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Combined Modelling of Groundwater Table and Open Water Level in Raised Mires

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Wetlands are mostly characterized by a large proportion of open water and frequent inundation. In most soil water flow models little attention is payed to phenomena related to open water. In this study, limitations of one dimensional soil water flow models in wetlands are identified. A simple model approach for incorporating the relation between open water and groundwater in soil water flow models is introduced. This model concept is implemented in an extended version of the SWATRE model and tested with data from three lowland raised mires (Engbertdijksvenen, Fochteloërveen (The Netherlands) and Leegmoor (Germany)). The model runs are evaluated by comparing measured and calculated groundwater levels. Results show that the runs with the extended SWATRE model (Standard Error of estimate 4.32-10.9 cm) are considerably better than runs with the standard SWATRE model (Standard Error of estimate 17.6-33.2 cm). It is concluded that a modified quasi two-dimensional approach improves the simulation of water table fluctuations in wetlands.

Introduction

In recent decades, the hydrology of many wetlands in north-western Europe has changed drastically as a result of human activities, such as drainage, peat excavation, groundwater extraction *etc*. These processes caused desiccation and resulted in changes in vegetation. Many typical wetland species have become rare or extinct. Only recently, the interest for wetlands and their restoration has increased (Wheeler *et al.* 1995). In The Netherlands and Germany the restoration of raised mires was in-

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vestigated a.o. by Blankenburg and Kuntze (1987), Eggelsmann (1987), Joosten (1992), Schouwenaars (1993). In many wetlands, measures have been prepared and undertaken to raise the groundwater levels.

Hydrological models are an important tool to predict the effectiveness of hydrological measures. Regional models are used to assess the impact of regional water management plans. One-dimensional site models however, are used to study groundwater behaviour at a specific site with a certain hydrological position. These one-dimensional, soil water flow models calculate both pressure heads in the unsaturated zone and groundwater table fluctuations; both important factors for vegetation development and growth. However, the handling of such soil-vegetation-atmosphere models in wetlands is often difficult, because such models are designed usually for the simulation of (ground)water flow in well drained, agricultural land. Instead, the hydrology of wetlands is commonly characterized by a large proportion of open water and frequent inundation. Schouwenaars (1995) and Beets (1992) described the importance of open water distribution on groundwater behaviour in cutover raised mires.

In this study, limitations of soil water flow models in wetlands are illustrated with the soil water flow model SWATRE (Belmans *et al.* 1983; Feddes *et al.* 1988). To solve these problems, modified concepts in a quasi two-dimensional modelling approach were proposed by Spieksma and Schouwenaars (in prep.). In this model approach, shortly discussed here, fluxes between open water and groundwater are calculated and both groundwater and open water levels are computed. These model concepts are incorporated in SWATRE. This extended SWATRE model is tested with data from three different cutover lowland raised mires; Engbertsdijksvenen, Fochteloërveen (The Netherlands) and Leegmoor (Germany).

Problem Identification

From efforts to simulate water movement in a bog wetland with the site model SWATRE the following became evident.

1) SWATRE calculates vertical water flow in the soil and drainage to or infiltration from a ditch. The model has an option to input the level of the open water in the ditch, so that infiltration from or drainage to the ditch can be calculated (Fig. 1). However, SWATRE does not calculate the open water level itself. In wetlands, this is an important omission, because the groundwater level and open water level are strongly related and both vary in time. Furthermore, no attention is given to differences in water storage between the soil and open water. This is demonstrated in Fig. 2a and 2b, where the calculated water table drops too much during the dry period.

2) In SWATRE a constant value for the maximum amount of water on the surface must be given. The water, exceeding this value will be discharged. This so called maximum inundation depth is not a realistic concept for wetlands, because the inun-

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dation depth varies considerably with rainfall and runoff. Another problem is the error propagation as a result of the concept of maximum inundation depth. If for instance no inundation is allowed in the model, all inundation water is discharged immediately and the groundwater level drops too fast and too much in the period after inundation (Fig. 2a). If a high maximum inundation is proposed, too much water is kept in the soil profile. As a result the inundation period is prolonged too long and the water table starts to drop too late, according to the model (Fig. 2b).

