constitutes 27% of the project area. The same area receives 25% of the total recharge

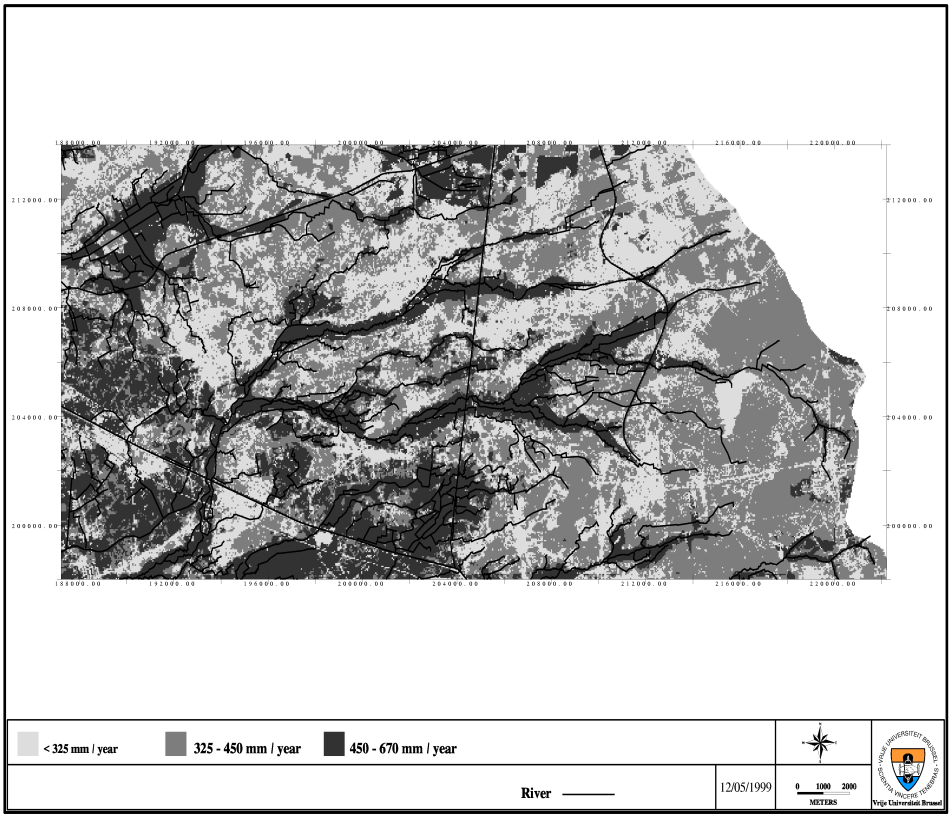

Figure 3. Evapotranspiration variation.

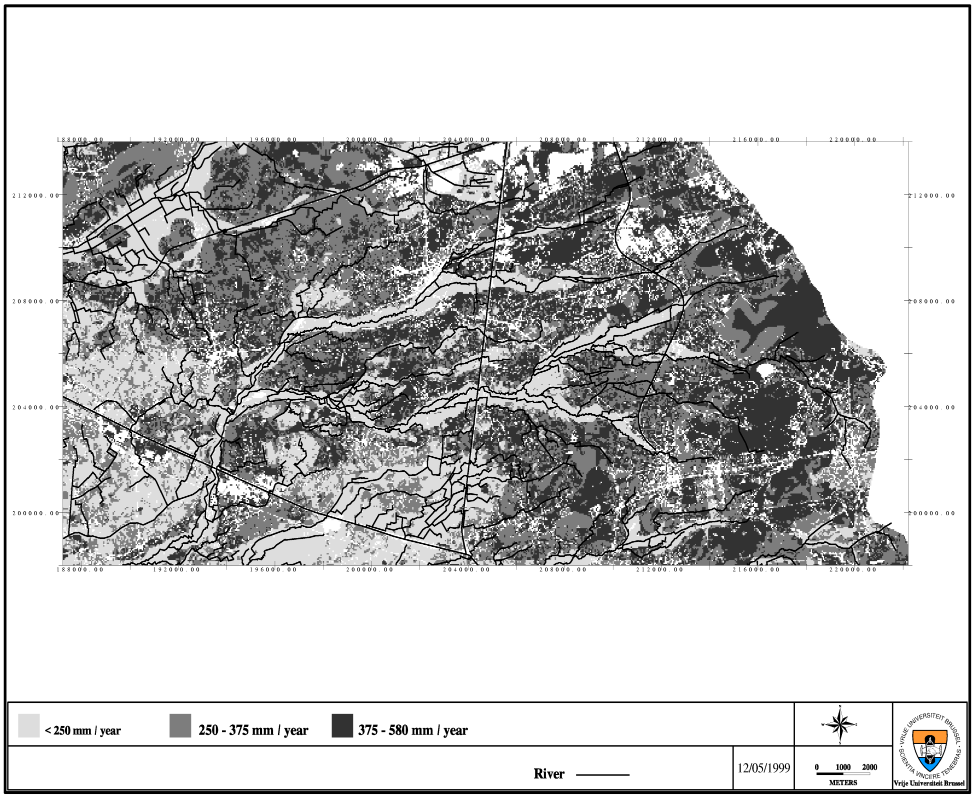

Figure 4. Groundwater recharge variation.

