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Investigation of Water Balance at Catchment Scale using MIKE-SHE

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Abstract: The paper presents water balance of Karup catchment, Denmark using integrated catchment modelling tool MIKE SHE. In the present study, water balance in saturated and un-saturated zone was investigated. Beside this, by changing land use water balance is simulated for Karup catchment. Unsaturated zone water balance is characterized by returning 48% water to the atmosphere as evapotranspiration, 49% as percolation and remaining 3% as un-saturated zone storage change. On the other hand, saturated zone water balance is characterized by flowing 28% water to the river as base flow, 50% as drain to river, 20% as saturated zone storage change and rest of are capillary rise and model error. Model simulation shows subsurface storage change was higher during November to February of each year. Beside this, model shows 1982 was quite dry year with low saturated zone storage.

Water balance in Karup catchment will be changed substantially if land use changed from forest and wetland to agricultural use. Model shows, the infiltration will be increased from 49% to 51% which can partly justified by loose soil due to agricultural practice. The storage in the saturated zone will be increased from 20% to 25% and drain to the river will be increased from 50% to 63% consequence of more infiltration. However, subsequently base flow to river will be decreased from 28% to 11%. For proper planning and better management of crops in catchment scale it is worth to have the knowledge about catchment scale water balance. Similar approach can be applied in other catchment to investigate water balance in catchment scale.

Keyword: Water Balance, MIKE-SHE, Karup Catchment, Denmark

1. Introduction

Knowledge about water balance (Carvajal et al., 2014; Darzi-Naftchali et al., 2013) is essential for proper planning and better management of crops in catchment scale. It also gives an essence about water storage in saturated and unsaturated zone. Crop water requirements (Barnard et al., 2013; Kuśmierek-Tomaszewska et al., 2012) is part of planning for sustainable agriculture (Singh, 2014) which is largely depends on our understanding of water balance in catchment scale.

Water balance equation can be used to describe the flow in and out of a system. Simplified form of the water balance equation is:

$$P = Q + ET + \Delta S \dots\dots\dots\dots (1)$$

Where, P is precipitation, Q is runoff, ET is evapotranspiration, and ΔS is un-saturated or saturated zone storage change. Above equation is in principle conservation of mass in a closed system whereby any water entering a system usually by precipitation must be transferred through surface runoff, evapotranspiration and rest amount are stored in subsurface by infiltration.

Crop water requirements are not same for all crops. It is largely depends on Leaf Index Area (Hebert and Jack, 1998; Yan et al., 2012), water availability at root zone, type of crops, spread of root zone etc. Selection of proper crop based on water availability at root zone in a catchment may increase agricultural productivity.

The aim of the work was to assess water availability at root zone as well as investigate water resources spatially and temporally at catchment scale by integrated catchment modelling tool MIKE SHE. Beside this, to simulate the water balances if the land use is changed from present condition of forest and wetland to agriculture.

2. Study area:

Karup catchment (Fig. 1) was taken for the investigation of water balance at catchment scale due to availability of high resolution spatial and temporal data. Karup catchment is located in a typical outwash plain in Western Denmark. Total area of the catchment is 440 km^2. Geology of the catchment homogeneous, consisting of highly permeable sand and gravel. The depth of the unsaturated zone varies from 25m at the eastern part. However, ground water divides about 1 m in the wetland areas along the main river. The aquifer is mainly unconfined with glacial deposit. The aquifer thickness varies from 90m in the east to 10 m in the west and centre part. Slope of the catchment is mild and is drained by the Karup River and about 20 tributaries.