Methods

The SWATRE Model

SWATRE simulates vertical water fluxes in the unsaturated zone of a heterogeneous soil profile with water uptake by roots (Feddes *et al.* 1978; Belmans *et al.* 1983; Feddes *et al.* 1988; Wesseling *et al.* 1989). With the finite difference technique, Richard's equation is solved

$$\frac{\delta h}{\delta t} \equiv \frac{1}{C(h)} \frac{\delta}{\delta z} \left(K(h) \left(\frac{\delta h}{\delta z} + 1 \right) \right) - \frac{S(h)}{C(h)} \qquad (1)$$

where h is pressure head (cm), t is time (d), $C(h)=d\theta/dh$ is the differential moisture capacity (cm^{-1}), z is the depth below soil surface (cm), $K(h)$ is the hydraulic conductivity ($\mathrm{cm\ d}^{-1}$) and $S(h)$ is the sink term for the water uptake by roots (d^{-1}). Feddes *et al.* (1978) described the relationship between the pressure head and the root water uptake as

$$S(h) = \alpha(h) S_{\max} \qquad (2)$$

where $\alpha(h)$ is a dimensionless function of the pressure head and $S_{\max}$ is the maximum rate of water extraction by the roots (d^{-1}).

Required model input includes daily data on rainfall, potential soil evaporation and potential transpiration, soil cover and rooting depth, which may vary in time. Besides this, water retention curves $\theta(h)$ and hydraulic conductivity $K(h)$ curves are needed. At the bottom of the soil profile various boundary conditions (pressure head or flux) can be defined.

The soil system is divided into several compartments of equal height. The profile can be split up into layers having different soil physical properties. The model has the option to describe the relationship between the phreatic level and the open water quasi two-dimensionally with drainage resistances. SWATRE also allows for inundation on top of the soil profile.

A Procedure to Describe the Role of Open Water in Water Level Fluctuations

Spieksma and Schouwenaars (in prep.) present a procedure which describes the impact of open water upon groundwater behaviour in wetlands. In Fig. 1 this modified

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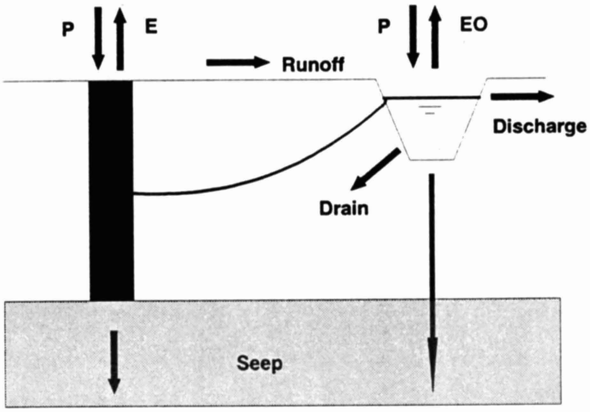

Fig. 1. Calculation of the open water level in the extended SWATRE model (the dark rectangle represents the soil system in SWATRE).

quasi two-dimensional modelling approach in SWATRE is illustrated. The procedure is outlined in short:

At the beginning of a time step, water fluxes and groundwater levels at a site are computed in a one-dimensional soil profile. Horizontal fluxes between the soil profile and the open water are also calculated. Initially, at the end of the time step i the open water level is calculated as

$$OWL(i) = OWL(i-1)+P(i)-EO(i)+SEEP(i)+(DRAIN(i)+RUNOFF(i))\,\frac{(1-FOWAT)}{(FOWAT)} \tag{3}$$

where *OWL(i)* is the open water level, *P(i)* is precipitation, *EO(i)* is evaporation of open water, *SEEP(i)* is downward or upward seepage, *DRAIN(i)* is drainage to or infiltration from the open water and *RUNOFF(i)* is the amount of water which is transported from the observation site, over the surface, to the open water (all in cm). Both the variables *DRAIN(i)* and *RUNOFF(i)* represent water transport between open water and an observation site. When determining these variables, the proportions of open water and land should be taken into account. For this purpose a dimensionless parameter, called *FOWAT*, representing the areal fraction of open water, is introduced. *DRAIN(i)* is calculated as follows

$$DRAIN(i) = \frac{(GWL(i-1)-OWL(i-1))}{\gamma}\,\Delta t \tag{4}$$

where *GWL(i*-1) is the groundwater level (cm), γ is the drainage resistance (*d*) and Δt is the length of time step *i*(*d*). Permeability of peat is highly variable. In this study on raised mires, the drainage resistance was derived from model calibration.