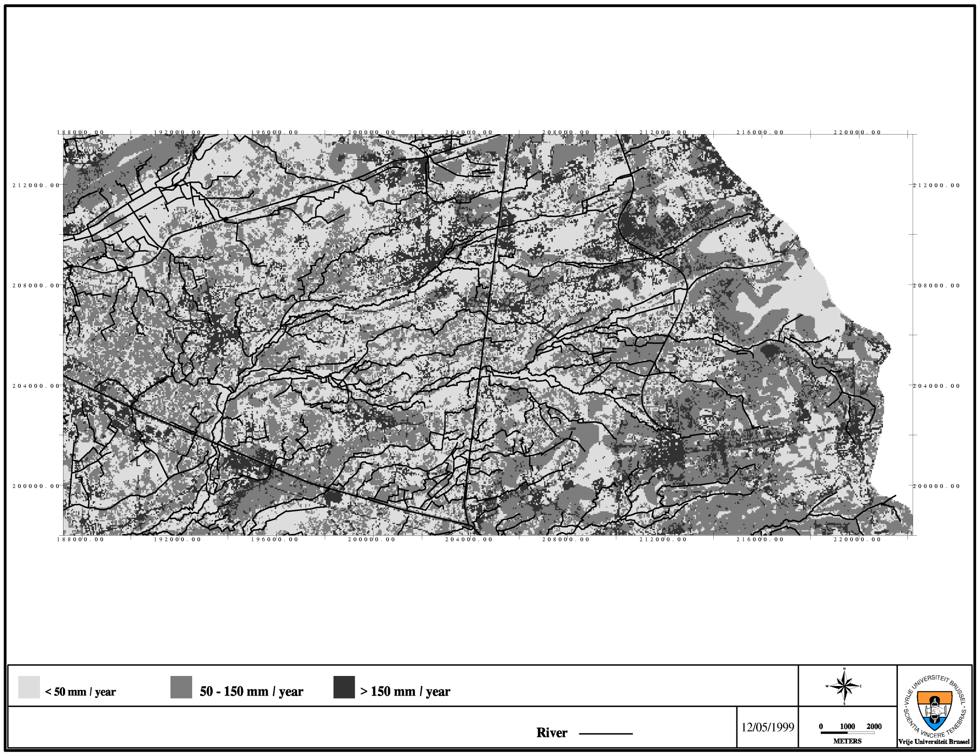

Figure 5. Surface runoff variation

Table 2. Soil types versus WetSpass outputs

	Evapotranspiration		Recharge		Surface runoff		Area
Soil Types	Total(Mm^3/year)	(%)	Total(Mm^3/year)	(%)	Total(Mm^3/year)	(%)	(%)
Sand	107.9	55.7	109.42	77.42	23.76	35.48	58.94
Loamy sand	56.82	29.4	25.28	17.89	7.18	10.72	23.21
Sandy loam	2.26	1.2	0.66	0.47	0.17	0.25	0.78
Silty loam	20.11	10.4	4.77	3.38	1.72	2.57	6.68
Clay loam	0.21	0.1	0.04	0.03	0.27	0.40	0.07
Impervious	6.21	3.2	1.15	0.81	33.87	50.57	10.32

Table 3. Land use types versus WetSpass outputs

	Evapotranspiration		Recharge		Surface runoff		Area
Land use	Total (Mm^3/year)	(%)	Total (Mm^3/year)	(%)	Total (Mm^3/year)	(%)	(%)
Crop/mixed farming	63.39	32.76	35.88	25.39	13.41	20.10	27.2
Short grass	37.85	19.56	33.63	23.80	4.53	6.79	19.4
Evergreen pine forest	19.71	10.19	20.21	14.30	3.17	4.75	10.9
D. broad leaf forest	42.85	22.14	31.65	22.40	4.85	7.27	20.0
Deciduous shrubs	9.79	5.06	11.59	8.20	1.65	2.47	5.6
Non-vegetated	12.75	6.59	8.36	5.91	38.15	57.18	14.9
Open water	7.16	3.70	-	-	0.96	1.44	2.0

When it comes to the surface runoff generation, 57% of the total runoff comes from the non-vegetated area, which constitutes 15% of the total project area. Such results are important in assessing the effect of future land use changes.