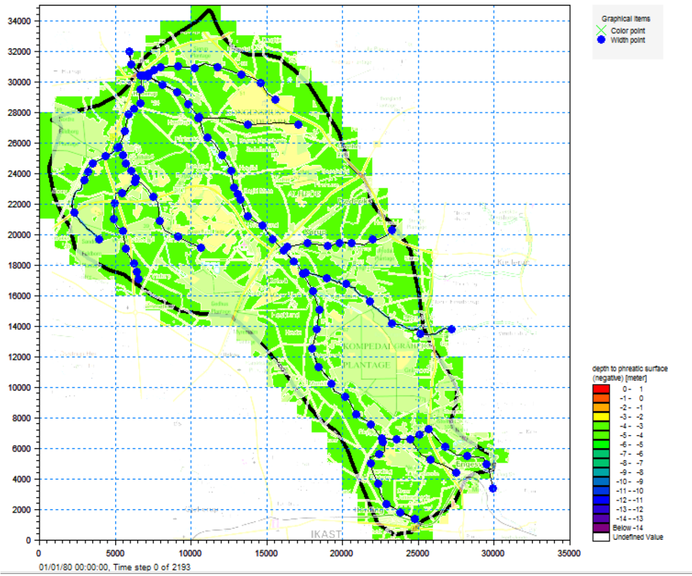

Figure1: Karup catchment with rivers network and computational grid

3. Methodology/Model description:

In the present study water balance of Karup catchment was accessed by MIKE-SHE (Abbott et al., 1986a; Abbott et al., 1986b; DHI, 2007) modelling tool. MIKE-SHE is physically-based, spatially distributed hydrological model that has been widely used to study water resource and environmental problems under diverse climatological and hydrological regimes (Refsgaard and Storm, 1995a).

3.1 Model conceptualization:

A reliable catchment mathematical model should reflect all the important natural processes and should provide the probable human interventions on the system. Important features in catchment scale are rainfall-runoff (Bahat et al., 2009; Post and Jakeman, 1999), irrigation-drainage, infiltration, capillary rise, evapotranspiration, soil moisture, base flow etc.

The usefulness of the MIKE SHE was shown in many works around the world (Carr et al., 1993; McMichael et al., 2006; Refsgaard and Storm, 1995b). It was chosen, MIKE SHE for the Karup catchment over other packages such as commonly used MODFLOW(Dong et al., 2012; Ou et al., 2013) because MIKE SHE is able to model in more detail the interaction between evaporation and shallow water table. It is also able to simulate in a modern way the interaction between surface water from channels and rivers and the ground water system (Demetriou and Punthakey, 1999). MIKE SHE provides a better evapotranspiration module with root extraction as well as a comprehensive module for river flow. Beside this, note that MIKE SHE provides a coupled saturated and unsaturated zone while MODFLOW is not able to simulate the flow through the unsaturated zone (Demetriou and Punthakey, 1999).

3.2 MIKE SHE water movement module

MIKE-SHE water movement module has been developed with a modular program structure containing of different process-oriented components, each describing a major flow process of the hydrological cycle. The component utilised in Karup catchment model are described in below:

Evapotranspiration and interception model:
The evapotranspiration component uses vegetative and metrological input data to predict, with empirically based equations and on spatially distributed basis, the total evapotranspiration and net rainfall amounts resulting from different process in the catchment. These processes include evapotranspiration from canopy surface, evapotranspiration from soil surface, interception of rainfall by the canopy, drainage from the canopy and finally, uptake of water by plant roots and its transpiration. This component interacts with the unsaturated zone component, providing net rainfall and evapotranspiration loss rates and using information in soil moisture conditions in the root zone. The model was developed by at the Royal Veterinary and Agricultural University in Denmark (Kristensen and Jensen, 1975). The calculated actual evapotranspiration is based on potential evapotranspiration rate and the actual soil moisture content in the root zone, are required as input data.

Overland flow and Channel flow component:
When the net rainfall rate surpasses the infiltration capacity of the soil, water starts to flow towards river system as surface runoff. The route and quantity is determined by the topography and flow resistance as well as by losses due to evaporation and infiltration along the flow route. River system gets water from surface and sub-surface flow. Both overland (2D) and the channel (1D) flow are modelled by the approximations of St. Venant equations (Gugat and Leugering, 2009).

Unsaturated zone component:
The unsaturated zone component links the two horizontal and three dimensional surface and surface and sub-surface flow processes together. The flow is described by the one-dimensional governing equation known as Richards' equation (Ritzema, 1994). Soil water systems comprise three phases; solid, liquid and gas that introduce non-linear terms in the Richards' equation. Note that, knowledge about soil physical properties is essential to solve Richards' equation. The upper part of the unsaturated zone includes root extraction for the transpiration process. The interaction between the unsaturated and saturated zone is solved by an iterative mass balance procedure.

Saturated Zone component:
The saturated zone component of the MIKE SHE calculates the saturated sub-surface flow in the catchment. MIKE SHE able to simulate fully three dimensional flows in a heterogeneous aquifer with condition shifting between confined and unconfined aquifer. The spatial and temporal variations of the dependent variable (the hydraulic head) is described mathematically by the non-linear Boussinesq equation (Zavala et al., 2007)and solved numerically by an iterative finite difference method (de Campos et al., 2014).

River/aquifer exchange component:

River system influences greatly on groundwater system in a catchment as it pass through the catchment in many directions. The impact of the river on ground water heads is on both horizontal and vertical directions. The surface area of the river system is small compared to the Karup catchment area and even some place width of the river is smaller than width of a single cell in the computational domain therefore separate cell was assigned for calculation of river flow. Interaction among the river, the ground water and the overland flow is assumed to take place in the middle of the intermediate river links connecting adjacent computational nodes.