If, after calculation of the open water level with Eq. (3), the open water level ex-

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ceeds surface level, then this water is distributed equally over the whole area, according to

$$INUN(i) = FOWAT(OWL(i) - SURFACE\ LEVEL) \tag{5}$$

where $INUN(i)$ is inundation depth (cm) and $SURFACE\ LEVEL$ is the surface level, usually taken as reference (0 cm). Because now $FOWAT$=1, it clearly follows that

$$OWL(i) \equiv SURFACE\ LEVEL + INUN(i) \tag{6}$$

Discharge can be expressed as a function of the water height above an outlet and is substracted from $OWL(i)$. Different adjustments of the open water level are needed for different stages of inundation (Spieksma and Schouwenaars, in prep.).

Procedures for Model Evaluation

To extend the applicability of the SWATRE model, the model approach as introduced in the preceding section has been attached to the SWATRE model. The extended SWATRE model is compared with the standard SWATRE model using data from Engbertsdijksvenen. The extended SWATRE model is tested further with data from two lowland bogs: Leegmoor and Fochteloërveen. The model runs are evaluated by comparing the measured and predicted (ground)water levels. For an accurate comparison, measured and predicted (ground)water levels were also plotted against each other.

To verify statistically whether the proposed model approach leads to better simulations, the following procedure was used. It is adapted from McCuen and Snyder (1986). If y_i is the measured water level on day i (i=1,..,n) and $\bar{y}$ is the mean water level of the considered period, then the total variation TV of the measured water levels y_i is represented by

$$TV = \sum_{i=1}^{n} (y_i - \bar{y})^2 \tag{7}$$

The total variation TV can be separated in explained variation (EV) and unexplained variation (UV) (see also the Appendix)

$$TV \equiv UV + EV \tag{8}$$

where

$$UV = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{9}$$

in which $\hat{y}_i$ is the water level predicted by the model. UV is easily transformed into the standard error of estimate

$$SE = \left(\frac{UV}{n}\right)^{\frac{1}{2}} \tag{10}$$

The standard error of estimate has the same dimension as y and its magnitude is a

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physical indicator of the error. The efficiency of fitting *EFF* is defined by the proportion of *TV* which can be explained

$$EFF \equiv \frac{EV}{TV} \equiv \frac{TV-UV}{TV} \tag{11}$$

Obviously, when the fit is perfect, $EFF=1$. For $0 < EFF < 1$, the prediction by the model $\hat{y}_i$ is a better estimator of the water level than the mean water level $\bar{y}$. *EFF* can even become negative when $UV > TV$. In that case $\bar{y}$ is a better estimator than $\hat{y}_i$.

Site Descriptions - Table 1/Map 1

Engbertsdijksvenen – Engbertsdijksvenen (850 ha) is a cutover raised mire, located in the province Overijssel in the eastern part of The Netherlands. The last peat cutting ended in 1984. Since the beginning of the '80s, attempts have been undertaken to restore conditions suitable for the reestablishment of the former bog vegetation by raising and controlling the water level (Beets 1993). Vegetation at the study site (25 ha) is dominated by *Molinia caerulea* with a root depth of 40 cm. Required model input data were derived from experimental research (Schouwenaars 1992; Schouwenaars and Vink 1992).

Leegmoor – Leegmoor (300 ha) is a cutover raised mire, situated in Lower Saxony, Germany. The area used to be part of the southern confines of the former, much larger, Esterwege Dose. In 1983 large scale, industrial peat cutting was stopped in a part of the Leegmoor (60 ha) and rewetting and regeneration started. At that time the surface was almost completely bare. The area was colonized by *Molinia caerulea* and *Eriophorum vaginatum* and in 1987 *Sphagnum* mosses reestablished. According to the growth of *Molinia caerulea* and *Eriophorum vaginatum*, the root depth increased from 10 cm in 1984 towards an estimated value of 25 cm in 1988. Required model input came from experimental research in Leegmoor (Eggelsmann and Blankenburg 1993). Water retention curves and unsaturated conductivities were obtained from Schouwenaars and Vink (1992).

Fochteloërveen – Fochteloërveen (1,700 ha) is located in the provinces Friesland and Drenthe in the north of The Netherlands. The last, local peat cutting concessions expired in 1980. Although peat cutting did not affect the whole of the Fochteloërveen, peat burning did. In 1985 large scale rewetting measures were carried out. At the study site (7 ha), the dominant vegetation is *Molinia caerulea*, with roots up to a depth of 50 cm. Since 1994, groundwater levels are measured daily, with data loggers. These data, as well as other required model input, were obtained from ongoing research.