DISCUSSION OF THE METHODOLOGY

The ODE integration is a state of art of integrating GIS and hydrological models. Integrating distributed hydrological model like WetSpass with ARC/INFO and making an interface facilitates input data preparation and output visualization. Scenario based runs can also be done to simulate the effects of future land use changes.

Using ODE makes it easier for one to select his/her own development environment so that one has better control in the functionality as well as appearance of the applications. The hydrological model will also run in the operating system rather than the ARC prompt(as is the case in an AML script), which gives increased speed of execution. This, in part, comes from the fact that the integration is done by a compiled languages than interpreted ones(like AML).

On the other hand development of applications by OSF/Motif and C needs lengthy programming. Even though it is called ‘Open Development Environment’, one still needs a license from ARC/INFO.

CONCLUSION

More and more environmental and hydrological problems, which require spatially distributed data, are addressed by distributed hydrological models. This often requires the integration of very large volume of disparate information from numerous sources. GIS provide the right environment for handling this type of information. GIS integrated hydrological models automates the repetitive work required in analyzing scenario based runs as well as provides a user interface. The ODE integration has shown a greater flexibility in the selection of development environment while the application itself requires a lengthy programming.

Future direction of works is to add groundwater flow models, to apply these for a better understanding of hydrological and environmental problems.

REFERENCE

1. Batelaan, O., De Smedt, F., OTERO, Valle, M., N. and Huybrechts, W. (1993). “Development and Application of groundwater model integrated in the GIS GRASS”. In: Application of Geographical Information Systems in Hydrology and Water Resources (ed. By K.Kovar and H.P. Nachtnebel)(Proc. Int. Conf. HydroGIS93, Vienna, April 1993), 581-589. IAHS publ. no. 211

2. Batelaan, O., Wang, Zhong-Min and De Smedt, F., 1996, "An adaptive GIS toolbox for hydrological modeling. In: Application of Geographical Information Systems in Hydrology and Water Resources (ed. By K.Kovar and H.P. Nachtnebel)(Proc. Int. Conf. HydroGIS96, Vienna, April 1996), 3-9. IAHS publ. no. 235.

3.Engel, B., Navulur, K. and Cooper, B. (1996) "Estimating groundwater vulnerability to non-point source pollution from nitrates and pesticides on a regional scale" In: Application of Geographical Information Systems in Hydrology and Water Resources (ed. By K.Kovar and H.P. Nachtnebel)(Proc. Int. Conf. HydroGIS96, Vienna, April 1996), 521-526. IAHS publ. no. 235

4.ESRI, "Working with the ARC/INFO Open Development Environment": C and Xlib API for UNIX Developers. Copyright 1987 – 1997, U.S.A.

5. Kopp, S.M. (1996) "Linking GIS and hydrological models: where we have been, where we are going?" In: Application of Geographical Information Systems in Hydrology and Water Resources (ed. By K.Kovar and H.P. Nachtnebel)(Proc. Int. Conf. HydroGIS96, Vienna, April 1996), 133-139. IAHS publ. no. 235.

6.Mallants, D. and Feyen, J., 1990, Quantitative and qualitative aspects of surface and groundwater flow (in Dutch), volume 2., KUL, 96p.

7. Olivera, F.(1996). "Spatially Distributed Modelling of Storm Runoff and Non-Point Source Pollution Using Geographic Information Systems (GIS)" PhD thesis, University Texas at Austin, Austin, Texas

8. Stewart, J. B. (1988), "Modeling surface conductance of pine forest, Agr. For. Meteo. 43

9. Van der Beken, A. and Huybrechts, W., 1990, The water balance of Flamish Region: A rational water management via the knowledge of the water balance (in Dutch). Water, 50, pp. 88-92.

10. Vandewiele, G.L., Xu, C-Y. and Ni-Lar-Win, 1993, "Methodology for constructing monthly water balance models on basin scale". VUB-Hydrologie, 20, VUB, Brussel, 57p.

11. Wang, Z. M., Batelaan, O. and De Smedt, F., 1997, "A distributed model for water and energy transfer between soil, plants and atmosphere (WetSpa)", Phys. Chem. Earth, Vol 21, no 3, pp. 189-193.

12. Xu, C-Y, 1992, "Monthly water balance models in different climatic regions". PhD thesis, Vrije Universiteit Brussel, 214 p.