3.3 Time step calculation

The time step for different flow processes in Karup catchment are varies. For instance, the surface flow component reacts much faster on a rainfall input than the subsurface flow component. Thus, optimal timestep size i.e. largest possible timestep without introducing any numerical errors is different for the each component. Beside this, the optimal timestep size varies in time as a consequence of different conditions in the hydrological regime within the catchment. MIKE SHE is capable to run different component with varying timestep. The unsaturated zone, exchange and open channel overland flow components use same timestep. As the results are less sensitive to timestep in the MIKE SHE water movement module saturated zone component, so users have the freedom to specify larger timestep for this component.

4. Result and discussion

After building the Karup catchment model, the model was run to investigate water balance in catchment scale. Figure 2 shows total water balance of Karup-catchment. Rainfall was the source of water in the given system. Water balance in unsaturated zone is shown in Table 1.

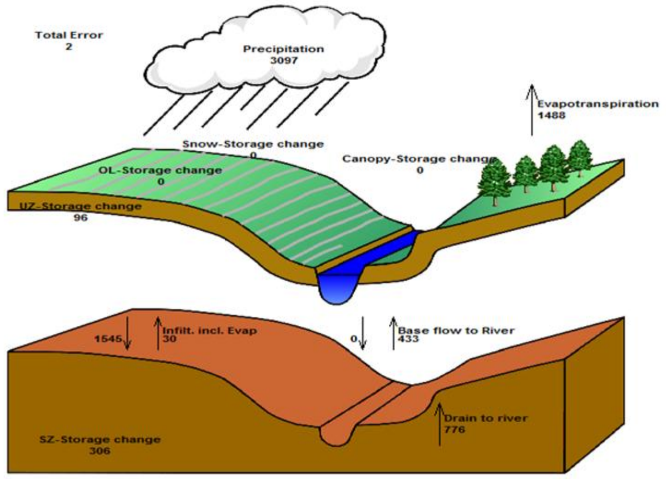

Figure 2: Total Water Balance in Karup catchment

Table 1: Water balance in unsaturated zone

Hydrological components	Water coming in (mm)	Water going out (mm)
Precipitation	3097	
Evapotranspiration		1488
Percolation		1545
Infl. incl. Evap.(capillary rise)	30	
Total	3127	3033

Precipitation – evapotranspiration - percolation + capillary rise + error = UZ Storage change

3097 - 1545 + 30 -1488 +2 =**96** mm

About 48% of the water returned to the atmosphere through the evapotranspiration, this value includes the water that evaporated from the soil and transpired through the plant. The evapotranspiration was high because of the land was cover with agriculture, forest & heath and some area of wetland. About 50% of the precipitation was infiltrates and percolates. The water that was able to infiltrate mainly return to the river via the drain and base flow. The canopy, snow and overland storage changes were 0 and the total amount of error from the model was 2. So it can be said that precipitation, evapotranspiration and infiltration were the main governing factors in the overall water balances. Figure 3 shows incremental water balance of the catchment.

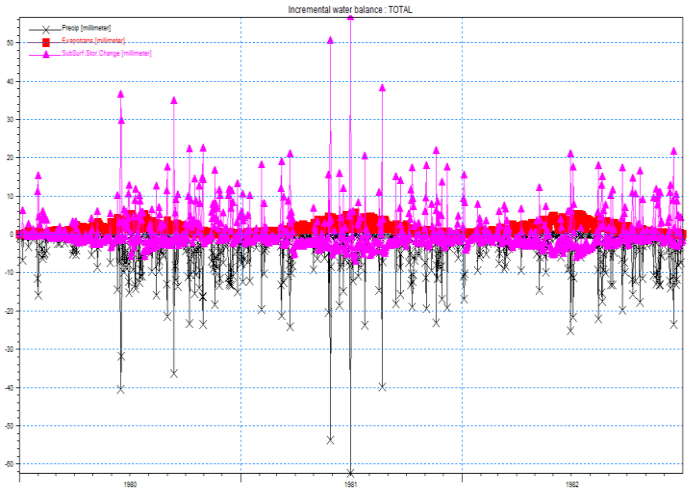

Figure 3: Incremental Water Balance

Figure 3 shows that the evapotranspiration (ET) was high from May to August. The precipitation was higher during June to August and the subsurface storage change was higher during November to February of each year. The highest peak of precipitation was occurred at the end of June 1981, the second peak was occurred at the beginning of June in 1980. However, 1982 was quite dry year with very low peak discharge. Figure 4 shows that the highest discharge was occurred at November 1981 and the second highest discharge was occurred at March in same year and very low flow during 1982. Water balance in saturated zone is shown in Table 2.