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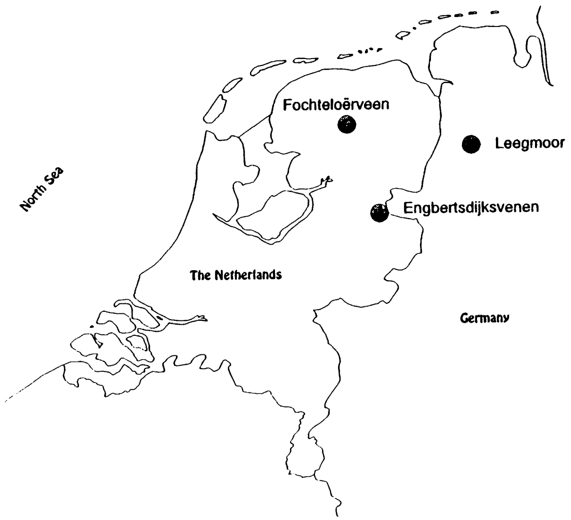
Table 1 – Characteristics of the study sites

study site	catchment size (ha)	rewetting since	peat (cm) thickness	root depth (cm)
Engbertsdijksvenen	25	1984	200	40
Leegmoor	60	1983	150	10-25
Fochteloërveen	7	1985	60	50



Map 1. Location of the study sites.

Results and Discussion

Modelling Results of the Extended SWATRE Model; Three Cases

Engbertsdijksvenen – For the simulation of water flow with the extended SWATRE model in a soil profile in the Engbertsdijksvenen, the same location and period, (1 Oct. 1988-31 Sept. 1989, was selected as for the model runs with the standard SWATRE. The peat base acted as bottom boundary of the model. The results are presented in Fig. 2c and can be compared with Fig. 2a and 2b. Fig. 2c shows that the calculated groundwater level estimates the measured groundwater level quite well. Both the fluctuations of the groundwater level and the inundation are described properly in Fig. 2c, whereas in Fig. 2a and 2b this was not the case.

The soil profile dried substantially due to a relatively small amount of rainfall in the calculation period (660 mm). The fraction open water (*FOWAT*) was estimated at 30%, the drainage resistance at 50 days. Here, as a result of peat cutting, a pattern of dry baulks (parallel strips of peat, width: 2-4 m) and inundated wet baulks (width: 2-4 m) was left behind. The low drainage resistance accounts for the accurate buffer-

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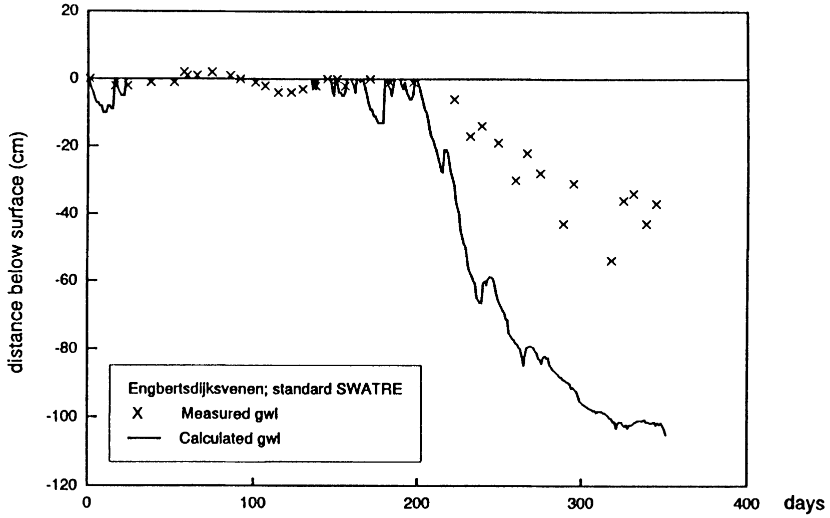

Fig. 2a. Measured and calculated groundwater levels in Engbertsdijksvenen (standard SWATRE model, no inundation allowed; period 1 Oct 1988-31 Sept 1989).

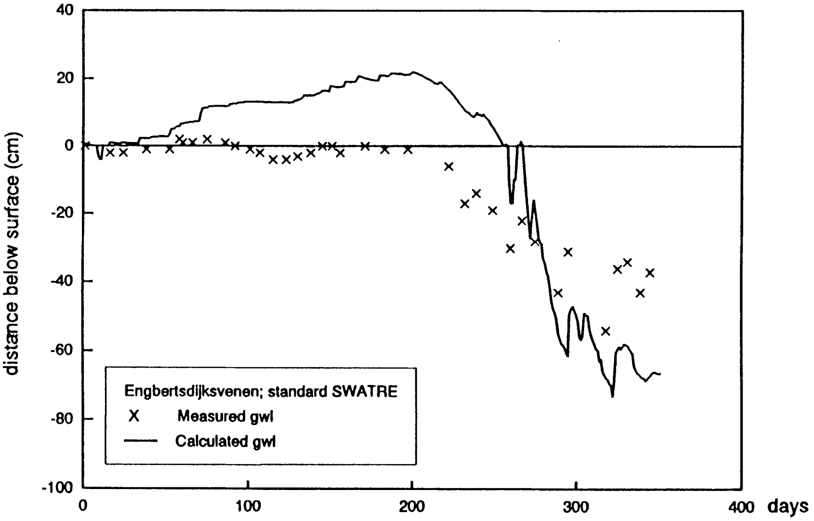

Fig. 2b. Measured and calculated groundwater levels in Engbertsdijksvenen (standard SWATRE model, unlimited inundation allowed; period 1 Oct 1988-31 Sept 1989).

ing of groundwater levels by the open water level during the dry season. The hydraulic head in the underlying sandy aquifer always remains below the peat base. The calculations with the extended SWATRE estimated the downward seepage at 66 mm. Calculated discharge amounted to 215 mm, whereas 187 mm was measured (Table 2).

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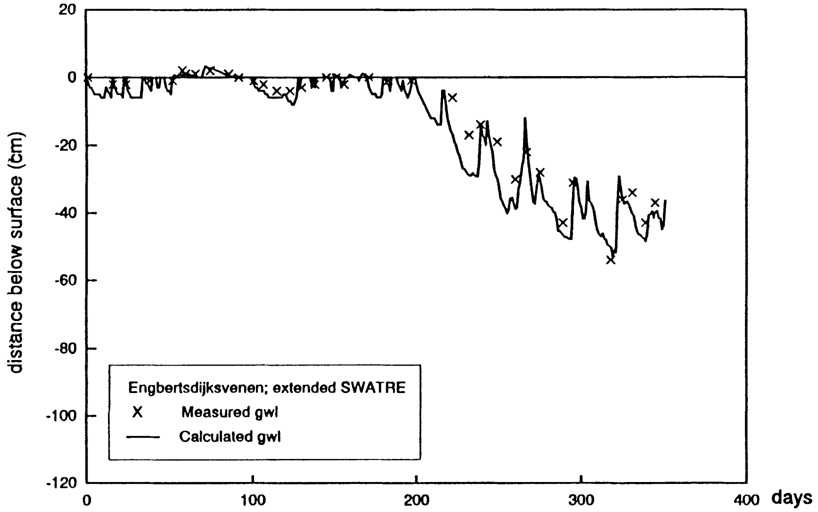

Fig. 2c. Measured and calculated groundwater levels in Engbertsdijksvenen (extended SWATRE model; period 1 Oct 1988-31 Sept 1989).

Table 2 – Rainfall, downward seepage and discharge at the study sites

site	rainfall (mm)	downward seepage (mm)		discharge(mm)	
		measured*	calculated	measured	calculated
Eng'venen '88-'89	660	74	66	187	215
Leegmoor '85	739	30	60	34	121
Leegmoor '86	687	30	65	62	142
Leegmoor '87	875	30	53	49	137
Leegmoor '88	917	30	54	232	268
Foch'veen '94	979	-	77	-	367

* derived from water balance studies

Leegmoor – For the Leegmoor area model runs were made with data from the period 1 Nov. 1984-31 Oct. 1988. The peat base acted as bottom boundary of the model. *FOWAT* was estimated at 20%, the drainage resistance at 200 days. The results are presented in Fig. 3.