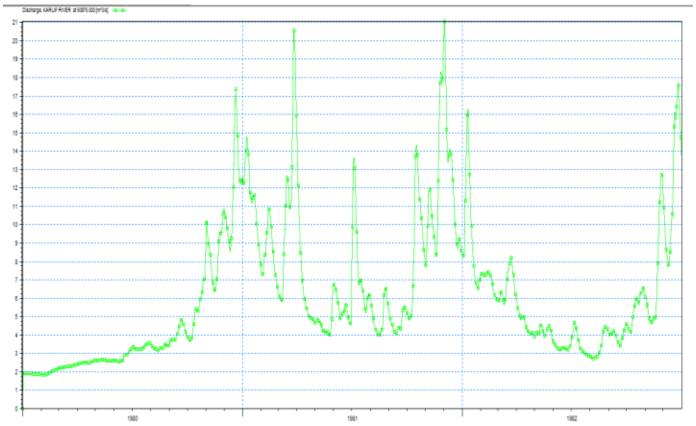

Figure 4: Hydrograph of Kharup River during simulation period

Table 2: Water balance in saturated zone

Hydrological components	Water coming in (mm)	Water going out (mm)
Percolation	1545	
Base flow to river		433
Infl. incl. Evap.(capillary rise)		30
Drain to river		776
Total	1545	1239

Percolation – Base flow to river - Infl. incl. Evap.(capillary rise) - Drain to river = SZ Storage change
1545- 433 - 30 -776 = **306** mm

It is shown in Figure 2, the infiltration has effect on the all hydrological components of the water balance in the saturated zone and the infiltration is proportionately related to the precipitation. The percolation to the saturated zone (recharge) was relative to the saturated zone storage change, when the infiltration was high the storage change in the saturated zone was also high and vice versa.

The infiltrated water was divided into two direct components, drain to the river and storage in the saturated zone. Then part of the saturated zone storage goes as a base flow to river. It also noticed that there was no flow from the river to the aquifer. From the time series data we noticed that the SZ storage change was high from November to February. It is also desired after some time lag of high precipitation period the saturated zone storage should be maximum. But for low rainfall at 1982 was effect on storage in the SZ (Figure 5).

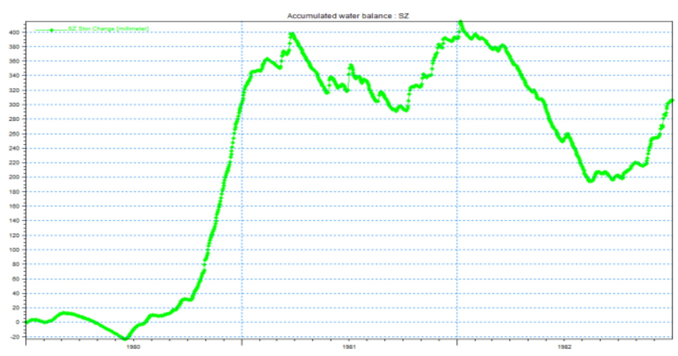

Figure 5: Saturated zone storage change

We also endeavor to see the scenario of water balance in Karup catchment if land use changed from forest and wetland to agricultural use. Figure 6 shows total water balance after land use change in Karup catchment. Table 3 and 4 shows water balance in saturated and unsaturated zone after land use change.

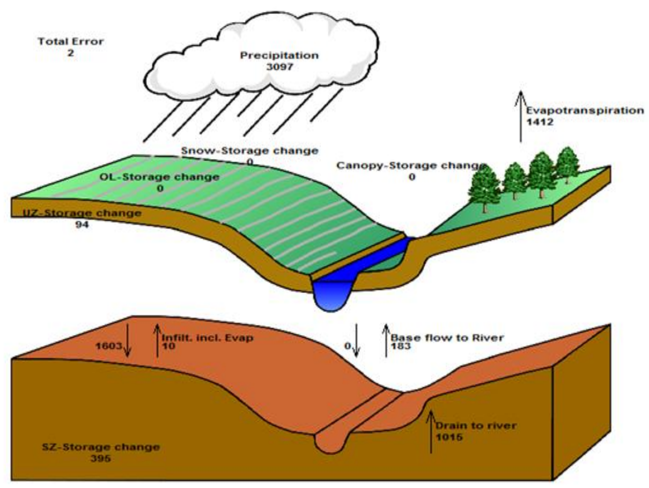

Figure 6: Total water balance after land use change

Table 3:Water balance in unsaturated zone after land use change.