Although the trend of the predicted and measured (ground)water levels is the same, the fluctuations as described by the model are somewhat overestimated. Generally, at the start of the calculations groundwater levels are higher than predicted levels, whereas in the last year calculated levels are lower. The cause for this probably lies in the soil physical data. The soil physical data from another area (Engbertsdijksvenen; Schouwenaars and Vink 1992) were used and, most likely, the soil physical properties of the soil changed gradually between 1984 and 1988 (parameter drift). In 1984 the study area was bare and rewetting just had started, while in 1988

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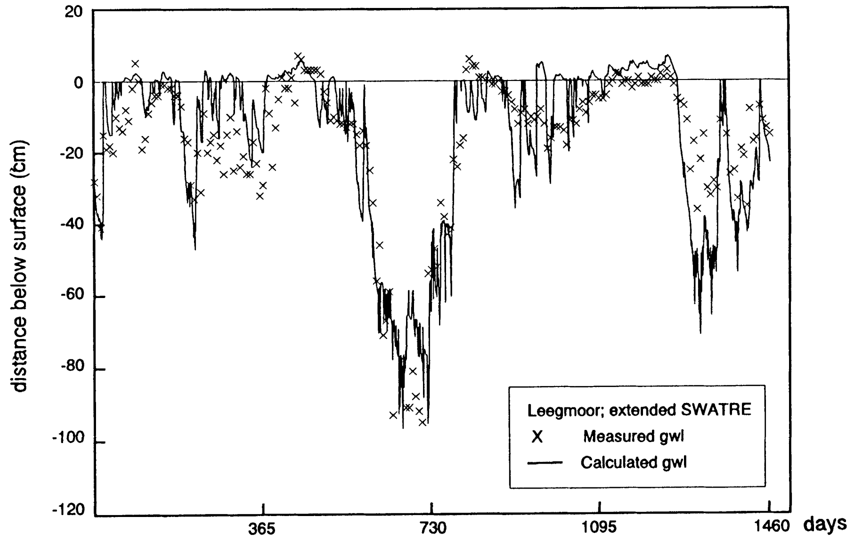

Fig. 3. Measured and calculated groundwater levels in Leegmoor (extended SWATRE model; period 1 Nov 1984-31 Oct 1988).

Sphagnum mosses had returned. SWATRE does not allow for a gradual change in soil physical data.

Also, both the calculated discharge and downward seepage are consistently higher than reported by Eggelsmann and Blankenburg (1993) which is probably due to the use of different rainfall stations (Table 2). Presumably, two factors are responsible; firstly, the input rainfall (3,316 mm) is higher than the rainfall in the water balance of Eggelsmann and Blankenburg (1993) (3,218 mm), secondly the complex structure of polders in the Leegmoor area induces surface water movement which was difficult to quantify.

Fochteloërveen – Data from the period 1 Jan. 1994-1 Jan. 1995 were available for simulations in Fochteloërveen. Because of the thin peat layer (60 cm) at the study site, the groundwater level drops below the base of the peat in summer. Therefore, the bottom boundary of the model is established at 150 cm below surface. The results are presented in Fig. 4.

At this location the groundwater level does not reach the surface. The matching of the calculated and measured groundwater level is good, although the extreme peaks in the summer (day 200-275) are not described adequately by the model. These extreme peaks are caused by some massive precipitation events (day 207: 42 mm; day 225: 30 mm; day 258-259: 60 mm). The open water at the study site is confined to one pool, which comprises 10% of the total area. The measured levels of this pool and the calculated open water levels are plotted in Fig. 5c. Drainage resistance was estimated at 100 days.

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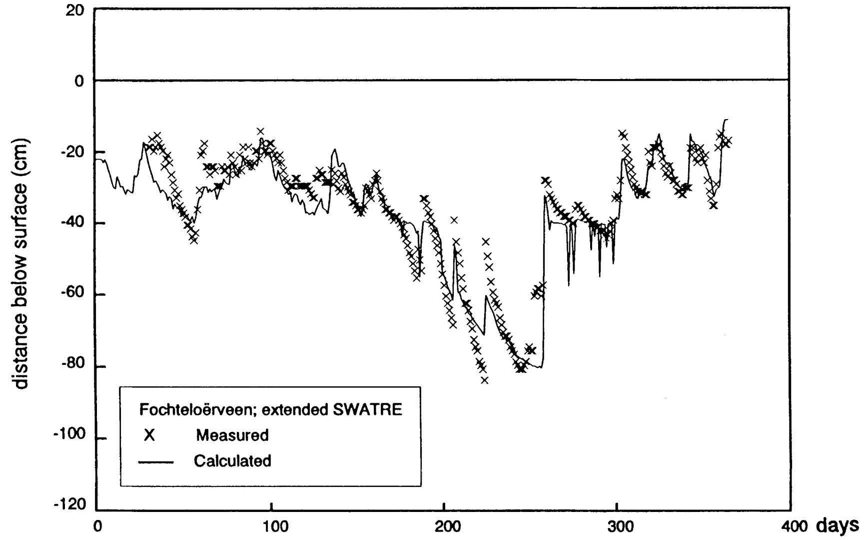

Fig. 4. Measured and calculated groundwater levels in Fochteloërveen (extended SWATRE model; period 1 Jan 1994-1 Jan 1995).