Hydrological components	Water coming in (mm)	Water going out (mm)
Precipitation	3097	
Evapotranspiration		1412
Percolation		1603
Infl. incl. Evap.(capillary rise)	10	
Total	3107	3015

Precipitation – evapotranspiration - percolation + capillary rise + error = UZ Storage change
3097 - 1412 + 10 -1603 +2 =**94** mm

Table 4: Water balance in saturated zone

Hydrological components	Water coming in (mm)	Water going out (mm)
Percolation	1603	
Infil. incl. Evap		10
Base flow to river		183
Drain to river		1015
Total	1603	1208

Percolation - capillary rise - Base flow to the river - Drain to the river = storage in Saturated zone.
1603 – 10 – 183 – 1015 = 395mm

Change the land use is one of the main conditions which influence hydrologic processes. Here the forest and wetland area were changed into agricultural uses. If we do this, the amount of evapotranspiration will be decreased in the catchment from 1488 mm to 1412 mm (Figure 6) because forest transpired more water and interception evaporation was also more in forest area beside evaporation rate was higher in wetland area than agriculture area. The infiltration will be increased from 1545 to 1603mm because the forest intercepted some water, but after deforestation more water reached into the soil and increased the infiltration beside this for agricultural practice the soil will be loose enough to permit more infiltration. The amount of storage water in unsaturated zone will be reduced from 96 to 94, because agricultural crops took the require water from the unsaturated zone. The storage in the saturated zone will be increased from 306mm to 395 mm consequence of more infiltration. For agricultural practice the soil was loose for this reason drain to the river will be increased from 776 mm to 1015 mm as a result base flow will be decreased to river 433 mm to 183 mm (Figure 6).

Figure 7 shows the comparison of storage change in saturated zone between initial model and after changes the land use. Figure 7 shows saturated zone storage will be increased after land use change.

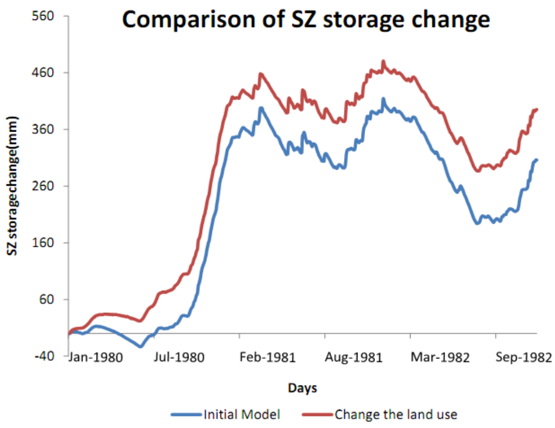

Figure 7: Comparison of accumulated water balance in saturated zone between initial model and after changes the land use

5. Conclusion

The paper presents water balance of Karup catchment, Denmark using integrated catchment modelling tool MIKE SHE. Major components of MIKE SHE using in Karup catchment modelling was described. The model was run for a period three years from 01/01/1980 to 01/01/1983.

Water balance in saturated and un-saturated zone was investigated. Precipitation was the main source of water in the Karup catchment. Unsaturated zone water balance is governed by returning 48% water to the atmosphere as evapotranspiration, 49% as percolation and remaining 3% as un-saturated zone storage change. On the other hand, saturated zone water balance is governed by flowing 28% water to the river as base flow, 50% as drain to river, 20% as saturated zone storage change and rest of are capillary rise and model error. Model simulation shows subsurface storage change was higher during November to February of each year. Beside this, model shows 1982 was quite dry year with low saturated zone storage.

We also endeavor to see the scenario of water balance in Karup catchment if land use changed from forest and wetland to agricultural use. Model shows, the infiltration will be increased from 49% to 51% because the forest intercepted some water, beside this for agricultural practice the soil will be loose enough to permit more infiltration. The storage in the saturated zone will be increased from 20% to 25% consequence of more infiltration. Due to agricultural practice and loose soil, drain to the river will be increased from 50% to 63% as a result base flow to river will be decreased from 28% to 11%.

For proper planning and better management of crops in catchment scale it is worth to have the knowledge about catchment scale water balance. Crop water requirements and water availability in a catchment is a resource for sustainable agriculture and food security. MIKE SHE is able to simulate water balance spatially and temporally in a sensible way. Similar approach can be applied in other catchment to investigate water balance in catchment scale.

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