EFF and SE Statistics

The *EFF* statistics were calculated to determine whether the improvements to the SWATRE model lead to a better simulation of the groundwater level. Table 3 shows that this is indeed the case. The simulations with the standard SWATRE model result in negative *EFF*'s, whereas those of the extended SWATRE model are close to 1. The model run of the Engbertsdijksvenen has the best efficiency of fitting. The standard errors of estimate of the simulations of the extended SWATRE model are reasonably small, indicating little systematic deviation between measured and predicted water levels, as well as absence of a systematic trend in the scatter of data points around the 1:1 line (Clemente *et al.* 1994). While systematic deviations usually can be corrected by model calibration, trends in the scatter of data points around the 1:1 line can be an indication of a lapse of the model.

In Fig. 5 the measured and the calculated groundwater levels of the three sites are plotted against each other. In Fig. 5c also the measured open water levels are plotted

Table 3 – Statistics of the model calculations

site	model	Fig.	SE (cm)	EFF (-)
Engbertsdijksvenen	standard SWATRE	2a	33.2	-3.32
Engbertsdijksvenen	standard SWATRE	2b	17.6	-0.21
Engbertsdijksvenen	extended SWATRE	2c	4.32	0.93
Leegmoor	extended SWATRE	3	10.9	0.70
Fochteloërveen	extended SWATRE	4	5.97	0.87

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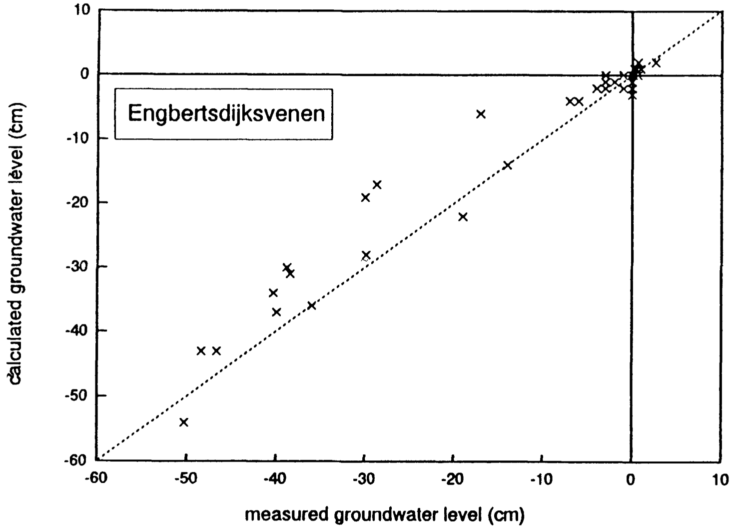
against the calculated open water levels. The scatter of data points of the groundwater levels of the Fochteloërveen site is evenly distributed around the 1:1 line (Fig. 5c). However, at the Leegmoor site there seems to be a trend in data scatter (Fig. 5b). Deep groundwater levels, measured at 60-100 cm below the surface, are generally calculated too shallow, whereas groundwater levels measured at 40-60 cm below the surface are calculated too deep. This may be a result of the previously mentioned change in soil physical properties and the complex polder structure at the site. Finally, at the Engbertsdijksvenen site, it is difficult to distinguish a clear trend (Fig. 5a).

a)



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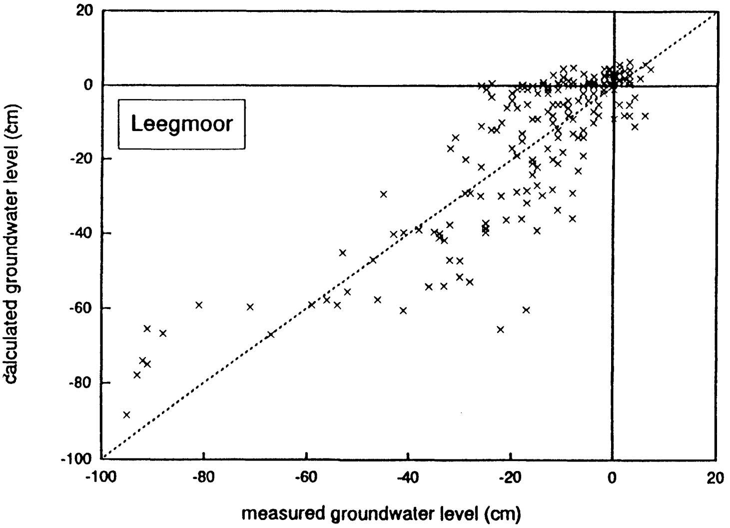

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c)

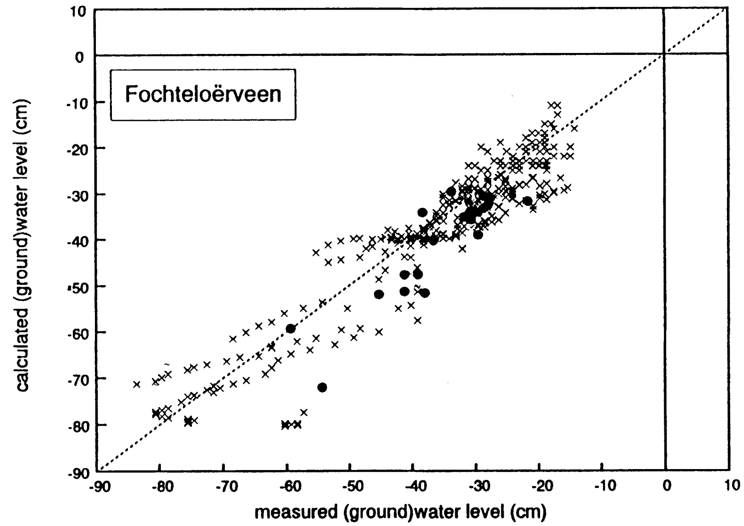

Fig. 5. Measured and calculated (ground)water level (extended SWATRE) plotted against each other. (× = groundwater level, • = open water level); 5a. Engbertsdijksvenen; 5b. Leegmoor; 5c. Fochteloërveen.

Conclusions

This study shows that a one-dimensional soil water flow model like SWATRE has difficulties in modelling water level fluctuations in bog wetlands. Most wetlands have a substantial area of open water, which has a significant influence on the water table. This important relationship between open water and groundwater needs to be taken into account when modelling wetlands. Also, the concept for the modelling of inundation in SWATRE had to be modified.

The extended version of SWATRE, which includes the modelling approach as proposed by Spieksma and Schouwenaars (in prep.), showed good results. Both the buffering of the groundwater by the open water in dry periods and inundation in wet periods, are described properly by the model. However, some problems are recognized: Surface water flow within the study site is not included in the model. Yet, it can be important, as was the case at the Leegmoor site. Secondly, the model run of the Leegmoor suggested that soil physical properties had changed during rewetting. Whereas for most mineral soils, physical properties are a constant, for rewetted peat soils this might not always be the case.

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Appendix

The model results of SWATRE can be regarded as a non linear regression which can be expressed mathematically as

$$\hat{y} = SWATRE\,(x_1, x_2, \ldots x_m) \tag{12}$$

where $\hat{y}$ is a vector containing the predictions of the water level by the SWATRE model and $x_1, x_2, \ldots. x_m$ are the input parameters of the model. The measured water levels y_i have a total variation which can be written as

$$TV \equiv \sum_{i=1}^{n} (y_i - \bar{y})^2 \equiv \sum_{i=1}^{n} (y_i - \hat{y}_i + \hat{y}_i - \bar{y})^2 \tag{13}$$

$$\equiv \sum_{i=1}^{n} (y_i - \hat{y}_i) + \sum_{i=1}^{n} (\hat{y}_i - \bar{y}) + 2\sum_{i=1}^{n} (y_i - \hat{y}_i)(\hat{y}_i - \bar{y}) \tag{14}$$

Because the total variation (*TV)* can be separated in explained variation (*EV*) and unexplained variation (*UV*) (McCuen and Snyder 1986)

$$TV \equiv UV + EV \tag{15}$$

and

$$UV = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{16}$$

it follows that

$$EV = \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2 + 2\sum_{i=1}^{n} (y_i - \hat{y}_i)(\hat{y}_i - \bar{y}) \tag{17}$$

Note that in case of a linear regression the second term of Eq. (17) is zero and *EV* becomes a sum of squares. However, this study does not deal with a linear regression (Eq. (12)). This means that in this study the second term of Eq. (17) is not necessarily zero and *EV* and *EFF* may become negative.

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